Investigating the performance and underlying mechanisms of a novel screening measure for developmental dyslexia: Implications for early identification

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A thesis submitted in partial fulfillment of the requirements of Edinburgh Napier University for the degree of Doctor of Philosophy

June 2018

Declaration

I hereby declare that this thesis is of my own composition, and that it contains no material previously submitted for the award of any other degree. The work reported in this thesis has been executed by myself, except where due acknowledgement is made in the text.

Signed,

Barbara Piotrowska

Acknowledgements

First and foremost, I would love to thank my supervisors, Dr Alexandra Willis, Dr Jennifer Murray and Dr MacLean for their invaluable support, dedicated guidance, and patience. I would never have accomplished my dream of starting and completing a PhD without their excellent supervision.

I would like to thank Professor Jon Kerridge from the School of Computing for providing me with an opportunity to use his novel test and for his constant support, involvement and enthusiasm. I cannot thank Jon enough for all the technical support and help with data collection. Also, Jon's students and collaborators made a positive contribution to the project.

My special thanks to the primary schools in Edinburgh for their enthusiastic participation and support in the project. Many thanks to all my little and grown-up participants without whom this thesis would not exist.

I'm grateful to all my friends and family members who believed in me and encouraged me to continue. In particular, I would like to thank: Kai Li Chung, Agnieszka Mastek, Marcin Palmaka, Anna and Christopher Thomson, Lee Curley, Brian Tame and Marcin Zawisza. Special thanks to my partner Rafal Zyskowski and to my stepmother Barbara Piotrowska for always being there for me.

This thesis is dedicated to the memories of my parents, Elżbieta and Krzysztof

Thesis Abstract

Developmental dyslexia is a common disorder affecting around 10% of the British population characterized by difficulties with reading despite adequate intelligence and education (IDA, 2007). Although most researchers and practitioners would agree that early identification is key in limiting negative consequences of reading problems, this is still difficult to achieve due to theoretical and practical inconsistencies in the field. This thesis focuses on investigating a novel, computer and tablet-based "dot-to-dot" (DtD) task that may aid the process of identification particularly in pre-reading children and English as additional language (EAL) individuals who, by definition, are more susceptible to misidentification. Performance on this task was tested in primary school children (N = 457) and in adults (N = 111) together with a set of dyslexia-sensitive, vision and reasoning tests. Performance on DtD (especially the first sector error) demonstrated significant differences between children at high and low risk of dyslexia (as assessed by Lucid Rapid), as well as between children prospectively identified as poor and typical readers. DtD measures added small but statistically significant unique contributions to the models predicting reading scores and reading level group membership, and DtD measures could distinguish between poor and typical readers as well as between adults with and without diagnosed dyslexia. The findings provide evidence for the DtD test to be a useful addition to existing tests as it presumably relates to a number of mechanisms in line with automaticity and cerebellar deficits theories of dyslexia. It also has a potential to identify a distinct type of dyslexia that is not related to phonological processing which has important theoretical and practical implications.

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List of Abbreviations

Dyslexia Assessment/Screening Tools:

DtD	Dot-to-Dot task designed by Prof. Jon Kerridge
DEST	Dyslexia Early Screening Test
DST	Dyslexia Screening Test
DAST	Dyslexia Adults Screening Test
WPSSI	Wechsler's Preschool and Primary Scale of Intelligence
WISC	Wechsler's Intelligence Scale for Children
WAIS	Wechsler Adult Intelligence Scale

Statistical Abbreviations:

ANOVA	Analysis of Variance
MANOVA	Multivariate Analysis of Variance
MANCOVA	Multivariate Analysis of Covariance

Other Abbreviations:

DD	Developmental Dyslexia
RD	reading disability
DSM	Diagnostic and Statistical Manual of Mental Disorders
BDA	British Dyslexia Association
EAL	English as an additional language
SpLD	Specific Learning Disabilities
SES	Socio-economic status
EF	Executive function
LGN	lateral geniculate nucleus
RAN	Random automatised naming
FDI	frequency doubling illusion
SOP	speed of processing
LD	Learning disabilities
DCD	Developmental Coordination Disorder

Preface

Research undertaken for this thesis has led to the following:

Publications:

1. Piotrowska, B., Willis, A. and Kerridge, J. (2015). *Performance on a novel visual-spatial-motor task may predict reading difficulties in children*. The Psychology of Education review, 39:2, pp. 42-47.

2. Piotrowska, B., Willis, A. (2014). *Visual-spatial-motor performance may predict reading difficulties in children and adults. Preliminary findings from a longitudinal study on young, pre-reading children*. Dyslexia Review, 25: 3, pp. 15-19.

Conference contributions:

1. Piotrowska, B., Willis, A., Murray, J., & Kerridge, J. (2017). *Investigation of visual aspects of developmental dyslexia in children*. Poster presented at the Visual Science Society conference, Florida.

2. Piotrowska, B., Willis, A., Murray, J., MacLean, R. & Kerridge, J. (2017). *Visual aspects of developmental dyslexia: implications for assessing the risk*. Poster presented at the APS Conference, Vienna.

3. Piotrowska, B., Murray, J., Willis, A., Kerridge, J., & MacLean, R. (2016). *Visual-motor integration in dyslexia*. Poster presented at the European Conference on Visual Perception, Barcelona

4. Piotrowska, B., Murray, J., Willis, A., Kerridge, J., & MacLean, R. (2016). *Beyond the phonological deficit in dyslexia: Are visual-motor abilities related to reading difficulties?* Talk given at Cognitive Psychology Section Annual Conference, Barcelona.

5. Piotrowska, B., Kerridge, J., Murray, J., Willis, A., & MacLean, R. (2016). *Visuo-motor integration in dyslexia. The development of a novel screening tool*. Paper presented at Edinburgh Napier University Postgraduate Conference. Edinburgh Napier University, Edinburgh, 6 April.

6. Piotrowska, B., Willis, A., MacLean, R., Murray, J., Kerridge, J. (2015). *Visual-spatial-motor integration in a cross-section of primary-aged children: implications for assessing risk of dyslexia*. F1000Research, 4:692 (poster) (doi: 10.7490/f1000research.1110435.1)

7. Piotrowska, B., Willis, A., Kerridge, J., Murray, J., MacLean, R. (2015). *Novel visual-spatial-motor task as a potential screening tool for dyslexia.* Poster presented at Edinburgh Napier University Postgraduate Conference. Edinburgh Napier University, Edinburgh, 26 March.

8. Piotrowska, B., Willis, A., Kerridge, J., Murray, J., MacLean, R. (2014) *Performance on a tablet-based visual-spatial-motor task is compromised in adults and children with dyslexia: implications for the development of a novel screening tool.* Paper presented at BPS Educational Psychology Section Annual Conference Learning and Teaching in a Changing Educational Context, Milton Keynes, 7-9 November.

9. Piotrowska, B., Willis, A., Kerridge, J., Murray, J., MacLean, R. (2014) *Performance on a tablet-based visual-spatial-motor task is compromised in adults and children with dyslexia: implications for the development of a novel screening tool*. Poster presented at Dyslexia Guild Annual Summer Conference, Lincoln, 19 June.

10. Willis, A., Bannach-Brown, A., Piotrowska, B., MacLean, R., & Kerridge, J. M. (2014). *Performance on a tablet-based visio-spatial-motor task is compromised in adults and children with dyslexia: Implications for the development of a novel screening tool.* Poster presented at the British Dyslexia Association International Conference, Guildford, UK.

11. Piotrowska, B., Willis, A., Kerridge, J., Murray, J., MacLean, R. (2014). *Visuo-motor integration in dyslexia: the development of a novel screening tool*. Paper presented at Edinburgh Napier University Postgraduate Conference. Edinburgh Napier University, Edinburgh, 3 April.

Awards and Prizes:

1. EPS Grindley Grant for conference attendance
2. Foundation Grand from Funds for Women Graduates (FfWG) (June 2016)
3. Best extended oral presentation award at Edinburgh Napier University Postgraduate Conference (6th April 2016).
4. Conference fees bursary awarded by European Conference on Visual Perception (August 2015)
5. Best Poster presentation awarded Edinburgh Napier University Postgraduate Conference (26 March 2015)
6. Conference fees bursary awarded by BPS Educational Psychology section (November 2015)
7. Conference fees bursary awarded by Dyslexia Guild. Annual Summer Conference, Lincoln, 19 June 2014.
8. PhD Fees-only Studentship awarded by Edinburgh Napier University, October, 2013.

Chapter 1

Research background and introduction to dyslexia

This chapter provides an introduction to the field of developmental dyslexia research. It will focus on the key aspects of the field, including debates around the definitions, the role of intelligence and socioeconomic background, inconsistencies around memory measures, the prevalence of dyslexia, and its comorbidities. The importance of early intervention and the current procedures and policies in regards to dyslexia identification are also discussed within this chapter, providing the rationale for the current research and emphasising the potential benefits reaped from the non-language task that is central to the current investigation within the thesis.

1.1 Research background and motivation

Developmental dyslexia affects approximately 10% of the British population and is broadly defined as difficulties with word recognition, spelling and decoding, despite adequate intelligence, education, and motivation (International Dyslexia Association, 2007). Although phonological difficulties are often seen as the primary features of dyslexia (Snowling, 2000), dyslexia is often associated with wider problems perceiving, attending to, organizing, integrating, timing, and sequencing information. Children identified as having dyslexia often demonstrate deficits in a range of sensory and motor tasks, including motor control (Fawcett, Nicolson, & Dean, 1996), visual motion perception (e.g., Kevan & Pammer, 2009), visual-spatial attention (e.g., Lallier, Donnadieu, & Valdois, 2013), and auditory timing (e.g., Goswami, 2011). However, whether problems in sensory and motor processing underlie phonological difficulties in dyslexia (Vidyasagar & Pammer, 2010) or whether these merely co-exist with them (Ramus, 2003) remains a topic of considerable debate.

Although the nature and causes of dyslexia are debated, as discussed more broadly in Chapter 2, there is a widespread consensus that early identification and intervention are of central importance in both language remediation, and in limiting the low self-esteem and behavioural difficulties so often reported in unrecognized dyslexia (Eissa, 2010; Vellutino, Scanlon, & Tanzman, 1998). A qualitative investigation of young adults' experiences has demonstrated that testing for dyslexia and receiving a dyslexia diagnosis improved their self-esteem (Mcnulty, 2003). Self-esteem has been demonstrated to lead to better educational and psycho-social outcomes for children (Booth & Gerard, 2011; Marsh, Byrne, & Yeung, 1999; Trautwein, Ludtke, Koller, & Baumert, 2006). Despite this, dyslexia diagnoses are often attained at a relatively late stage in a child's educational career (Singleton, 2009).

Longitudinal studies have shown, however, that it may be possible to recognise children at risk of developing reading and writing problems at as early as three years old (Lyytinen et al., 2005). However, schools do not tend to screen children before they start learning to read (Dyslexia Scotland, 2015). The formal identification of reading and writing problems within UK schools typically occurs after children have failed to learn to read, and interventions are only provided when a child falls significantly behind his or her classmates (Singleton, 2009). As dyslexia is a developmental disorder, it is counterintuitive to consider it manifesting itself only after the formal teaching of reading has been introduced. Therefore, research aimed at establishing reliable predictors of reading difficulties at a pre-reading stage is crucial, as it would allow the provision of early support and targeted intervention to minimise a negative cycle of achievement (Stanovich, 1986).

The identification of dyslexia is particularly difficult in individuals who have English as an additional language (EAL). As all of the existing screening tests for dyslexia are based on phonological and language skills, these people may be disadvantaged and perform poorly on the tests in comparison to their English as a first language peers. Everatt, Smythe, Ocampo, and Gyarmathy (2004) emphasised that the assessments designed for English native speakers should be used with caution in individuals speaking English as a second or additional language, as such a practice may lead to underperformance of bilingual individuals without dyslexia. Traditional assessments do not consider language proficiency and bilingualism. Also, the fact that the type of orthography in a person’s first language determines the stage at which reading difficulties might emerge as well as their manifestations are often overlooked (Cummins, 1984; Geva & Siegel, 2000; Goswami, 2000).

Decades of research have shown that, along with the phonological problems being experienced by the individuals with dyslexia, other motor and visual processes may also be compromised. In particular, brain-based hypotheses have suggested that the underlying causes of phonological problems are related to deficits in cerebellar functioning (Fawcett et al., 1996), and/or to deficits in low- and high-level visual processing (Stein, 2001). If dyslexia is caused by these deficits in the brain, then the problems should manifest not only during reading but while performing tasks that require same brain resources as those required during reading. It is argued that if these deficits underlie developmental dyslexia, they should be apparent in children even before they learn to read. If so, it should be possible to develop a screening tool for dyslexia that assesses basic visual and motor skills.

Professor Jon Kerridge and Dr Alexandra Willis from Edinburgh Napier University developed a simple, computer-based “Dot-to-Dot” (DtD) task which is believed to require a combination of visual and motor skills and which may be useful in predicting and screening pre-reading age children for dyslexia. If successful, the task may help educators identify individuals at risk of dyslexia earlier and more quickly than existing tests. Unlike existing tests, it does not depend on any phonological or general knowledge; as such, it has the potential to be developed for use in pre-reading children, and in children and adults from a wide range of linguistic and cultural backgrounds, including those for whom English is an additional language.

1.2 Purpose of the research

This thesis was motivated by the desire to investigate whether non-linguistic, sensorimotor deficits occur in developmental dyslexia, and if so, whether they are apparent and distinctive in young children at risk of dyslexia and in adults with dyslexia. These questions were investigated by the means of a set of quasi-experimental and correlational studies exploring relationships between cognitive, psychometric and perceptual measures. The predictive value in reading skills of these measures was investigated. A particular focus was on the assessment of the new DtD task's potential in identifying and predicting future reading problems. Correspondingly, comparisons of the performance on the DtD measures and established measures for dyslexia between children deemed at risk of dyslexia, children identified as poor readers and adults with a diagnosis of dyslexia versus control groups were examined. Detailed research questions are provided in Chapter 2.

The practical value of this thesis lies in the investigation whether the DtD test can be used as an addition to existing screening tools and to establish whether any measures from this novel test may reliably predict future reading difficulties in primary-aged children. This was particularly important as, if successful, it could potentially help to indicate children at risk earlier than it is currently possible and lead to appropriate interventions being put in place. If demonstrated to be a good predictor, the DtD task could also be used to quantify any changes in sensorimotor skills after interventions have been applied. As dyslexia is often unrecognised throughout primary and secondary school education (Lefly & Pennington, 2000), there is also a need for a suitable screening tool that could be feasibly and reliably used with a minimum of cost layout in adult populations.

The current thesis also adds a valuable theoretical debate on possible causes and the core deficits in dyslexia to the existent literature. Many debates and inconsistencies around dyslexia emerge from a lack of clear operational definition of dyslexia in empirical research (Wagner, Francis, & Morris, 2005). Therefore, the current set of studies explored the impact of different definitions, specifically the cut-off points used to indicate poor readers, on the types and combinations of weaknesses in poor readers. Both of these theoretical and practical issues are addressed in this thesis.

Before focusing on the practical and theoretical issues around dyslexia, it is important to discuss dyslexia in the political and educational context. It is useful to understand current approaches to managing dyslexia by educational staff members in schools, higher education institutions, and in workplaces. The next section provides this context and also offers a discussion of challenges in addressing reading problems.

1.3 Current approaches and challenges to addressing reading problems in educational and workplace contexts

In the UK individuals with dyslexia are protected under the Special Educational Needs and Disability Act (SENDA, 2001) and the Equality Act of 2010. Both laws recognize dyslexia as a type of specific learning disability. SENDA requires that schools take necessary measures to ensure that children and adolescents with disabilities are treated fairly and are offered needed support. Following the Special Educational Needs Code of Practice (Department for Education, 2001), all teachers, from early years up to secondary school level, should be able to recognise the characteristics of dyslexia. When these appear and are identified by a teacher, the child should be referred to the school's Support for Learning teacher, who is then obligated to perform a series of actions, such as building a 'strengths and needs' profile leading to a creation of an individualised program to address the child's weaknesses. While this procedure appears sensible, it has some pitfalls. First, identifying dyslexia is far from straightforward and requires expertise (Rose, 2009). Moreover, typical characteristics of dyslexia are not always easily recognised (Rose, 2009). This may be due to coping strategies developed by children (Tamboer, Vorst, & Oort, 2016), or poor understanding of dyslexia amongst teachers (Dyslexia Action, 2012).

Teachers' knowledge of instructions for beginner readers and those with learning disabilities, including dyslexia, has been a popular topic of research in the last two decades (Bos, Mather, & Dickson, 2001; Piasta, Connor, Fishman, & Morrison, 2009; Spear-Swerling, 2007; Washburn, Binks-Cantrell, & Joshi, 2014). Regan and Woods (2000) showed that primary school teachers and learning support assistants from different Local Education Authority (LEA) areas in England and Wales had diverse understanding of dyslexia, which, in light of policy recommendations that teachers should be able to identify possible weaknesses in children's reading (Department for Education, 2001), is disappointing. Another study by Bell, Mcphillips, and Doveston (2011) investigated the ways in which primary school teachers and specialists in the UK and Ireland understood dyslexia. Dyslexia was mostly described at a behavioural level (e.g., single-word reading problems) by the teachers in both countries. Discounting and the lack of understanding of the biological and cognitive levels of dyslexia and not recognising that problems faced by individuals with dyslexia go beyond just reading difficulties could lead to inadequate assessments and interventions offered by the teachers. The role of diagnosis and whether its importance is recognised by teachers were also addressed in the literature.

Gwernan-Jones and Burden (2010) investigated teachers' attitudes towards dyslexia diagnosis. The majority (68%) of the participants felt that the label of dyslexia can be helpful to teachers and students, although 22% were neutral or unsure about the label being helpful. Furthermore, more than half of the teachers taking part in the study expressed that more training about dyslexia and how to work with dyslexic readers is needed. It has also been argued that those who teach reading should know more about dyslexia (Brady & Moats, 1997; Rose, 2009). Indeed, a report by Dyslexia Action (2012) demonstrated that parents are often the ones who raise the concerns about their children and suggests that training of education staff is required to improve alignment to the procedures outlined in their Code of Practice (Department for Education, 2001). This is particularly important in the light of research findings indicating that teachers overidentify children with reading problems (Madelaine & Wheldall, 2007; Madelaine & Wheldall, 2010; Snowling, Duff, Petrou, & Bailey, 2011). To reiterate, despite all the research and guidance, it seems that teachers may still find it difficult to understand dyslexia, its identification and remediation.

Further to this, there seems to be little consideration of the EAL children within any of the Government policies. While it can be argued that it is not always easy to spot the weaknesses indicating dyslexia in children, it is even more difficult to identify these weaknesses in EAL children. Bigozzi, Tarchi, Pinto, and Accorti Gamannossi (2015), for instance, demonstrated that phonological awareness, which is a good reading predictor in English, is not the best predictor in regular orthographies such as Italian (for more discussion on dyslexia in other languages see section 1.4.2.3). Grimm and Schulz (2014) further demonstrated that bilingual children tend to be over-diagnosed with Specific Language Impairment (SLI) where the central issue may actually be dyslexia. The misinterpretation of dyslexia indicators is therefore problematic among both native English and EAL children, leading to mis- and potentially under-diagnosis.

Dyslexia is a lifelong disorder which does not disappear with age or experience (Bruck, 1992; Swanson & Hsieh, 2009). Improvements in our understanding of dyslexia, in support services and legislative changes (Equality Act, 2010), mean that it is likely that more adults with dyslexia and other learning disabilities are entering into higher education today than in the past (Barnard-Brak, Lechtenberger, & Lan, 2010; Leyser & Greenberger, 2008; Vogel, Vogel, Sharoni, & Dahan, 2003). Students within higher education come from various cultural and language backgrounds. Detailed data on the number of students in the UK higher education institutions that have English as an additional language could not be found. However, it has been estimated that over 20% of first-year students in the UK universities come from outside the UK (Higher Education Statistics Agency, 2016). Although most often the level of their English is relatively high (which is assured by the admission criteria), it is quite unlikely that those individuals have comparable phonological and reading skills to native speakers, and therefore they may be indicated as at high risk of dyslexia on standard, language-based screening tests (Lam, 1993; Lockiewicz & Jaskulska, 2016; Sanchez et al., 2013).

Conversely, it is difficult to determine the contribution of literacy experience, the impact of learning English as an additional language, and whether its orthography is similar to the native language orthography (opaque vs transparent), to literacy acquisition in EAL adults (Harrison & Krol, 2007). In other words, EAL students within higher education may have their reading problems mistakenly interpreted as caused by poor English proficiency. Research suggests that educators are inaccurate in identifying EAL students at risk of reading disabilities (Limbos & Geva, 2001). Regarding adults in higher education, a dyslexia diagnosis is particularly important as it is necessary before gaining appropriate support from the university and to apply for Disabled Student Allowance (SENDA, 2001). To access support in Higher Education, a student needs to have an assessment report post-16 years from either a Psychologist registered with the Health Care Practitioner Council (HCPC) or a specialist dyslexia teacher with an SpLD (Specific Learning Disabilities) Diploma in Further/Higher Education, and an Assessment Practising Certificate (British Dyslexia Association, 2017). However, before students are referred to a certified specialist they have to go through an initial assessment conducted by university support staff.

The complications related to the misclassification of students may occur simply because the majority of the information on developmental dyslexia available to educators is based on research from English-speaking countries (Callens, Tops, & Brysbaert, 2012). This is problematic as English is characterised as having an opaque, or an 'outlier', orthography and the specific difficulties experienced by those for whom English is a native tongue may be different from those speaking other languages, especially those with transparent orthographies (e.g., Italian, Spanish, Polish) (Bigozzi, Tarchi, Pinto, & Gamannossi, 2016; Nalesnik & Baluch, 2010; Tilanus, Segers, & Verhoeven, 2013). In consequence, international students with unidentified dyslexia may not be provided with accurate support, which can contribute to a negative learning experience and anxiety (Mann, Ngor, & Wong, 2013).

Dyslexia has also been found to negatively affect almost all of the domains of functioning within a workplace context, as found by a recent systematic review including 33 studies (de Beer, Engels, Heerkens, & van der Klink, 2014). The negative factors found by the authors were: persistent difficulties in reading, negative feelings about dyslexia, difficulty acquiring and then keeping a job. This was the case regardless of the type of job, a blue- or white-collar. Employers have a duty under the Equality Act of 2010 to safeguard employees with disabilities and should offer adequate adjustments and support. Professional diagnosis of dyslexia is again required to access this support, but the assessments are expensive and time-consuming (BDA, 2017), and, again, may not be reliable for non-native English speakers which may lead to the lack of much-needed support for those affected by dyslexia.

Educational and workplace settings are not the only contexts in which individuals with dyslexia, and particularly those with undiagnosed dyslexia, can be disadvantaged. Adding further complexity to our understandings, there are not many studies which investigate general populations outwith these contexts. Conversely, much interest has been seen in prison populations where dyslexia is more prevalent. Studies exploring the relationship between dyslexia and crime have recognised that under-diagnosis is very common amongst offenders (Dyslexia Action, 2005; Reid & Kirk, 2001; Selenius, Daderman, Meurling, & Levander, 2006; Selenius & Hellström, 2015). This finding further supports the argument that assessment and intervention must take place early in childhood, and that if the education system fails, that the diagnosis must be obtained in adulthood to provide appropriate support.

The discussed government policies highlight the need to assess individuals' weaknesses in addition to their strengths. This may lead to a more vigorous implementation of the positive dyslexia approach proposed by Nicolson (2015). The theme of this approach is to 'work to your strengths' (Nicolson, 2015; p. i), and it emphasises the importance to not only recognise strengths of dyslexia but also to desire them. Nicolson particularly indicated the strengths found in individuals with dyslexia to cluster around the unconventional thinking and the social (teamwork, empathy, communication), cognitive (being able to see the 'big picture', visualisation, creativity) and work (determination, resilience, proactivity and flexible coping) domains. Also, an ability to solve problems seems to be more profound in individuals with dyslexia (Reid & Kirk, 2001). Furthermore, some studies suggested that individuals with dyslexia display more creativity than typical readers (Cancer, Manzoli, & Antonietti, 2016; Eide & Eide, 2012; Wolf, 2008; although see Mourgues, Preiss, & Grigorenko, 2014 for contrasting findings).

This approach is very appealing and could have a very positive impact on individuals with dyslexia's lives. Although all children, regardless of a dyslexia diagnosis, should be given opportunities to work on their strengths and nourish their talents, children with dyslexia may particularly benefit from this (Nicolson, 2015). Bearing all this in mind, it seems imperative to aid the dyslexia identification process with valid and reliable screening tools, not only to provide children with interventions remediating their reading problems but also to encourage them to explore their outside-reading aptitudes as soon as possible. The remainder of this chapter will discuss reading and dyslexia and identify the challenges related to lack of unified definition of developmental dyslexia.

1.4 Introduction to reading and dyslexia

1.4.1 Brief historical background of dyslexia

Developmental dyslexia was initially conceptualised as a disorder of the visual system and was mostly within the research interest of ophthalmologists (Guardiola, 2001). The first case of a teenage boy who could not learn to read despite his high intelligence was reported by W. Pringle Morgan (1896 In Guardiola, 2001), who was inspired by the visual memory and word blindness article written by James Hinshelwood (1896 In Guardiola, 2001). Hinshelwood later published a number of clinical cases suggesting the disorder's hereditary nature (Guardiola, 2001). Another important historical figure within the field was the American neurologist Samuel Torrey Orton, who observed writing and reading errors often committed by individuals with dyslexia (Orton, 1937 In Guardiola, 2001). He called these errors *the reversal errors* as they involved inversion of letters; *b* for *d*, for instance. Another neurologist, Knud Hermann, contributed to the field by providing a classical definition of developmental dyslexia: 'a deficit in the acquisition of an age-appropriate level of reading and writing ability' (Hermann, 1959 cited in Guardiola, 2001, p. 11). Hermann saw the causes of this deficit in hereditary factors too. He also proposed that dyslexia exists in the absence of other cognitive or sensory deficits or inhibitory influences from the environment.

Once the field of dyslexia started to be explored by professionals other than physicians, and in particular by psychologists, new theories emerged. Since then, the idea that dyslexia could be originating from various causes became more prevalent (e.g., Pennington, 2006). The most convincing findings were delivered by cognitive psychologists and neuroscientists. Soon, the field shifted its attention to the role of language and phonology in dyslexia (e.g., Muter, Hulme, Snowling, & Stevenson, 2004)

1.4.2 Defining dyslexia

A valid and reliable definition that researchers and practitioners agree on is essential for understanding the causes and nature of dyslexia (Elliott & Grigorenko, 2014). As Siegel and Lipka (2008) pointed out, without an agreed-on operational definition, there is no way of verifying the assessment and diagnostic tools that are used for classification purposes. The researchers in their discussion on learning disabilities (LD) argue that although the conceptual definition of LD is fairly accepted within the field, it is the operational definition that leads to confusion and misunderstandings. That is also the case in dyslexia research. The purpose of an operational definition is to identify and clearly state how disability is measured to ensure the universal agreement on the aspects of given deficits that should reflect a conceptual definition (Siegel & Lipka, 2008). Kavale and Forness (2000) emphasised the importance of operational definition for diagnostic purposes. In the research context, clear classification criteria are needed in order to achieve generalisability and usefulness of the findings obtained.

Dyslexia can be defined as a ‘learning difficulty that primarily affects the skills involved in accurate and fluent word reading and spelling’ (Rose, 2009, p. 10) and it is a ‘continuum of difficulties in learning to read’ (Scottish Government, 2009); individuals with dyslexia can show a combination of difficulties affecting learning process (BDA, 2007). DSM-5 (APA, 2013) uses an overarching category of Specific Learning Disability (within which reading problem is contained) that is seen as a neurodevelopmental disorder impeding to learn academic skills. These are only some parts of existing dyslexia definitions. Although there is a consensus as to some aspects of dyslexia (e.g., problems with reading), there are many inconsistencies between various definitions in regards to the type of difficulties experienced by those with dyslexia. Furthermore, some definitions are quite broad making the operationalisation of dyslexia very difficult.

Dyslexia is only one of the terms used by the researchers and practitioners. Some of the other terms are sometimes used interchangeably with the term *dyslexia*. Several researchers do not distinguish between the terms *dyslexia* and *reading disability* (e.g., Pennington & Bishop, 2009; Siegel & Mazabel, 2013). Furthermore, the term *reading disability* is interchangeably used with terms such as *reading disorder, specific reading disability, learning disability in reading* (e.g., Swanson & Hsieh, 2009b). Siegel and Lipka (2008) pointed out the distinction between the terms used in the USA and the UK. The term *learning disability* used in the USA, that incorporates learning problems with academic skills such as reading, writing and maths, is equivalent to the British term *learning difficulty*. In opposition, a number of researchers and practitioners use the term dyslexia only for a specific, small group of poor readers that are distinctive from other poor readers. This distinction is further related to different contrasting and disputed definitions (Elliott & Grigorenko, 2014). Rice and Brooks (2004) emphasized that the critical question researchers in the field ask is not whether individuals identified as dyslexic differ from typical readers, but whether they are distinctive from other poor readers.

The purpose and the context in which a definition is being used is also important (Stanovich, 1992). Fairly strict criteria in defining dyslexia are used in a scientific context. Such stringency is, however, neither needed nor desired by educators and school teachers. The latter context is related to additional educational resources that are allocated on the basis of learning difficulties displayed by individuals. In this context, the broader the definition, the more children getting additional help (Stanovich, 1992).

There is one established core problem in dyslexia, regardless of how broad the definition is; namely the problem with decoding written text (Elliott & Grigorenko, 2014). Elliott and Grigorenko (2014) argue that this problem must be contrasted with text comprehension problems. Fletcher (2009) distinguishes and specifies types of reading difficulties. He sees individuals with dyslexia as those who have particular difficulties with single word decoding and, by extension of course, they may have problems with comprehension and fluency. The importance of the single-word reading problems has been echoed by other researchers (Vellutino, Fletcher, Snowling, & Scanlon, 2004), as during tests based on single-word reading individuals cannot compensate by relying on their knowledge of semantics and/or syntax, as would be the case in passage reading tasks. The comprehension and fluency problems would, as Fletcher (2009) suggests, occur due to the decoding 'bottleneck'. He distinguishes poor decoders from those readers who experience fluency and comprehension but not so much single word reading difficulties. This smaller group of individuals can usually overcome problems of decoding, but continue to read without fluency.

There is no doubt that many researchers, government bodies, charities and authoritative institutions that work within and contribute to the field of dyslexia recognise the importance of providing a comprehensive definition of dyslexia and the specificity of different forms of reading problems. Some of the definitions proposed are in line with those first offered by Hermann (1959 In Guardiola, 2001); that dyslexia is a reading acquisition deficit not related to other cognitive and sensory deficits.

This approach to defining dyslexia, especially the idea of identification based on specific exclusion criteria, was popular until the early 2000s. Heaton and Winterson (1996) recognised six additional factors that may cause poor reading, apart from dyslexia. These were: low intelligence, low socio-economic background, poor schooling, physical disabilities (visual or hearing impairments), neurological impairments, and emotional or behavioural factors affecting attention and concentration. The idea that one can be diagnosed by excluding these factors was endorsed by some (Lyon, 1995) but it is now largely rejected by research communities (Elliott & Grigorenko, 2014; Lyon & Weiser, 2013).

Symptomatology, in particular, seems important when it comes to diagnosis. Numerous lists of dyslexia's symptoms have been produced by researchers and practitioners that include such problems as phonological awareness difficulties, poor short-term, working and/or verbal memory, poor sequencing, spelling difficulties, poor sense of rhythm, clumsiness, poor balance, and many more. As discussed above, the aetiology, definitions, and manifestations of dyslexia are regularly revised due to new research findings. Researchers from different fields, such as education, psychology, biology and neuroscience, contribute to the understanding of reading disorders by focusing on various aspects. Depending on the nature of the organisation or the researchers' fields the definitions they propose can vary. Table 1.1 presents various components indicated in dyslexia definitions provided by the ten prominent organizations and professional bodies.

Table 1.1 *Components of dyslexia in definitions of key organisations and professional bodies*

Dyslexia deficits	BDA	BPS	DA	RR	DS	ICD-10	DSM-IV	DSM-5	IDA	NIH	Total
Literacy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
Phonological	✓	o	✓	✓	✓	✓	✓	✓	✓	✓	9
ST/W memory	✓	o	✓	✓	✓	✓	o	✓	o	o	6
Alleviated by intervention	✓	o	o	✓	✓	o	✓	✓	o	✓	6
Lifelong	✓	o	o	o	✓	✓	o	✓	o	✓	5
IQ discrepancy	✓	o	x	x	x	✓	✓	x	✓	✓	5
Processing speed	✓	o	o	✓	o	o	✓	✓	o	✓	5
Genetics	o	o	✓	o	✓	o	✓	✓	o	o	4
Auditory	✓	o	✓	o	✓	✓	o	x	o	o	4
Visual	✓	o	x	o	✓	✓	o	x	o	o	3
Cross cultural	o	o	o	o	✓	✓	o	✓	o	o	3
Motor	✓	o	✓	✓	o	o	o	x	o	o	3
Comorbid	o	o	✓	o	o	o	o	✓	o	o	2

Note. Organizations providing definitions (year of publication if available): BDA: British Dyslexia Association; BPS: British Psychological Society (1999); DA: Dyslexia Action; RR: Rose Review (2009); DS: Dyslexia Scotland (2009); ICD-10: International Classification of Diseases, by WHO (2017); DSM: Diagnostic and statistical manual by American Psychological Association (2000, 2013); IDA: International Dyslexia Association (2002); NIH: National Institutes of Health, US (2017); Dyslexia components/deficits indicated by the above organisations: IQ discrepancy: discrepancy between the reading level and what it expected from the IQ level of an individual (BPS, 1999); Phonological deficit: difficulty in manipulating and processing sounds; Literacy: problems with aquiring reading, spelling or writing; ST/W memory: difficulty reteining information/words/numbers; Comorbid: with other developmental disorders, e.g. dypraxia, dyscalculia, ADHD; Visual/Auditory/Motor: any mention within these modalities; Processing speed: slow rate of information processing

✓-indicates that the particular component is recognised in dyslexia; × -indicates that the component is not used or recognised to define dyslexia; **o** – the component not mentioned in the definition.

It is clear from Table 1.1 that there is some, but not complete, overlap of the symptoms and classification components included in these definitions. The Rose Report (2009) also indicated that different symptoms would be shown at various ages. Pre-schoolers would be more likely to demonstrate delayed speech, problems in detecting rhymes, and with learning letters. Early school age children would show poor letter-sound correspondence, poor phoneme awareness and spelling, as well as difficulties in copying patterns. Later, in middle school, children would have problems with reading speed, spelling and non-word/new word decoding. Adolescents and adults with dyslexia most often show problems with fluent reading, a speed of writing, spelling, and reading comprehension.

The problem, however, with generating such lists of symptoms, is that none of these symptoms seem *necessary* for one to be diagnosed with dyslexia. Also, no single symptom is *sufficient* on its own for a diagnosis (Elliott & Gibbs, 2008; Rice & Brooks, 2004). Furthermore, some of these symptoms can also manifest themselves in non-dyslexic poor readers and in good readers.

The above concerns exemplify one of the greatest issues in defining dyslexia, namely the extent of the definition's inclusivity. A definition can be criticized for being too broad and too inclusive by some, as it would not allow the distinction between the true dyslexic and poorly reading individuals. An example of such definitions that sparked debates are definitions independently put forward by the British Psychological Society Working Party (1999) and the Rose Report (2009). The BPS defined dyslexia as being 'evident when accurate and fluent word reading and/or spelling develops very incompletely or with great difficulty' (p. 64). The Rose Report, which was sponsored by the UK Government, provided a similar definition, acknowledging problems with both accuracy and fluency of reading. These definitions were criticized for being too broad and not useful for diagnosis (House of Commons, 2009).

Furthermore, such general definitions are particularly strongly criticised by those who argue that there are clear cognitive differences between poor readers and dyslexic readers (Thomson, 2003). Another criticism that this kind of definition can meet is that it only describes problems with reading disregarding any other symptoms that individuals with dyslexia experience. Cooke (2001) expressed her concern that individuals who no longer experience particular problems with reading, or who found ways to cope with these, still have difficulty in performing a range of other tasks known to be compromised in dyslexia, such as filling in forms correctly, due to personal disorganisation.

The definitions also change over time which can be illustrated by the scrutiny of definitions proposed by DSM. An earlier version of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV, APA, 2000) defined dyslexia (here also referred to as a *reading disorder*) as ‘reading achievement, as measured by individually administered standardized tests of reading accuracy or comprehension, is substantially below that expected given the person's chronological age, measured intelligence, and age-appropriate education’ (APA, 2000, p. 50). This version of the manual recommended the use of the term *dyslexia*, instead of the *learning disability* term, in order to echo the international use of the term (Elliott & Grigorenko, 2014). The assumption of discrepancy between reading ability and intelligence in children proposed by this version of the manual has been widely used by the practitioners and researchers over the years. This definition is, however, purely behavioural and leaves the issue of causality open.

In the most recent (5th) edition of the DSM (2013), there is a markedly different approach to learning disorders. It is no longer recommended to use the terms such as *dyslexia* or *dyscalculia*. Instead, this version of the manual proposes the use of an overarching term: *Specific Learning Disorder* (SLD), which is defined as a neurodevelopmental disorder hindering the ability to learn one or more of three academic skills: reading, writing and mathematics. Reading problems are recognised here as reading accuracy, fluency and comprehension problems. This version also eliminated the intelligence-achievement discrepancy criterion. The changes in definition were met with criticism from practitioners and educators. For instance, a prominent group of researchers form the Yale Center for Dyslexia and Creativity: Colker, Shaywitz, Shaywitz, and Simon (2013), discussed their legal, medical and scientific trepidations in the context of the newly proposed definition in an essay published on their institution's website. While this was not peer-reviewed, the esteem of this research group afforded the document prominence upon its release. Specifically, they suggested dividing the specific learning disabilities (SLD) into two subtypes: *dyslexia* and other *learning disorders* which would more accurately reflect the amount of evidence for these two groups. They argued that dyslexia is a well-described and world-widely acknowledged disorder.

Within the debates on the definition of dyslexia, another aspect that remains controversial and inconclusive is whether dyslexia should be seen as a continuum of difficulties or as a distinct category in which case the symptomatology and causality of dyslexia are of central concern. Although the Rose Report (2009) suggested that the idea of a continuum is more accurate for dyslexia, the Report still argues that a diagnosis can be provided by professionals. If dyslexia is to be seen as a continuum, then the key concern is where an individual's abilities would be placed on the reading continuum (Swanson & Hsieh, 2009). Consequently, individuals who can be considered as having dyslexia would demonstrate reading scores below a certain threshold of a normally distributed sample of readers. This threshold or cut-off point differs across studies. Some researchers use the 10th percentile as cut-off point (e.g., Mazzocco & Grimm, 2013) while others use 1.5 SD (e.g., Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012) or 2 SD (e.g., Ruffino et al., 2010) from the mean.

1.4.2.1 IQ-reading level discrepancy definition debate

One very much debated aspect in dyslexia research is the role of intelligence. A considerable amount of attention has been given to the idea of two groups of poor readers: one group, the 'dyslexics', comprising poor readers with normal-to-high intelligence; and the second group, so-called 'garden variety' poor readers (GVPR), whose reading problems are more likely related to low intelligence. This classification is based on an idea of aptitude-achievement discrepancy (Reynolds, 1981). As early as 1988, Siegel conducted a study to determine whether reading disabled and non-reading disabled children with different IQ scores would show distinctive patterns of performance on cognitive tasks. The result was that the IQ scores did not appear to be significant predictors of the cognitive processes involved in reading, spelling, language skills, and memory tasks. The lack of strong evidence supporting the validity of the reading-IQ discrepancy classification was previously shown by many studies (Carroll, Solity, & Shapiro, 2016; Felton & Wood, 1992; Fletcher, Francis, Rourke, Shaywitz, & Shaywitz, 1992; Stanovich & Siegel, 1994). Further meta-analyses of 19 studies (Hoskyn & Swanson, 2000) and of 46 studies (Stuebing et al., 2002) provided corroborating results, showing that the effect sizes of the differences between the two groups were either negligible or small.

Several studies have shown that the main deficits in dyslexia are consistent regardless of IQ (Stanovich, 2005; Tanaka et al., 2011), although other studies have demonstrated different patterns of reading profiles based on participants' IQ levels (Ferrer, Shaywitz, Holahan, Marchione, & Shaywitz, 2010; Morris et al., 1998; O'Brien, Wolf, & Lovett, 2012). Studies have also demonstrated that IQ is not a reliable predictor of how responsive poor readers will be to intervention (Gresham & Vellutino, 2010; Stuebing, Barth, Molfese, Weiss, & Fletcher, 2009; Vellutino, Scanlon, & Lyon, 2000). There is also no compelling evidence for information on children's intelligence being useful in deciding on the type of intervention to be offered to them (Schneider, Kaufman, & Schneider, 2017). Flowers, Meyer, Lovato, Wood, and Felton (2001) further demonstrated that IQ discrepancy cannot predict future reading skills.

Further to this, there is voice concern about the validity of several commonly used IQ tests in the diagnosis of dyslexia (Siegel, 1990). Standardized IQ tests, such as those derived from Wechsler Intelligence Scales (1997, 2004, 2013) measure, among other abilities, expressive language skills, short-term memory, a speed of information processing, a speed of responding, and knowledge of specific facts (Siegel, 1990). Studies indicate that these functions are deficient in many individuals with learning disabilities (e.g., Siegel, 1985; Siegel and Feldman, 1983; Swanson, 1993; 1994). Therefore, the IQ test may not be a valid measure of the intelligence of individuals with dyslexia. There is also a claim that IQ tests are not valid as measures of intellectual ability. Researchers have suggested alternative ways to conceptualize intelligence (e.g., Gardner, 1983; Goleman, 1995; Lazear, 1994). Gardner (1983) suggested the concept of multiple intelligences. He claimed that there is not just one type of intelligence that correlates with success in life but several kinds of intelligencies. He defined intelligence as a multidimensional phenomenon that is present at multiple levels of our brain. He noted that IQ tests are based on a very limited idea of intelligence.

Another variable that might influence the validity of the IQ measure as part of the reading difficulties formula is the 'Matthew Effect' (Stanovich, 1986). Stanovich (1993) described this effect associated with reading suggesting that reading itself develops related cognitive abilities. Ritchie, Bates, and Plomin (2015) more recently demonstrated that improvements in reading ability might lead to improvements in verbal and non-verbal reasoning abilities. Therefore, the cognitive skills in individuals who read less, such as students with dyslexia, may be underdeveloped, thus resulting in lowered performance on IQ tests.

Although there appears to be no compelling evidence for differentiation between dyslexia and garden variety poor readers, there are some arguments within the literature that such a differentiation should be included to accord with social justice. Stanovich and Stanovich (1997) suggest that inclusion of individuals indicated as dyslexic on the basis of the IQ-achievement discrepancy is crucial as these children whose reading level is within a norm but intelligence much above the average cannot realise their educational potential. This argument was also raised by a group of researchers (Colker et al., 2013), who protested against the removal of the discrepancy criterion from DSM-5 (APA, 2013).

Other reasons as to why practitioners and some researchers persist on the use of IQ tests in their diagnostic and screening procedures is the overwhelming view that dyslexia is an unexpected difficulty in learning to read for individuals of average or above average intelligence (Nicolson & Fawcett, 2007). The IQ criterion is often used by researchers in their studies in order to understand the cognitive mechanisms underlying this disorder (Snowling, 2008).

Although the idea of exclusion criteria is not adhered to anymore by practitioners and some would express their discontent with their use (Fletcher, 2009; Stanovich, 2005), such exclusionary definitions are employed by researchers to enable them to investigate group differences (Rice & Brooks, 2004) or to separate underlying cognitive processes of researchers' interest (Snowling, 2008). In these cases, it would be incorrect to assume that such selective samples are representative of all individuals with dyslexia (Elliott & Grigorenko, 2014).

The earlier mentioned changes suggested by DSM-5 in regards to the use of IQ-discrepancy definition were met with criticism from practitioners and educators. Researchers emphasised that the empirical findings indicate dyslexia to be an unexpected reading difficulty. In typically developing children reading and intelligence develops together and influence each other (Ferrer et al., 2007). In individuals with dyslexia, this dynamic relationship does not seem to exist (Ferrer et al., 2010). The authors also underlined the fact that those children and adults with reading problems who display high intelligence will no longer be diagnosed, if DSM-5 criteria were used, as dyslexic as their reading level may not be well below the average. While their reading level may be within the norm, it will be below the level expected from their IQ. By discarding the discrepancy criterion from dyslexia diagnosis, such individuals will face a lack of support and potentially poorer academic and employment outcomes, Colker and colleagues (2013) argue.

1.4.2.2 The role of socioeconomic status

The importance of socioeconomic background in dyslexia cannot be underestimated. It has been shown that children from families with higher socioeconomic status who have access to more resources tend to outperform other children (Buchmann & Hannum, 2001) and are less likely to develop reading difficulties (Chaney, 2008; Whitehurst & Lonigan, 1998). This claim is supported by the Scottish Survey of Literacy and Numeracy results, which show that children from deprived areas within primary 4, primary 7, and secondary 2 performed significantly worse in both literacy and numeracy tests (Scottish Government, 2013b; Scottish Government, 2014). The most robust differences between lower and middle-income children are in language abilities and executive function, especially in the areas of working memory and cognitive control (Farah et al., 2006; Noble, McCandliss, & Farah, 2007; Noble, Norman, & Farah, 2005).

There is also some evidence in support of a relationship between phonological awareness and socioeconomic status (Noble et al., 2007). What is more, the behavioral genetics evidence regarding a broader measure of cognitive development suggest that while cognitive ability is highly heritable within middle and high SES population, environment accounts for the majority of IQ variance in underprivileged families (Harden, Turkheimer, & Loehlin, 2007; Turkheimer, Haley, & Waldron, 2003).

One of the potential explanations for the differences in so many aspects of cognitive development, particularly in reading, between individuals of low and high SES is the level of parental literacy. Hart and Risley (2003) followed up 42 low SES families for two and a half years by visiting and observing them at their homes for an hour every month. They reported that children who were brought up in a privileged area of California knew twice as many words as children from worse-off areas. Exposure to not only spoken, but also to written, words seems to be also limited in poorer communities (Neuman & Celano, 2001).

Further to this, in their meta-analysis of 99 studies focusing on leisure time reading of young children and university students, Mol and Bus (2011) found a significant positive correlation between print exposure and reading comprehension, technical reading and spelling. A more recent study investigating the effects of home literacy environment on children’s literacy development (Hamilton, Hayiou-Thomas, Hulme, & Snowling, 2016) found that shared storybook reading and parental teaching of literacy skills at four years old predicts literacy and reading comprehension in children at family-risk of dyslexia two years later. Furthermore, the number of books in the home was found as a significant predictor of children’s reading fluency (van Bergen, van Zuijen, Bishop, & de Jong, 2017).

Studies exploring the issue of socioeconomic background from a neuroscientific perspective have contributed important insights. Jednoróg et al. (2012) for instance, provided evidence for brain structure differences between 10-year old children from disadvantaged environments and those from non-disadvantaged environments. They found that low SES was associated with smaller grey matter volumes in many brain areas (e.g., hippocampus) but no associations were found with white matter. Using behavioural measures, the researchers also confirmed that language is one of the cognitive areas most affected by SES. In their longitudinal study, Hanson et al. (2013) demonstrated that children from different socioeconomic backgrounds had the same grey matter volume when they were infants. However, by the age of four, brain development differences were noticeable. Children from low SES had lower volume in the frontal and parietal lobes than those children from more privileged environments. The aggressive and hyperactive behaviour observed at this age was associated with the lower grey matter volume in these brain areas.

Another study looking into relationships between SES and the cortical surface area in a large sample of 1000 individuals with age ranging from 3 to 20 years of age was conducted by Noble et al. (2015). The findings revealed a positive relationship between family income and the cortical surface area in frontal, parietal and temporal lobes as well as with reading, attention, memory and vocabulary tests performance. Executive function (EF), which is dependent on the prefrontal cortex, has also been shown less developed in infants (Lipina, Martelli, Vuelta, & Colombo, 2005) and young children (Hughes, Ensor, Hughes, & Ensor, 2005) from low SES backgrounds. The evidence from these behavioural studies was supported by neuroscientific research (D'Angiulli, Herdman, Stapells, & Hertzman, 2008; Stevens, Lauinger, & Neville, 2009).

There is convincing evidence that socio-economic status plays a role in many aspects of children's development, including reading, and this needs to be recognized. However, Fletcher, Lyon, and Barnes (2007) argued that it is impossible to expect that biological causes, once detected, can lead to a diagnosis of dyslexia. According to these researchers, an assumption that environmental disadvantage is the only cause of poor reading of those from such environments may be wrong. The environmental and neurobiological causes are extremely difficult to distinguish between when it comes to an individual poor reader's needs. Therefore, it would be unfair and inappropriate to decide on a child's access to additional support and intervention on the basis of his or her socioeconomic circumstances. Dyslexia risk identification is underlined by the multiple cognitive and environmental components that interact with reading performance. One of these components is SES.

1.4.2.3 Dyslexia across languages

There is a considerable variability in the level of transparency across orthographies. Particularly, a distinction between opaque (deep) orthographies, such as English, and transparent (shallow) orthographies is crucial in the context of reading development. Harris and Hatano (1999) showed that children learning to read in transparent orthographies (e.g., German, Italian, Spanish) progress faster than those learning to read English. Seymour, Aro, and Erskine (2003) conducted a study involving 13 different European languages and found that after the first year of formal reading instruction, a performance of children with transparent orthographies was ceiling, while children speaking English, Danish or French (deep orthographies) were struggling. English is considered to have the hardest orthography to master (Snowling & Hulme, 2005), however, most of the studies on reading and reading disorders comprise English speakers.

The differences in orthographies are also reflected in dyslexia research, particularly when it comes to dyslexia predictors. English-based research indicated phonological processing to be a key reading predictor (e.g., Vellutino et al., 2004). Share (2008) suggested that the role of phonological processing might have been overestimated due dominance of English-based research. The rhyming task, for example, was shown to be a good reading predictor in English (Bradley & Bryant, 1983) but it turned out to be a poor predictor in German (Wimmer, Landerl, & Schneider, 1994) and Dutch (de Jong & van der Leij, 1999). In these shallow orthographies, rapid naming, verbal short-term memory and visual-verbal paired associate learning showed to be more useful in predicting reading ability (Wimmer, Mayringer, & Landerl 1998). This is evidenced further by large cross-linguistic research looking into various orthographies. Ziegler et al. (2010) used a large sample of children from five countries with orthographies increasing in complexity (Finnish, Hungarian, Dutch, Portuguese, French) and found that phonology although still associated with reading across languages is less relevant the more transparent an orthography is. Dyslexia in transparent orthographies manifests itself by reduced reading rate rather than reduced accuracy (Oren & Breznitz, 2005; Suárez-Coalla & Cuetos, 2012).

Studies looking into Chinese and Japanese languages which are non-alphabetic are particularly interesting. Chinese is a logographic language which has no grapheme-phoneme correspondence rules. Chinese writing system has numerous visual symbols (characters) that represent morphemes that convey meaning rather than sounds (phonemes) which is the case in alphabetic orthographies. Chinese characters are visually compact (Ho, Chan, Lee, Tsang, & Luan, 2004) and resemble two-dimension pictures (Zhang, Guo, Ding, & Wang, 2006). Research shows that due to this complexity of visual information, visual skills are particularly key in Chinese reading (Chung et al., 2008; Li, Shu, McBride-Chang, Liu, & Peng, 2012). Other cognitive deficits such as poor phonological processing and rapid naming are also found in Chinese readers (Ho, Chan, Tsang, & Lee, 2002; Shu, McBride-Chang, Wu, & Liu, 2006).

Orthographies' characteristics of the language are also important in individuals who speak more than one language. When assessing these individuals, one needs to differentiate reading problems in additional language between a consequence of poor language-proficiency or reading disorder (Nijakowska, 2011). The assessment is particularly difficult as different criteria that are specific to each language need to be considered. Oren and Breznitz (2005) investigated differences between bilingual typical readers and bilingual dyslexic readers; both groups with Hebrew as the first language and English as the second language. They found that adults with dyslexia were significantly slower and less accurate than the control group during reading in both languages. The authors suggest that despite each orthography has unique features, there is also evidence for central deficit that applies to all languages. The debate whether dyslexia has a universal neurological basis (Martin, Kronbichler, & Richlan, 2016; Paulesu et al., 2001; Paulesu, Brunswick, & Paganelli, 2010) or whether different orthographies are associated with different brain deficits (Hadzibeganovic et al., 2010) is ongoing.

1.4.2.4 Prevalence of dyslexia

Due to the inconsistencies in defining dyslexia, it is difficult to estimate the prevalence of this disorder. The occurrence of dyslexia, therefore, tends to vary in literature depending on the definition used, the cut-off points adopted and whether the sample was obtained from a clinical or general population (Rose, 2009). The estimates of prevalence may range from 4% to 10% (Flannery, Liederman, Daly, & Schultz, 2000; Maughan & Carroll, 2006; Pastor & Reuben, 2008). Some researchers estimate it to be as high as 17.5% or 20% (Shaywitz et al. 1994; Shaywitz, 1996; Shaywitz & Shaywitz, 2005). Some experts in the field acknowledge that the use of the cut-off points is rather arbitrary and provide different prevalence estimates in different publications ranging from 4% to 8% (Snowling, 2000) or 3% to 6% (Hulme & Snowling, 2009) up to a range between 3% and 10% (Snowling, 2013).

There are also gender differences in reading abilities and disabilities. Berninger, Nielsen, Abbott, Wijsman and Raskind (2008) found that girls tend to be better readers and writers than boys. Lundberg, Larsman, and Strid (2012) also suggested that boys tend to have greater difficulties with phonological processing. Reading disability has been shown to be more prevalent in boys (Miles, Haslum, & Wheeler, 1998) however how big is this gender gap is still debated due to the application of different definitions. Studies using clinical samples have reported male-female ratios ranging from 2-3: 1 (Katusic et al., 2001) up to 5.9:1 (Finnucci & Childs, 1981). Rutter et al. (2004) reviewed epidemiological studies and also found a significant gender gap with ratios ranging from 1.39:1 to 3.19:1. Shaywitz (1996), however, found no gender differences in a longitudinal study when her team themselves performed the dyslexia identification, indicating potential gender bias amongst teachers.

1.4.2.5 Comorbidity

Difficulties of establishing the specificity of dyslexia are also related to the comorbidity of this disorder with other deficits. Paracchini, Diaz, and Stein (2016) suggested that there are very few people affected purely by dyslexia. They proposed that there is such a large overlap of symptoms in dyslexia and in other neurodevelopmental conditions that diagnosis often depends on what specialist a child is seen by.

One of the most strongly co-occurring deficits with dyslexia is dyspraxia, also referred to as Developmental Coordination Disorder (DCD), which is defined as an impairment of the organisation of movement (Dyspraxia Foundation, 2007). Iversen, Berg, Ellertsen, and Tønnessen (2005) found that 60% of poor readers with dyslexia diagnosis and 53% of poor readers identified by teachers showed severe motor difficulties in line with DCD diagnosis. Some studies suggested that dyslexia and DCD may both be related to the cerebellar dysfunction (Brookes, Nicolson, & Fawcett, 2007; Cantin, Polatajko, Thach, & Jaglal, 2007). Brookes et al. (2007) also demonstrated that the two disorders show commonalities when assessed by brain-based tests such as prism adaptation task. The significant role of the cerebellum in DD and DCD has been recently supported by a review of neuroimaging studies (Biotteau et al., 2016). Poor handwriting is a difficulty also associated with DCD and reported in dyslexia (Snowling, 2000) and a number of neuroimaging studies showed an activation of the cerebellum during writing tasks (Dufor & Rapp, 2013; Horovitz, Gallea, Najee-ullah, & Hallett, 2013; Katanoda, Yoshikawa, & Al, 2001). A key role of cerebellum in writing was confirmed by meta-analyses (Planton, Jucla, Roux, & Démonet, 2013; Purcell, Turkeltaub, Eden, & Rapp, 2011).

DCD is also a frequent (estimated at 50%) comorbidity in children with attention deficit hyperactivity disorder (ADHD) (Kadesjö & Gillberg, 1998, 2001) although there is no agreement as to the nature of the association between these two disorders (Goulardins, Marques, & Oliveira, 2017). ADHD, however, strongly co-occurs with reading disorder. This has been found in clinical samples studies (Cheung et al., 2012) and in general population samples (Gilger, Pennington, & DeFries, 1992). McGrath et al. (2011) estimated that out of all children diagnosed with dyslexia, between 25% and 40% would also meet the criteria for ADHD. However, the prevalence of these two disorders is not always clear due to lack of consistent definitions or different methodologies used in studies (Sexton, Gelhorn, Bell, & Classi, 2012). Further, other studies estimated that up to 50% of children indicated as dyslexic readers would also meet the criteria for ADHD, SLI, or dyspraxia (Pauc, 2005; Rice, Smith, & Gayán, 2009; Snowling, Muter, & Carroll, 2007). It is not entirely clear if these overlaps are triggered by common genetic factors. It has been suggested that genes contributing to reading and language are also those identified for dyslexia or SLI (Newbury et al., 2011; Scerri et al., 2011).

Comorbidity of reading and mathematical difficulties has also been explored in the field. Willcutt et al. (2013) estimated the co-occurrence of these two disabilities to be between 30% and 70%. This variation stems from differences in definitions, in particular, different cut-off points, and measures used across the studies. Bishop (2001) suggested that the less rigorous the reading disability criteria, the more children with mainly socioeconomic problems are included. Thus, an inclusion of individuals from underprivileged backgrounds that affect their performance across various learning domains leads to elevated comorbidity rates.

The term comorbidity, however, is seen as somewhat problematic (Kaplan, Dewey, Crawford & Wilson, 2001). The term was borrowed from medicine where it meant to have two or more diseases. In the mental health context, some use the term incorrectly by not empirically distinguishing between symptoms and disorders. Kaplan et al. (2001) argue that when a child shows problems associated with ADHD and a reading disorder or a developmental coordination disorder, for example, it is questionable whether the child has several comorbid disorders or different manifestations of one underpinning impairments. This underlying impairment could indicate atypical brain development (Kaplan et al., 2001). Similarily, motor deficits could be seen as a symptom of DCD or a manifestation of dyslexia.

Studies with selected samples of children with dyslexia or ADHD with no other neurological-behavioural problems associated with them undoubtedly help to understand the pure disorders. However, such an approach does not correspond to clinical reality as the number of ‘pure’ cases is relatively low (Kadesjö & Gillberg, 1998; Kaplan et al., 2001). Kaplan et al. (2001) carried out an epidemiological study covering seven different disorders and found that 48% of their sample (n=179) only had dyslexia.

1.4.3 Chapter synthesis and thesis structure summary

The current chapter has discussed the background and rationale for the current investigation, emphasising the importance of the early identification of dyslexia and a value of including of non-language based tasks to aid the identification of dyslexia, particularly in assessing children and adults whose first language is not English. Increased movement of people between countries means that educational staff are often faced with children and adults from different language backgrounds who require adequate assessments to ensure that they are provided with the right support.

Identification of individuals with problems related to reading as early as possible and then providing them with appropriate intervention, as well as monitoring their progress along the way, seems to be the best approach to remediate the negative consequences of reading disability. Nurturing potential talents in these individuals may additionally help them to cope and to succeed in life. The importance of early identification allowing early interventions in children with English as an additional language was also highlighted. It has been argued that existent tests that rely on language skills may not always be the most accurate in child and adult populations who are bi- or multilingual. The need of an additional reliable tool that would be associated with other problems, such as motor or visual, is therefore proposed.

The lack of consistency in the definition of developmental dyslexia, and the way that it has been diagnosed previously and more recently, may cause problems in evaluating the quality of research conducted in different years. Different studies would naturally echo definitions appropriate to their times and the differences in findings due to this must be kept in mind. These complex issues related to defining dyslexia make the remediation of the problems even more challenging (Wanzek &

Vaughn, 2007; Wanzek et al., 2013). The role of socioeconomic status in reading development, as well as various comorbidities, were also discussed in this chapter.

The incongruities of the definitions discussed in this chapter need to be borne in mind throughout the remaining chapters. The terms development dyslexia (DD), dyslexia, and reading disability (RD) will be used interchangeably in the literature review with the explanation of particular constructs employed by the researchers whose papers will be cited, where necessary.

Chapter 2 provides a discussion of the key theories which aim to explain dyslexia. The chapter explores the theories providing evidence for proximal causes (such as phonological deficits hypothesis) in addition to those working around the distal causes. The latter group of theories focuses around abnormalities in brain areas (such as visual pathway and the cerebellum) and learning processes (procedural learning hypothesis). It is crucial to discuss different theoretical models in order to understand the novel DtD task being investigated in the current thesis and to hypothesise which skills would be related to a good performance on this novel task.

Chapter 3 provides a description of the general methods used within the subsequent studies. Here, the detailed explanation of the DtD task is provided together with pilot and anecdotal evidence of its screening potential.

Chapter 4 is the first empirical study looking into the cross-section of children in three different age cohorts (nursery and Primary 1, Primary 3, and Primary 5) from three schools characterized with diverse socioeconomic backgrounds. Children were tested on a number of measures: the DtD test, phonological processing, memory, rapid naming, verbal and non-verbal reasoning. As the DtD software generates many variables presumably associated with different skills, a correlational analysis was conducted to identify whether any of the dyslexia sensitive or reasoning abilities were related to the DtD task. Dyslexia risk was estimated by the existing screening test (Lucid Rapid), and children were assigned to high, medium or low risk of dyslexia group. Group differences were investigated. The scores from this study were treated as a baseline to the following prospective investigation.

Chapter 5 offers a prospective investigation of the reading level (poor vs typical) group differences in the baseline measures and, most importantly, examines which of the many DtD and dyslexia-sensitive measures can accurately predict reading level (as a continuous variable) and reading level group membership (as a dichotomous variable). Furthermore, a detailed investigation of weaknesses found in poor readers and the impact of different operational definitions on the results are provided. The impact of the school children went to and their gender on their performance was also investigated. This chapter provides a more detailed discussion of the findings from both the cross-correlational and the prospective investigations.

Chapter 6 provides an investigation of visual perception in a subgroup of children to identify whether the performance on the DtD task is related to their sensitivity to stimuli preferentially activating low or high level visual processing pathways. The long lasting debate on the role of the magnocellular pathway and dorsal stream in dyslexia is addressed here by correlational and quasi-experimental designs.

Chapter 7 delivers a final empirical investigation of the potential use of the DtD test in indicating adult individuals with dyslexia. The adult participants were also tested on a range of dyslexia-sensitive and reasoning tasks in order to investigate the relationships between them and the DtD task.

Chapter 8 offers a general discussion of the findings of the thesis, together with their implications and directions for further research.

Chapter 2

Understanding the causes of developmental dyslexia: A review of theories.

'Learning involves the nurturing of nature'

Joseph LeDoux (2009, p. 9)

'Knowing how something originated often is the best clue to how it works'

Terrence Deacon (1997, p. 23)

It is estimated that the human brain has existed for 60,000 years whilst the alphabetic code has existed for only 5,000 years (Breznitz, 2008). Reading is, therefore, a relatively new invention and is not a part of an evolutionary heritage. It is perhaps one of the most remarkable creations in human history (Wolf, 2008). This creation was only possible thanks to an extraordinary ability of the human brain to be re-shaped through experience. Learning to read is a demanding act involving the training of neural mechanisms that are believed to underlie an array of cognitive, perceptual, and motor skills originally devoted to other purposes (Vidyasagar & Pammer, 2010). To understand why one fails to learn to read successfully, all of these aspects need to be considered.

This chapter will introduce a number of theories looking at developmental dyslexia from different perspectives and recognizing this disorder at three different levels of explanation: behavioural, cognitive, and biological (Frith, 1997). The three levels of explanation interact with one another and with the environment (Hulme & Snowling, 2009). The behavioural level focuses on the symptoms of dyslexia, such as poor reading (as discussed in Chapter 1). Cognitive-level theories seek to explain the causes of those observable symptoms, for example, by looking at underlying cognitive domains such as phonological awareness. Finally, biological explanations investigate the underlying brain and genetic mechanisms of dyslexia. Frith (1997) identified the importance of inclusion of all of the three levels of explanation in order to understand dyslexia fully (see Figure 2.1).

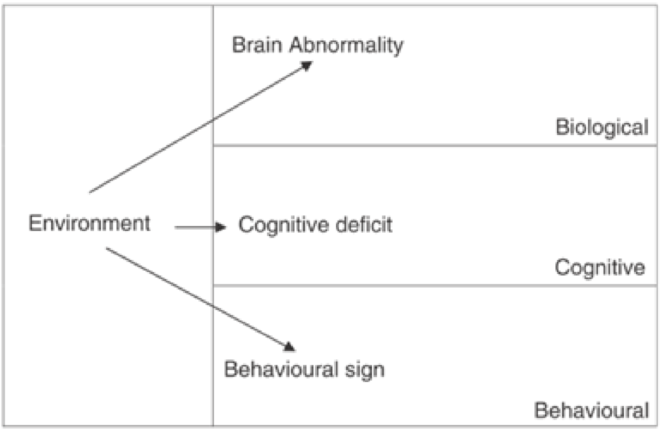

Figure 2.1 A causal modeling framework (Frith, 1995, p. 10)

Some of the theories work on more than one level of explanation. For instance, phonological deficit theory is cognitive at its core, but it considers evidence from brain-level research. The magnocellular deficits theory on the other hand inherently derives from the brain-level explanation but also provides cognitive-level accounts. To avoid confusion, each theory will be discussed as a whole within its core level of explanation.

2.1 Cognitive theories

2.1.1 Phonological deficit hypothesis

'(…) we need to understand the cognitive difficulties that underpin reading problems, regardless of whether their origin is constitutional or environmental'

Snowling and Hulme (2011, p. 4)

The earliest modern theory of dyslexia is focused on phonological processing (Bradley & Bryant, 1983; Stanovich, 1988; Stanovich & Siegel, 1994), which remains the key indicator in various diagnostic and screening tests. The phonological deficit hypothesis is based on linguistics and has a cognitive explanation at its core

(Vellutino et al., 2004). The basic principle of this theory is that the key features of dyslexia, such as problems with reading, writing and spelling are caused, entirely or partially, by difficulties in the phonological processing of language.

The explanation of the reading impairment in individuals with dyslexia is based on the fact that learning to read requires learning of the correspondence between graphemes (letters) and phonemes (sounds of speech), which is seen as a foundation or a basis of alphabetic reading systems (Ramus, 2003). It is assumed that if the sounds are defectively represented, stored in and retrieved from memory, then the learning of the grapheme-phoneme correspondence will be difficult (Snowling, 2000). This theory initially indicated weaknesses in phonological representations as a cause of dyslexia (Bradley & Bryant, 1978; Vellutino, 1979; Snowling, 1981; Ramus, 2003; Snowling, 2000). Vellutino et al. (2004) defined phonological representations (or, as they are sometimes referred to, phonological coding) as 'the ability to use speech codes to represent information in the forms of words and word parts' (p.12). Thirty years of research has shown that there are three main dimensions related to phonological representations (Wagner & Torgesen, 1987). These are: poor phonological processing/awareness, poor short-term/working memory, and slow lexical retrieval (Johnson, Humphrey, Mellara, Woods, & Swanson, 2010; Wagner & Torgesen, 1987). These will be now discussed in turn.

Phonological processing

The first dimension enables one to perceive and manipulate speech sounds (Liberman & Shankweiler, 1985) at both phoneme and syllable levels (Bryant, MacLean, Bradley, Crossland, 1990) and can be tested using different tasks depending on the individuals' age. These could be breaking down words into parts, for instance dividing the word 'cat' into the sounds /k/ /æ/ /t/, or making judgments, for example identifying whether /cat/ rhymes with /mat/.

A vast amount of research points to the phonological awareness as key for reading development (Goswami, 2003; Gabrieli, 2009; Peterson & Pennington, 2012; Snowling, 2001; Shaywitz et al. 2004; Vellutino et al., 2004; Ziegler & Goswami, 2005). Over three decades ago, Snowling empirically demonstrated that individuals with dyslexia have problems with phonological tasks (Snowling, 1981). Bradley and Bryant (1983) also showed that phonological processing skills were impaired in children with dyslexia and that these problems continued until their adult lives. These findings were confirmed by recent reviews (Hulme & Snowling, 2009; Vellution et al., 2004).

The National Early Literacy Panel (2008) conducted a meta-analysis of correlational studies and found that phonological awareness was statistically correlated with word decoding. This correlation was slightly stronger (.42) than that between syllable awareness and decoding (.36). Strength of the correlations also depended on the task used. Tasks that required children to analyze, delete, count or substitute speech sounds were better at predicting reading than those that involved making judgments on how to combine sound parts or the tasks in which children were asked to identify sound units by matching them in words. Rhyming tasks were the weakest correlates with reading. Another meta-analysis of correlational studies which explored verbal short-term memory in addition to the phonological awareness aspects revealed that phonemic awareness remained the best reading predictor (Melby-Lervag et al. 2012). This was also confirmed by a more recent study by Willcutt et al. (2013). Phonological awareness, however, does not seem to be of the same level of importance in other, particularly transparent, orthographies such as Dutch, Swedish, Norwegian, German, Finnish, Hungarian, Portuguese and French (Arnoutse, van Leeuwe, & Verhoeven, 2005; Furnes & Samuelsson, 2010; Landerl & Wimmer, 2000; Ziegler et al., 2010).

The above studies used correlational or cross-sectional designs; therefore their findings cannot aid the discussion on the casual factors in dyslexia which are difficult to establish (Castles & Coltheart, 2004). As discussed in Chapter 1, external factors, such as those environmental and socioeconomic, may contribute to phonological processing weaknesses, suggesting that poor phonological processing may be a consequence, rather than a cause, of poor reading development (Corriveau, Goswami, & Thomson, 2010). Consequently, the need to look into the findings of prospective, longitudinal and intervention studies is important.

Evidence from longitudinal studies seems to lend further support for the suggestion that problems with phonological processing predict subsequent reading and writing problems. Hulme and Snowling (2009), for example, showed that phonological measures obtained before children started formal reading education could predict their reading abilities in the future. Studies selecting samples of children with a familial risk of dyslexia and comparing them with control groups also provided some insight into causality. Lyytinen et al. (2006) and Richardson, Thomson, Scott, and Goswami (2004) found that poor readers showed difficulties in differentiating speech sounds as early as six months old and that this difficulty was also evident in their parents with dyslexia.

Memory

The second dimension related to phonological representations is memory. Learning to read requires the key aspects of memory: coding, storing and retrieving information; namely the associations between the written and the spoken language (Elliott & Grigorenko, 2014). Memory deficits in dyslexia are well recognised in the literature (Cohen-Mimran & Sapir, 2007; Gathercole, Alloway, Willis, & Adams, 2006; Nelson & Warrington, 1980; Schuchardt, Maehler, & Hasselhorn, 2008). Verbal short-term memory, working memory, and long-term memory deficits have been found in individuals with dyslexia (Gathercole et al., 2006; Nelson & Warrington, 1980). However, the literature is fairly inconsistent when it comes to the use of terminology. Some researchers use the terms short-term memory (STM) and working memory (WM) interchangeably.

The most commonly used memory test in dyslexia research and a part of most screening/diagnostic test batteries for dyslexia and general educational ability is the digit span task (Nelson & Warrington, 1980). The task requires one to recall and repeat a set of numbers in either a forwards or a backwards order. In Wechsler Intelligence Scales (1997, 2004, 2013), both forward and backward digit span scores are combined into one score and represented as a WM measure. Others would argue that both these tasks require STM rather than WM (Engle, Kane, & Tuholski, 1999; Rosen & Engle, 1997).

Although both STM and WM relate to an ability to hold information for a short time, there is one key difference. STM involves a passive storage of information, whilst WM involves both the storage in addition to active processing of information (for a more detailed discussion see Cowan, 2009). Tasks that measure WM assess an ability to actively maintain information relevant to performing the task, for example, remembering the task details or remembering to ignore some elements of the task, and at the same time to process information (e.g., Baddeley & Logie, 1999; Unsworth & Engle, 2007). Therefore, WM relies on the central executive systems also associated with these attentional mechanisms.

Difficulties in WM and STM seem to be independent of intelligence (Swanson, Zheng, & Jerman, 2009) but both seem to be related to difficulties with reading (Gathercole, Pickering, Knight, & Stegmann, 2004; Kibby, Marks, Morgan, & Long, 2004). However, it is not clear which of these types of memory is more important for explaining reading disorder. A meta-analysis by Swanson et al. (2009) found that both types of memory were compromised in individuals with dyslexia comparing to typically reading participants.

Dyslexia researchers also measure different modalities/levels of memory: verbal, visual and visuo-spatial. Visuo-spatial short-term memory and visuo-spatial working memory that both rely on visuo-spatial sketchpad (Baddeley, 2012) are measured by the means of tests in which the recall of visually presented information is required such as the Corsi Block-Tapping task where participants are shown a number of blocks and have to tap them in a sequence presented by the examiner (Kessels, van Zandvoort, Postma, Kappelle, 2000). Johnson et al. (2010) found a greater effect for verbal working memory than for visual working memory in their review of studies comparing children with and without dyslexia. Verbal short-term memory and verbal working memory are sometimes seen as similar concepts when it comes to applied research with children (Hutton & Towse, 2001). However, some researchers would disagree with this simplification of terms suggesting that only working memory incorporates both the phonological loop and the central executive, and that in reading, WM plays a twofold role: it allows holding the information that has just been processed and retains the essence of a passage allowing the comprehension of the text (Swanson & O’Connor, 2009).

Rapid naming and double deficit model

The third dimension is related to the retrieval of phonological representations from long-term memory, as typified by rapid automatic naming (RAN) tasks (Ramus & Szenkovits, 2008). The RAN task measures the ability to name stimuli such as letters, digits or colours as quickly as possible. The stimuli are presented visually. Investigating the mechanisms behind RAN is important as it provides a better understanding of reading itself. The pioneering studies conducted by Denckla and Rudel (1974) showed that normally reading children significantly outperformed children with dyslexia in colour naming when speed rather than accuracy was taken into consideration. Today, there is enough empirical evidence to see RAN as an important predictor of dyslexia, as the rapid naming deficit has been found in many dyslexic readers (Semrud-Clikeman, Guy, Griffin, & Hynd, 2000; Wolf, Bowers, & Biddle, 2000). RAN has been shown to be a good predictor of word reading ability as well as a reading disability (Lervåg & Hulme, 2009).

Although the RAN task is very easy and quick to administer, it is a complex task requiring a range of skills. The RAN involves speeded access to verbal information (names of pictures), articulation, keeping the track of items and ability to sustain concentration throughout (Cummine, Chouinard, Szepesvari, & Georgiou, 2015). Amtmann, Abbott, and Berninger (2007) suggested that reading and speeded naming both require executive processes such as attention, working memory, and inhibition.

The pioneers of this area of research, Denckla and Rudel (1976), suggested that visual-attentional processes are delayed during rapid naming in individuals with dyslexia. Others would suggest that it is a part of general processing speed disorder that impacts an integration of visual and phonological information (Kail & Hall, 1994). A number of studies that followed this crucial finding aimed to explore the relationship between RAN and reading. The most recent review on the subject indicated that what connects the two is the involvement of serial processing and articulation of the names (Georgiou, Parrila, Cui, & Papadopoulos, 2013). Some further theoretical accounts have been offered aiming to explore the relationship between RAN and reading. So far there is no conclusive evidence on which of these components is deficient in individuals with dyslexia. Some researchers suggest that rapid naming deficit is an extension of phonological processing deficit (Wagner, Torgesen & Rashotte, 1994). This assumption, however, can be undermined by studies showing that RAN deficit can be found in poor readers who do not experience phonological problems (Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Wimmer, Mayringer, Landerl, & Landed, 2000).

Successful reading requires one to incorporate a number of different processes: perceptual, attentional and naming skills that all work together to match the visual representation to phonological codes quickly and accurately (Bowers & Wolf, 1993; Norton & Wolf, 2012; Wolf & Bowers, 1999). Therefore, problems with tasks such as RAN can signify different difficulties at the low and high level of processing. The main question, however, proposed by researchers in the field is whether RAN should be seen as a test of the phonological processing or whether it is independent of phonological processing (Norton & Wolf, 2012). Torgesen et al. (1994) suggested that RAN belongs to the phonological processing family and is a good predictor of reading because it involves a retrieval of phonological representations from long-term memory, which is also a requirement in reading. Nicolson, Fawcett, and Dean (2001) also proposed that what links RAN and reading are common motor programming and articulatory processes which are dependent on the functioning of the cerebellum.

The investigation of neural correlates underlying RAN and reading has only recently been employed but already provided interesting insights (Cummine et al., 2015). Using fMRI, Cummine et al. (2015), for example, found that RAN and single-word reading activate the same areas of the brain. The regions that were activated are associated with motor planning (cerebellum), semantic access (middle temporal gyrus), articulation (supplementary motor areas), grapheme-phoneme conversion (supramarginal gyrus), and speech monitoring (anterior cingulate). Regarding the magnitude of RAN activation and reading activated regions associated with the processing of orthographic (inferior temporal gyrus) and phonological (SMG, superior temporal gyrus) information differed. Both of these regions showed higher activation during reading tasks comparing to RAN. This finding indicates that the RAN is not strongly related to phonological and orthographic processing. However, the activation was similar in its magnitude in regions associated with articulatory and motor processing (e.g., cerebellum). Cummine et al. (2015) concluded that motor-sequencing and articulatory processes are at the core of RAN-reading relationship. Nevertheless, it is important to note that only healthy adults took part in the study. It would be beneficial to investigate the brain activation of people with dyslexia due to the fact that, as will be explored later in this chapter, brains of those with dyslexia can be different from those without dyslexia.

RAN performance has repeatedly been shown to be compromised in children with dyslexia compared to typical readers (Wolf et al., 2000) and this appears to continue into adulthood (Pennington, Orden, Smith, Green, & Haith, 1990; Vukovic, Wilson, & Nash, 2004). Research investigating the predictive value of RAN yield different findings depending on the type of visual information (colours, letters, numbers) being used (Barlett & Gentile, 2012; Mazzocco & Grimm, 2013) and whether the predicted outcome is a test of reading fluency or accuracy (Savage & Frederickson, 2005). Studies have also shown that the predictive value of RAN differed depending on whether outcome measure was the reading progress of typical or dyslexic readers (National Early Literacy Panel, 2008). RAN was only moderately related to reading when the sample contained typical readers but strongly when poor readers' scores were included as an outcome variable (Lervag, Braten & Hulme, 2009). RAN skills and their role in reading may also depend on the age of individuals. Wolf et al. (2000) showed that RAN was better at predicting reading of younger children than when an older cohort was considered.

Although the relationship between reading and RAN can be found across different languages, its predictive value seems to be greater in transparent languages (e.g., Furnes & Samuelsson, 2010; Torppa, Lyytinen, Erskine, Eklund, & Lyytinen, 2010) rather than in opaque orthographies (Compton, 2003; Compton, DeFries & Olson, 2001). This can be supported by the findings that dyslexia manifestations in transparent languages differ from those of opaque languages and are more likely related to the fluency rather than accuracy (Klicpera & Schabmann, 1993).

The three dimensions related to phonological representations, as discussed, are seen as the key deficits in dyslexia according to the phonological deficit hypothesis (Wagner & Torgesen, 1987). Although it has been consistently shown that these deficits are present in individuals with dyslexia, there are some inconsistencies within the hypothesis and a lack of clarity when it comes to the use of the terminology of the key components. Specifically, the term phonological awareness (often used interchangeably with 'phonological processing') is sometimes used as an umbrella term encompassing both STM and RAN (lexical retrieval) measures, along with the phonological awareness measures (Duff, Hayiou-Thomas & Hulme, 2012). The latter are sometimes referred to as explicit phonological processing as they require conscious manipulation of speech sounds, whilst the other two are seen as implicit as no conscious operations of the phonological units are involved (Melby-Lervag, Lyster, & Hulme, 2012). However, this inclusion of two dimensions related to memory and retrieval of information into the phonological component is contested by some researchers (e.g., Nicolson & Fawcett, 2008).

Several studies have conversely indicated that RAN's unique contribution to variance in reading is independent of the contribution of the phonological awareness (Parrila, Kirby & McQuarrie, 2004). This is also known as double-deficit hypothesis (Wolf & Bowers, 1999). In the double-deficit view, phonological awareness and RAN are distinct. According to this model, individuals with dyslexia can be divided into three separate groups depending on the difficulties they experience. The first group comprises individuals with the most severe reading problems displaying both phonological and rapid naming difficulties (double deficit). A combination of both of these deficits may be additive, therefore, more severe (Compton et al., 2001; Kirby, Parrila & Pfeiffer, 2003; O'Brien et al., 2012; Papadopoulos, Georgiou & Kendeou, 2009; Wimmer et al., 2000; Wolf & Bowers, 1999). The second group encompasses those with phonological but no RAN difficulties. The third group comprises individuals showing the opposite pattern: RAN but no phonological difficulties. There seem to be a relatively small number of children who only display the RAN deficit (Vukovic & Siegel, 2006), with estimates of 10% of all dyslexic readers being included in this category (Vaessen, Gerretsen & Blomert, 2009). Corroborating evidence for the double deficit group showing more severe reading problems than single deficit group has been found in studies investigating both transparent (Torppa et al. 2010) and opaque (Wolf et al., 2000) languages.

The double-deficit hypothesis was also investigated in adult populations. Cirino, Israelian, Morris, and Morris (2005) investigated the contribution of phonological awareness and visual naming speed to decoding and comprehension deficits in a sample of university students. They found that the two variables contributed differently to the prediction model depending on the type of tests used to establish reading disability. When timed decoding and timed reading comprehension were used as the core reading disability deficits, almost 27% and 35% of students, respectively, who were defined as disabled readers, had no phonological awareness or visual naming speed deficits. This finding suggests that at least some adults with developmental dyslexia may have other than language-based deficits that Cirino and colleagues (2005) did not test. Nelson (2015) also found that the majority of variance in reading in adults was not accounted for by phonological awareness, rapid naming, or both variables together. These findings indicate that phonological awareness and rapid naming are not sufficient to understand reading problems of individuals with developmental dyslexia; the double-deficit cannot be a standalone theory explaining the causal mechanisms in dyslexia.

Phonological representations

Another contentious issue in the phonological deficit theory is the nature of the phonological representation problem (Ramus & Szenkovits, 2008). All three dimensions of the phonological deficit, the phonological awareness, memory and rapid naming, are associated with phonological representations. It, therefore, seems reasonable to assume that the phonological deficit in developmental dyslexia can be explained by the fact that these representations are in some way degraded.

Phonological representations may be ‘fuzzier’, ‘noisier’ or inadequate in terms of their size or specificity (Ramus & Szenkovits, 2008). The phonological deficit hypothesis does not, however, identify which levels of phonological representations are supposed to be deficient in dyslexia. Therefore, Szenkovits and Ramus (2005) used a number of tasks investigating levels of phonological representations in a series of experiments involving a group of participants with diagnosed dyslexia and a group of normal readers. The researchers found significant group differences in all of the conditions. This finding provides evidence to suggest that the phonological deficit is apparent regardless of the level assessed: lexical (words) and sublexical (nonwords), input (hearing speech), in addition to output (producing speech). What is more, individuals with dyslexia have been found to perform poorer in discrimination tasks than in the repetition tasks which indicates a more profound deficit in input representations (Ramus & Szenkovits, 2008).

However, a number of further investigations have shown that the poorer performance found in people with dyslexia on a range of phonological tasks may not be caused by degraded phonological representations, but instead by a limited access to them; emphasizing the crucial role of short term memory within dyslexia (Ramus & Szenkovits, 2008). In other words, although the phonological deficit exists in dyslexia, it cannot be tracked directly to the problem with phonological representations. The phonological measures that have heavily relied on STM and abilities to quickly retrieve information were the most difficult for individuals with dyslexia to perform (Ramus & Szenkovits, 2008). Ramus and Szenkovits (2008) have hence provided compelling evidence supporting the idea that phonological representations are intact in individuals with dyslexia, but the access to them is limited and problematic.

Undoubtedly, researchers exploring the nature of phonological deficit and its components, as discussed above, are yet to reach a consensus. A full discussion of these is outwith the current thesis, however what has been consistently shown is that most researchers agree with the premise that phonology plays a central role in developmental dyslexia (Goswami, 2003; Gabrieli, 2009; Peterson & Pennington, 2012; Snowling, 2001; Shaywitz et al. 2004; Vellutino et al., 2004; Ziegler & Goswami, 2005). Overall, there appears to be a compelling body of research using different methods of investigation which, when taken together, indicates that phonological processing is related to reading abilities. Training and intervention studies further provide persuasive evidence for the causal link between dyslexia and phonological deficits (Bowyer-Crane et al., 2008; Snowling & Hulme, 2012). Finally, instructions targeted to facilitate phonological awareness have been shown to enhance reading ability (Vellutino et al., 2004).

While the phonological deficit hypothesis operates at the cognitive level of explanation, its biological bases have also been debated. Classical work by Galaburda and colleagues (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Geschwind & Garaburda, 1987) provided anatomical evidence for a left perisylvian dysfunction linked to the phonological deficit. A recent study that used a large sample of children (n = 236) has also confirmed this finding (Plonski et al., 2017).

Neurologically speaking, dyslexia is considered to be an inborn dysfunction of left-hemisphere brain areas associated with phonological representations (Brunswick, McCrory, Price, Frith, & Frith, 1999; McCrory, Frith, Brunswick, & Price, 2000; Paulesu et al., 1996; Pugh et al., 2000; Shaywitz et al., 2002; Temple et al., 2001). Figure 2.2 presents findings from a selection of studies showing a functional neural basis of phonological deficits.

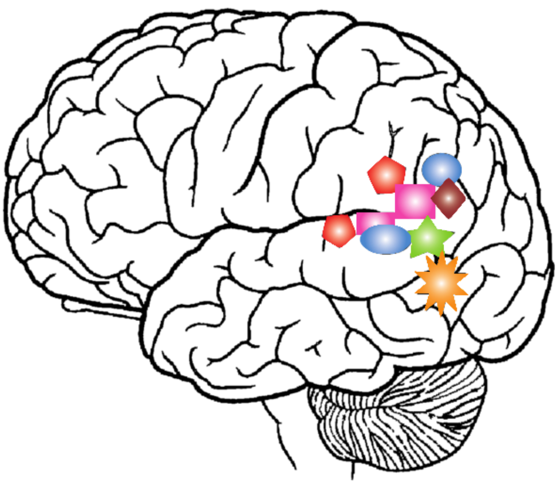

Figure 2.2 Neural disruption in phonological processing. Approximate anatomical locations of hypoactivity in DD individuals during phonological tasks. Taken from Temple (2002, p. 179)

Legend:

- Paulesu et al. (1996): PET; letter rhyme task
- Rumsey et al. (1997): PET; pseudo-word task
- Shaywitz et al. (1998): fMRI; letter rhyme task, pseudo-word task
- Brunswick, McCrory, Price, Frith & Frith (1999): PET; pseudo-word task, explicit and implicit tasks
- Temple et al. (2001): fMRI; letter rhyme task
- Paulesu et al., (2001): PET; explicit and implicit tasks

One of the weaknesses of the phonological deficit hypothesis is that it cannot explain why some children who are poor readers do not have problems with phonological processing. Research has demonstrated that not all dyslexic readers have the phonological deficit (Castles & Coltheart, 1996; Ramus & Ahissar, 2012; White et al., 2006), and children with poor phonological processing may still become good readers (Catts & Adlof, 2011; Howard & Best, 1996). In addition, no study has provided indisputable evidence, controlling for existing literacy skills in their participants, that there is a causal link between competence in phonological processing and success in reading and spelling acquisition (Castles & Coltheart, 2004). Studies investigating interventions targeting the phonological skills have found that improvements in phonological awareness do not automatically transfer to better reading (e.g., Agnew et al., 2004; Galuschka et al., 2014; Strong, Torgerson, Torgerson, & Hulme, 2011).

In light of the debates around the phonological processing and its role in dyslexia, Snowling (2008) suggested that if it is not seen as a marker of dyslexia, it can be hypothesized to be understood as an endophenotype, a process operating between the genotype and the genes' expression (phenotype). In this sense, phonological processing deficits manifest themselves in individuals independently of dyslexia. Support for this suggestion can be found in studies that showed that children at familial risk of dyslexia who develop normal reading skills often show mild phonological deficits (Boets, Vandermosten, Poelmans, & Luts, 2011; Van Bergen, De Jong, Plakas, Maassen, & Van Der Leij, 2012).

2.1.2 Sensory deficits

While the phonological processing clearly is a big part of dyslexia, there are several theories within the dyslexia research that incorporate low-level sensory, visual, auditory and motor deficits into the phonological deficit description. These approaches do not deny the relevance of phonological processing in reading disorder but place it on the surface of other, more basic processes. For some, phonological deficit is underpinned by basic visual and/or auditory processing (Ramus, 2003; Tallal & Gaab, 2006; Vidyasagar & Pammer, 2010).

At the cognitive level of explanation, an auditory temporal deficit was proposed. Tallal (1980) reported significant correlations between auditory processing and reading, hypothesizing a rapid processing deficit in individuals with dyslexia. This hypothesis was further supported by studies which showed that individuals with dyslexia performed poorer than normal readers on auditory temporal order perception tasks (Tallal, 1980; Tallal et al., 1996; Tallal, Miller, & Fitch, 1993). Auditory difficulties found in dyslexic readers were identified as important in developing phonological awareness. These were problems related to prosodic cues such as rhythm, prominence of syllables or phrases (Goodman, Libenson, & Wade-Woolley, 2010).

Research has suggested that lower-level auditory deficits can explain phonological processing difficulties (Banai et al., 2009; Bishop, Carlyon, Deeks, & Bishop, 1999; Goswami, 2011b; Tallal & Gaab, 2006). Such atypical processing has been demonstrated in pre-reading children at dyslexia risk (Boets, Vandermosten, Cornelissen, Wouters, & Ghesquière, 2011; Leppänen et al., 2010; Plakas, et al., 2013; Van Zuijen et al., 2012). Basic auditory processing difficulties have been considered by some researchers as causes of the phonological deficit (Farmer & Klein, 1995; Tallal & Gaab, 2006). Others proposed that auditory deficits are unnecessary for phonological problems to be present (Hämäläinen, Salminen, & Leppänen, 2013) or even as the consequences of phonological deficit (Ramus, 2004). Plakes, van Zuijen, van Leeuwen, Thomson, and van der Leij (2013) suggested that auditory processes are unlikely to cause dyslexia on their own, but they could be a risk factor that together with other processes may contribute to the development of dyslexia. The auditory deficit hypothesis provided an important contribution to the field of developmental dyslexia, despite some inconsistencies as to the causal role of auditory processing as well as uncertainty as to the prevalence of these deficits in individuals with dyslexia.

Given that reading requires visual recognition of letters before any grapheme-phoneme mapping can be applied (Share, 1995) it does not come as a surprise that individuals with dyslexia have been shown to experience a number of visual problems. Research suggested that dyslexia is correlated with visual anomalies such as binocular instability (Evans, 2001) and visual perceptual distortions due to eyestrain or visual stress that are often treated with coloured overlays (Evans & Joseph, 2002; Irlen, 1991; Wilkins et al., 1994).

The main theory which considers the visual deficit in dyslexia is the magnocellular theory (Stein, 2001), or more recently its extended version the magnocellular-dorsal theory. Due to cognitive manifestations of the magnocellular deficit, such as processing of rapidly moving stimuli (Vidyasagar, 2012), this theory is sometimes discussed together with the cognitive explanations of dyslexia (e.g., Elliott & Grigorenko, 2014; Vellutino et al., 2004). However, within this thesis, it is treated as a predominantly brain-based explanation and will, therefore, be discussed together with other biological explanations within the present chapter (see section 2.2.1.1).

2.1.3 The role of visual attention

Rapid orientation of visual attention allowing one to select relevant information (letters) is necessary for the reading process (Yeshurun & Rashal, 2010). Visual attention allocation is a prerequisite for correct grapheme-phoneme integration (Hari, Renvall, & Tanskanen, 2001; Ruffino et al., 2010b; Vidyasagar & Pammer, 2010; Zorzi et al., 2012). Ruffino et al. (2010) found that spatio-temporal distribution of attention engagement that is inefficient may impair letter string parsing during phonological decoding. Furthermore, it has been shown that children with dyslexia display ineffective spatial orienting of visual attention (Brannan & Williams, 1987; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Facoetti & Molteni, 2001; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti, Luisa Lorusso, Paganoni, Umiltà, & Gastone Mascetti, 2003). In particular, an asymmetric distribution of attentional resources across the visual field was demonstrated by mild left inattention in cue-target reaction time tasks and abnormally high sensitivity in the right visual field (Facoetti & Molteni, 2001; Facoetti et al., 2000; Hari et al., 2001). Children with dyslexia were found to have abnormally high performance on processing sets of erratically located letters in the right visual field, which is suggestive of a difficulty in inhibiting peripheral information (in the direction of reading) and focus attention in the center of the gaze (see also Rayner, Murphy, Henderson, & Pollatsek, 1989). More recently, a diffused attention allocation was shown in individuals with DD, which is indicative of problems with focusing the attention (Facoetti et al., 2000). Facoetti et al. (2003) also found that individuals with dyslexia take longer to capture attention. Once caught, the attention is not as easily disengaged, though (Hari, Valta, & Uutela, 1999).

In contrast, Bosse, Tainturier, and Valdois (2007) proposed that a reduced number of items that can be processed simultaneously by individuals with DD contributes to their difficulties in reading. This idea was referred to as visual attention (VA) span hypothesis. This hypothesis proposed that deficits in attention allocation across letters restrict the number of elements that can be processed in parallel. VA span deficit seems to be unrelated to the phonological deficit suggesting a different subtype of dyslexic readers (Valdois, Lassus-Sangosse, & Lobier, 2012). The independence of visual attentional and phonological problems has been supported by many empirical investigations (Bosse et al., 2007; Dubois et al., 2010; Kevan & Pammer, 2008; Lobier, Zoubrinetzky, & Valdois, 2012; Peyrin, Démonet, N'Guyen-Morel, Le Bas, & Valdois, 2011).

The concept of limited VA span contrasts with the notion of slow attention shifting. The amodal sluggish attentional shifting (SAS) hypothesis suggests that individuals with dyslexia have a parietal attentional dysfunction which could explain temporal deficit found in them (Hari et al., 2001). In this hypothesis, when dyslexic readers are presented with rapid sequences of stimuli the attentional systems disengage inefficiently leading to problems when moving from one item to another (Hari et al., 2001; Lallier et al., 2010).

Behavioural studies have provided evidence to support this hypothesis by showing that children with dyslexia display slower covert attentional orienting skills in visual and auditory modalities (Facoetti et al., 2010; Facoetti, Lorusso, Cattaneo, 2005). Such multisensory deficit of attention would affect the process of segmenting into auditory (speech signals) and visual (letter strings) components. Furthermore, stimulus integration and/or segregation deficits are found to be related to reading problems (Lallier et al., 2010). Studies incorporating behavioural and neuroimaging findings provide quite consistent support for amodal SAS (Goswami, 2011; Lallier et al., 2010; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014; Valdois et al. 2012).

Visual problems that affect reading may be explained by a disrupting influence of adjacent letters that is known as abnormal crowding (Cassim, Talcott, & Moores, 2014; Moores, Cassim, & Talcott, 2011). Crowding is an inability to recognize objects (such as letters) when they are surrounded by similar objects. It is usually observed in peripheral vision (Gori & Facoetti, 2015). Partial support for this hypothesis was found in studies showing that some dyslexic readers benefit from increased spaces between letters during reading (Spinelli et al. 2002; Martelli et al. 2009). Such a benefit, however, was not found in age-matched control children suggesting that the crowding effect is not a consequence of lack of reading experience (Zorzi et al., 2012).

This large body of research provides evidence for the visual attentional deficit possibly contributing to reading problems. Such a disorder that affects parallel processing speed (Yap & van der Leij, 1993) may make one confuse letter sequence in words and make reading errors, particularly errors in decoding of similarity looking words. Casco, Tressoldi, and Dellantonio (1998) also showed that performance on tasks involving selective attention, such as cancellation task, is related to reading performance. The double dissociation between the phonological processing and visual attention deficit indicating that both of them are significant but independent predictors of reading was shown in English (Lallier, Donnadieu, Berger, & Valdois, 2010) and in French (Valdois & Bosse, 2004; Valdois et al., 2003).

2.1.4 Automaticity deficit

Another competing explanation for DD is the automaticity deficit. In the early 1990s, a group of researchers from the University of Sheffield found that children with dyslexia show a range of problems related to their balance (Fawcett & Nicolson, 1992), motor skills (Fawcett & Nicolson, 1995) and rapid naming (Fawcett & Nicolson, 1994). These researchers suggested that phonological deficit is unlikely to be the only problem in dyslexia. Based on their research, Nicolson and Fawcett (1990) offered the dyslexia automatisation deficit hypothesis. They hypothesised that children with dyslexia have difficulties in gaining fluency for any skill, such as reading or riding a bicycle, which should be automatised with practice.

Nicolson and Fawcett (2008) indicated three features of automaticity: quality of performance (speed and accuracy), effortlessness, and strength of automatisation (resistance to interfering or unlearning). According to the automaticity hypothesis, individuals with dyslexia manage to mask their poor automatization of motor skills by a process of conscious compensation by putting an extra effort. However, when the task becomes more difficult they are no longer able to mask the deficits (Nicolson & Fawcett, 1994). Following this, the true automaticity is revealed. In other words, improved task performance achieved with practice does not necessarily indicate achieved automatisation (Lang & Bastian, 2002).

The stage of automatisation typically occurs at the end of consolidation after a long period of training (Doyon et al., 2009) and sleep over at least several nights (Walker, 2005). The best way to test if the automaticity level has been achieved is by dual-task paradigm (Gopher, 1980; Passingham, 1996). In such a task, the skill that is to be automatized is performed together with another task. Children with dyslexia have been shown to experience difficulties with everyday automatic skills, such as cycling or reading, and with performing two different tasks at the same time (Legrand et al., 2012). The automaticity deficit in dyslexia is widely accepted, although the causal links are still debatable.

Automaticity is, or at least should be, an end product of procedural learning. The concept of automaticity provided the basis to a theory looking into the role of the cerebellum and to the procedural learning deficit that links the neural aspects with cognition. Both of these hypotheses are discussed in the following sections.

2.2 Biological theories

As mentioned at the beginning of this chapter, reading is a complex task that involves many different brain areas. Within this section, a number of biological theories of DD will be presented. First, the brain-based theories are discussed: the magnocellular-dorsal hypothesis and the cerebellum deficit hypothesis. Also the procedural learning defcit is disussed along the cerebellum deficits. Next, a brief discussion on current understanding of genetic factors is provided.

2.2.1 Brain based theories

2.2.1.1 Magnocellular-dorsal deficit hypothesis

The magnocellular theory (Stein, 2001) suggests that the cause of dyslexia lies in a deficit within the magnocellular visual pathway. This concept emphasises a visual contribution to reading and provides a neurobiological basis to DD when considered as a reading disorder. The theory emerged from a discovery of deficits in the magnocellular pathway of the visual system in individuals with dyslexia (Galaburda & Livingstone, 1993; Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove, Martin, & Slaghuis, 1986). Although the magnocellular theory first proposed by Stein (2001) focused on the role of the M cells and their dysfunction, Stein and Walsh (1997) proposed that small deficits found in the magnocellular pathway may cumulate and lead to more severe deficits in the posterior parietal cortex, in the motion processing area of the brain (the dorsal stream). As the magnocellular neurons project the information to the higher level processing structures, mostly the dorsal stream of the visual system, Stein (2001) suggested that a deficit somewhere along the magnocellular pathway and in the areas of the brain that rely on M cell projections could be the cause of dyslexia. Further studies showed that the higher level visual processing related to the dorsal stream functioning is also impaired in people with dyslexia (Cornelissen Richardson, Mason, Fowler, & Stein, 1995; Slaghuis & Ryan, 1999). Therefore, when referring to the visual deficits, researchers tend to use the term magnocellular-dorsal (MD) deficits or M system deficits (Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016). It needs to be recognised that some researchers use the terms *magnocellular cells* and *dorsal stream* interchangeably. However, from the tasks used, one can decipher what level of functioning they aimed to measure and so this mixing of terms is not strictly correct.

Low-level visual processing

The magnocellular pathway originates in the parasol retina ganglion cells, passes through the two inferior layers of the lateral geniculate nucleus (LGN) and projects information to the back of the brain, the occipital lobe and further to the parietal lobe intermingling with other streams (Maunsell & Newsome, 1987; Merigan & Maunsell, 1993). M retinal ganglion cells have large visual fields and thick, rapidly conducting axons. They are larger than the remaining 90% of the ganglion cells, called parvocellular cells (P cells). M cells have extensive dendritic trees that gather information from a large area of retinal receptors which makes them more sensitive to large, dim, low contrast stimuli but insensitive to very detailed, small visual information, such as colour (Maunsell, Nealey, & DePriest, 1990). They are also much more responsive to rapidly changing stimuli (they are ‘rapidly adapting’). P cells, on the other hand, are more responsive to fine details. M cells mature later than P cells and their development may be impaired in prematurity (Stein, 2008). In the LGN, the M and P cell inputs are anatomically separated (Merigan & Maunsell, 1993). There is a number of conditions, apart from dyslexia, that are associated with magnocellular dysfunction such as glaucoma (Maddess & Severt, 1999) and autism spectrum disorder (Greenaway, Davis, & Plaisted-Grant, 2013).

High-level visual processing

Visual information from the occipital lobe is further transferred into two separate streams: dorsal and ventral (Enroth-Kugel & Robson, 1966; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982). The dorsal stream mostly receives information from magnocellular neurons. The dorsal stream stretches to the visual motion area (V5/MT) which is sensitive to global motion. This system plays a role in the visual guidance of the eye and limb movements by projecting to the posterior parietal cortex (Milner & Goodale, 1995). Psychophysical tasks are often used to stimulate a particular part of the visual system. One activating the dorsal stream is the measure of global motion processing which involves one to detect coherent motion amongst randomly moving dots (stimuli also known as dynamic random dot kinematogram or RDK). The task has been tested in monkeys (Newsome & Pare, 1988) and in humans (Talcott, Hansen, Assoku, & Stein, 2000) and has been confirmed as a reliable measure of magnocellular-dependent visual system by fMRI studies (Demb, Boynton, & Heeger, 1998; Eden et al., 1996) and electrophysiological studies (Livingstone et al., 1991). The ventral stream, which mainly receives projections from the parvocellular neurons, is involved in detail and colour identification (Maunsell et al., 1990). It is located towards the visual word form area (VWFA) at the anterior end of the fusiform gyrus. This stream is more sensitive to static, detailed stimuli. For a schematic representation of the streams, see Figure 2.3.

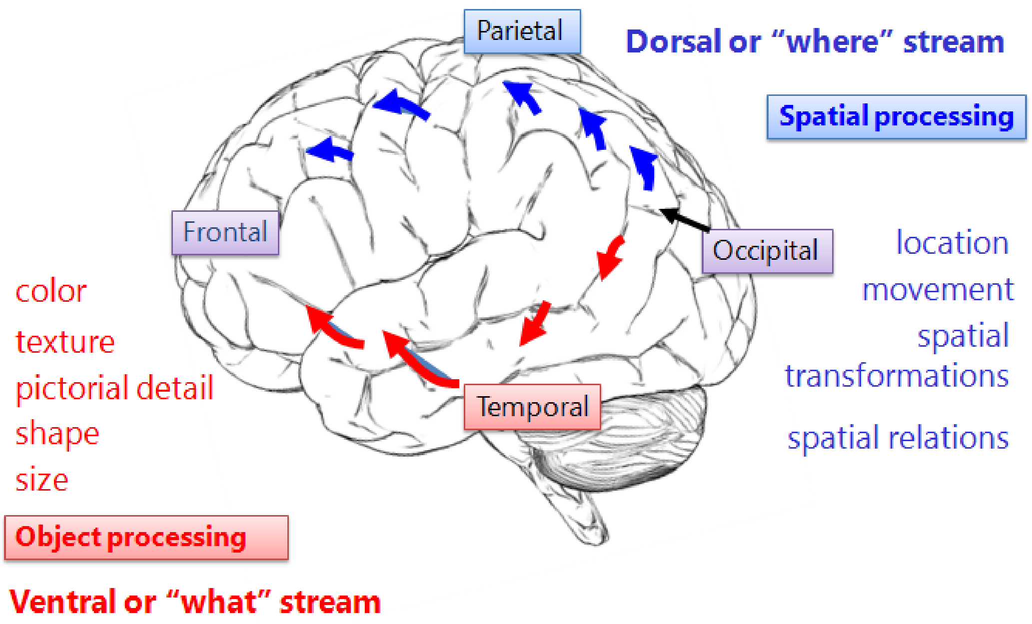

Figure 2.3 Schematic representation of the two separate streams with their main cell projections: M cells to the dorsal stream and P cells to the ventral (from Li, 2015).

Evidence supporting the magnocellular theory of dyslexia can be found in anatomy/physiology studies in which abnormalities of the magnocellular layers in the brain (LGN) were well documented in the past (Livingstone, Rosen, Drislane, & Galaburda, 1991) and replicated recently (Giraldo-Chica, Hegarty, & Schneider, 2015). This contrasts with the arguments that only the language areas in the brain are affected in dyslexia. Furthermore, brain imaging studies show that individuals with dyslexia display reduced brain activity in the primary visual cortex (Demb et al., 1998) and in the V5/MT area (associated with dorsal stream) (Eden, VanMeter, Rumsey, Masiog, Woods, & Zeffiro 1996) during the perception of motion. Demb et al. (1998) also demonstrated that there was a positive significant correlation between visual cortex (V1) and MT activity, performance on a speed discrimination task, and reading.

Compelling evidence for the magnocellular deficit comes from psychophysical studies measuring performance of dyslexic readers and normal readers on tasks aiming to preferentially activate the magnocellular cells, such as those measuring contrast sensitivity at low spatial frequencies (Lovegrove, Bowling, Badcock, & Blackwood, 1980; Slaghuis & Ryan, 1999), those measuring speed discrimination thresholds (Demb et al., 1998), and visual search tasks (Vidyasagar & Pammer, 1999).

The use of visual illusions has proven to be particularly useful in understanding of visual deficits in developmental disorders; that was, however, only recently fully appreciated (Gori et al. 2016). For example, Pammer and Wheatley (2001) conducted a study in which they compared sensitivity to the frequency doubling illusion (FDI) (Kelly, 1966) in children with and without dyslexia. The FDI depends on the spatial and temporal frequency of flickering gratings. If the gratings are of low spatial and temporal frequency, the participant looking at the gratings would perceive a stable grating with twice as big spatial frequency as the actual frequency. For instance, *seeing* four bars where there are only two bars flickering.

There is evidence that response to this flickering stimuli is unique to M cells as they respond optimally to the ‘illusory’ spatial frequency (e.g., Maddess & Henry, 1990; Tyler, 1974). Pammer and Wheatley (2001) found that reading disabled participants were less sensitive to this illusion than their reading and age matched normally reading counterparts. Corroborating evidence using the same illusion was found by Buchholz and McKone (2004) and Gori, Cecchini, Bigoni, Molteni, and Facoetti (2014). Also, Kevan and Pammer (2008) conducted a study in which they looked at two groups of pre-reading children; one at familial risk of dyslexia and the second with no history of reading difficulties within families. Those children who were at risk of dyslexia performed significantly worse on tasks associated with the magnocellular and dorsal stream functioning than the control group. A coherent form task was also included in the study to see if the children at dyslexia risk were generally bad at visual tasks or if the deficit was specific to the magnocellular-related systems. Both groups of children showed the same levels of sensitivity to this control stimulus. In addition, Kevan and Pammer (2009) found that that performance on frequency doubling task in pre-reading children could predict their early literacy skills. These findings are particularly important as the study involved children before they started formal reading education, thus provided compelling evidence for rejecting the idea that the low-level visual deficits are a consequence of poor reading.

Stimuli preferentially activating the dorsal stream are of rapid and dynamic nature. Over the last two decades, a growing body of research has provided evidence for a link between dyslexia and impairments in the detection of dynamic visual stimuli (Farmer & Klein, 1995). Witton et al. (1998) were the first to show the dissociation between dynamic (related to the dorsal stream functioning) and static (relying on the ventral stream receiving information form the parvocellular cells) stimuli. Hansen, Stein, Orde, Winter, and Talcott (2001) have also demonstrated this dissociation. The researchers found that people with dyslexia were less sensitive to coherent motion, indicating a dorsal stream deficit, but did not differ from the controls on the coherent form detection task known to be dependent on the ventral stream function.

Coherent motion perception task is perhaps one of the most popular choices in research. Benassi, Simonelli, Giovagnoli, and Bolzani (2010) conducted a meta-analysis of 35 studies using this particular task and found a small mean effect size (*d* = 0.178) for correlational studies investigating relationships between coherent motion and reading. Large mean effect size (*d* = 0.747) was found for differences between groups of dyslexic readers and age-matched control groups. Sensitivity to visual motion has been shown as a good predictor of reading ability cross-sectionally. The evidence for this was obtained through psychophysical (Talcott et al. 2000) and fMRI (Demb, Boynton, & Heeger, 1997) studies. Schulte-Körne and Bruder's (2010) review found an inconsistent evidence for contrast sensitivity tasks but more supportive evidence for a role of coherent motion processing. Several studies showed that approximately one-third of individuals with dyslexia display motion processing deficits (Conlon, Lilleskaret, Wright, & Power, 2012; Conlon, Sanders, & Wright, 2009; Franck Ramus, Pidgeon, & Frith, 2003b; Wright & Conlon, 2009).

Further evidence comes from a neurophysiological study conducted by Eden et al. (1996), which revealed that dyslexic participants do not show activation in visual cortex (called V5/MT) when presented with motion stimuli, which is typically observed in controls. Both studies by Eden et al. (1996) and Lovegrove, Bowling, Badcock, and Blackwood (1980), as described previously, demonstrated that individuals with dyslexia show lower levels of sensitivity than a control group to luminance patterns and motion displays with high temporal and low spatial frequency. In contrast, while Olulade, Napoliello and Eden (2013) more recently also found lower activity for children with dyslexia in V5/MT, their findings disagree with the notion that these deficits are of causal nature. Instead, they suggested that such deficits are a consequence of poor reading. Ollulade et al. (2013) motivated their suggestion by showing that if dyslexic readers are matched with reading-level controls, the differences disappear. However, more recent research looking at interventions demonstrated that visual pathways training significantly improved reading speed and comprehension, phonological processing and memory in seven-year-old children (Lawton, 2016; Lawton & Shelley-Tremblay, 2017). Similar findings were also obtained for chinese sample of Children (Qian & Bi, 2015). As discussed earlier, intervention studies are amongst the most indicative of causal relationships.

One of the key limitations of the magnocellular-dorsal deficit theory, however, is that there are gaps at the theoretical level of magnocellular dysfunction and its relation to reading. The theory does not provide a convincing account as to why children with dyslexia are compromised whilst reading single words (Skottun & Skoyles, 2008). Also, it is not entirely clear what is the role of the magnocellular pathway in reading. It has been suggested by some researchers that there is a lack of synchronization in timing between magnocellular and parvocellular processing in individuals with dyslexia which may then prevent effective sequential processing, analysis of patterns (associated predominantly with parvocellular-related ventral stream) and figure-ground discrimination (a type of motion perception) impeding development of reading and efficient attention skills (Stein & Walsh, 1997; Vidyasagar, 2012; Lawton, 2000, 2007, 2008, 2015, 2016; Stein, 2001). Others would suggest attentional links between visual processing and reading (Vidyasagar, 1999, 2012; Solan et al., 2001; Valdois, Bosse, & Tainturier, 2004; Facoetti et al., 2006; Lawton, 2016).

Furthermore, some methodological issues within the studies exploring the theory have been acknowledged. Amitay, Ben-Yehudah, Banai, and Ahissar (2002) pointed to the problem of the use of behavioural measures that would isolate the magnocellular or parvocellular functioning, which is also seen controversial amongst other researchers (Merigan, personal conversation). This is an issue across experimental and quasi-experimental psychological research. In addition, the use of small samples and a lack of control over the comorbidities have also been recognised (Shulte-Korne & Bruder, 2010).

2.2.1.2 Cerebellar deficit hypothesis

In addition to phonological processing, short-term/working memory, rapid naming and magnocellular and dorsal stream deficits, individuals with dyslexia often have problems with balance and motor control. Dyslexia is known to often present comorbidity with dyspraxia (Iversen et al., 2005). One of the most influential theories aiming to explain the motor deficit found in dyslexia is the cerebellar theory proposed by Nicolson and colleagues (1995). The cerebellar deficit hypothesis proposed that dyslexia could be explained by mild cerebellum impairment and offered an explanation for the main cognitive deficits found in dyslexic readers. A line of evidence for this hypothesis was provided by means of clinical tests of cerebellar dysfunctions (Fawcett & Nicolson, 1999; Fawcett et al. 1996), brain imaging studies (Eckert, 2004; Nicolson et al., 1999; Sun, Lee, & Kirby, 2010), and by a post mortem study (Finch, Nicolson, & Fawcett, 2002).

The cerebellum acts as the brain's 'autopilot' and is responsible for the coordination of actions (Eccles, Ito, Szent, & Agothai, 1967; Holmes, 1939; Ito, 1984). The cerebellum contains half of all the neurons in the brain (Ramnani, 2006). Traditionally, the role of the cerebellum was seen in motor control (Brindley, 1964; Eccles et al. 1967). However, with time and new brain imaging techniques, its role was further found to be associated with language processing (Leiner, Leiner, Dow, 1991; 1993) and automatisation of skills, including the cognitive ones. A review by Desmond and Fiez (1998) further demonstrated the cerebellum's role in verbal working memory and in explicit memory retrieval and sequence learning amongst others. Cerebellar impairment has been linked to the inability to develop automaticity of skills that are crucial for learning to read. Motor problems here are not seen as causal in reading problems but as an indicator of the cerebellum dysfunction (Nicolson et al., 2001).

It has been well established now that cerebellum is anatomically connected with the frontal cortex which is related to language processing areas (Broca's area) (Kelly & Strick, 2003; Ramnani, 2006), and is involved in the performance of language-like tasks, as shown in brain imaging research in clinical samples of patients with cerebellar lesions (De Smet et al. 2007; Justus & Ivry, 2001; Marien et al. 2001; Marien & Verhoeven, 2007). The cerebellum is also highly connected with other brain regions related to reading such as left hemisphere reading network that includes the occipital-temporal cortex, related to word form processing, the temporal-parietal cortex, involved in visuo-auditory associations, and the inferior frontal gyrus which is associated with articulation (Dehaene, 2009).

Particularly the lateral zone of the cerebellum, the so-called neocerebellum, generated a lot of interest due to its role in cognitive processes. This part of the brain is associated with the control of limb movements, particularly those fast and skilled ones. It receives input from frontal association cortex and from primary motor cortex. It also collects somatosensory detailed information on the limb movements (Fawcett & Nicolson, 2008). The cerebellum hardly ever acts on its own; it works in combination with other brain parts to enhance or optimise the skills controlled by these parts (Albus, 1971; Ito, 1984; Marr, 1969). Because of the complexity of cerebellar functions and incredibly complicated structure, any damage to its parts may result in various symptoms. The development and the formation of the cerebellum take longer than the development of any other brain structures. It is particularly vulnerable to damage during embryogenesis (Wang & Zoghbi, 2001). Studies also showed that premature birth that potentially may cause damage to the cerebellum may lead to motor, language and cognitive problems (Limperopoulos et al. 2007; Steinlin, 2007).

The cerebellum receives magnocellular projections from all sensory and motor centres. A cerebellar shortfall provides a straightforward explanation for poor quality handwriting, as it is often seen in an individual with dyslexia (Benton, 1978; Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008; Miles, 1983; Stein, 2001), and copying (Badian, 1984; Rudel, 1985). Gross motor and coordination problems in individuals with dyslexia were first presented anecdotally (Augur, 1985) and later demonstrated empirically. National cohort studies of children between 10-11 years old showed that a failure on motor tests, such as throwing and catching a ball or walking backwards in a straight line, was associated with dyslexia (Haslum, 1989) and that 51.7% of children recognized as likely to be severely dyslexic failed at least one motor test (Haslum & Miles, 2007).

According to the cerebellum deficit model, literacy difficulties may arise from different routes. The central route starts with cerebellar abnormalities at birth, which leads to both mild motor and articulatory difficulties. The second route, in turn, leads to a poor representation of the phonological features of speech. The consequence could be a phonological awareness deficit (Nicolson et al. 2001). On the basis of the research and their cerebellar model, Nicolson et al. (2001) included gross motor (balance) and fine motor (bead threading) tasks as part of their screening tests for children (Dyslexia Early Screening Test - DEST) and its equivalents for older age groups. The theory was subsequently improved and tested to explain the causal link between cerebellum and reading difficulties (Nicolson et al. 2001).

Expanding on the idea that the cerebellum is related to dyslexia, Fawcett and Nicolson (1995) investigated whether articulation was affected in DD, too. They found that individuals with dyslexia did indeed have slower speed of articulation when compared to their normally reading counterparts. Further studies have shown that the problems in articulation may have been related to poor motor planning and poor motor speed (Fawcett & Nicolson, 2002). This provides further evidence for the deficiencies in motor- and language- cerebellar circuits within people with dyslexia.

Despite consistent research findings providing evidence for the cerebellar deficit in some individuals with dyslexia, the theory has some theoretical weaknesses. The difficulty of isolating and pinpointing the function of the cerebellum comes from its ‘collaborative’ nature. The cerebellum is believed to work with other brain areas to enhance their performance, measuring the function of cerebellum behaviourally is therefore very difficult. The problem of the lack of the specificity of the cerebellum deficit is one of the criticisms of the cerebellar deficit hypothesis of dyslexia. Fawcett and Nicolson addressed this use by refining their cerebellar theory of dyslexia through the ‘converging operations’ approach (2008; p. 10). That is, a range of different tasks are investigated which require cerebellar input as well as input from other structures. The only common feature of all these tests, when taken in aggregation, is their reliance on cerebellar functioning. The use of motor tasks not involving language is a good example. The issue of isolating cerebellar performance could also be addressed by direct tests of cerebellar function (Nicolson, Daum, Schugens, Fawcett, & Schulz, 2002; Nicolson & Fawcett, 2000; Nicolson et al., 1999) and anatomy (Eckert, 2004).

Another criticism of the cerebellar deficit theory is that this deficit seems not to be causal in dyslexia. Zaffiro and Eden (2001) suggested that the cerebellum is merely a *bystander* that does not cause the problem but simply receives faulty information from other parts of the brain. Stein (2008) further argued that the deficit found in the magnocellular cells that project their signals into the cerebellum should be blamed, not the cerebellum itself. Stoodley and Stein (2013) agreed that cerebellar dysfunction in unlikely to be a primary cause of dyslexia, however, they argue that the cerebellum is undoubtedly involved in reading and is one of many parts of a reading brain network that is affected in individuals with dyslexia. Raschle, Chang, and Gaab (2011) also suggested that differences in cerebellum found in dyslexic readers are a result rather than a cause of reading failure.

Another criticism of this hypothesis is that not all children have the motor deficit (Ramus et al., 2003), therefore this deficit is not necessary for dyslexia diagnosis. Furthermore, correlational studies show weak relationships between moto-cerebellar tasks and readings skills (White et al. 2006). This criticism was discussed by Nicolson and Fawcett (2006). The authors agree with the idea that dyslexia may have many causes or risk factors and suggest that the cerebellar deficit is but one of them. Also, research on the cerebellar deficit usually focuses on the motor tasks, which are not the only cerebellum-sensitive tasks. It is possible that individuals with dyslexia may have the parts of the cerebellum that are not related to motor skills dysfunctional.

Both brain-based theories discussed so far, the magnocellular-dorsal and the cerebellum deficit theories, contributed greatly to the current understanding of dyslexia. The following section provides a short account on another theory that proposes a more global deficit in procedural learning. The theory also touches on the aspects of automaticity.

2.2.1.3 Procedural learning deficit hypothesis

The procedural learning deficit hypothesis (Nicolson & Fawcett, 2007) derived from an idea that many brain areas are involved in acquisition and implementation of cognitive and motor skills, therefore, they all need to be understood as a whole. This theory involves an investigation of neural systems needed for learning and the cognitive neuroscience of the cerebellum. The procedural learning deficit (Nicolson & Fawcett, 2007) suggests that individuals with dyslexia are impaired in procedural learning (learning how to do something), whilst their declarative learning (learning facts) may be intact. The theory built on a premise first introduced by Ullman (2004) that there are two language systems: declarative memory and procedural memory. Declarative memory which is underpinned by the temporal lobe of the brain acts as a storage of knowledge of facts. The mental lexicon also depends on declarative memory. The procedural memory system underpins the learning of new procedures that are based on rules or regularities of language; it is important for the so-called 'mental grammar' (Nicolson & Fawcett, 2007, p. 137). The procedural memory system also has been found to underlie learning and execution of motor and cognitive skills habits (Packard & Knowlton, 2002; Ullman, 2004). Learning and knowledge do not rely on conscious awareness; they are implicit. The learned skills, therefore, can be processed automatically and quickly. Learning itself is fairly slow and requires a lot of practice.

The evidence for the procedural learning impairments in individuals with dyslexia was provided by studies looking at language-related tasks where the dyslexic readers take a lot more time to read accurately pseudo and irregular words (Nicolson, Fawcett, Brookes, & Needle, 2010). The evidence also comes from tasks not involving language or reading. Nicolson and Fawcett (2000) showed that individuals with dyslexia failed to learn a simple choice response task that involved reacting to particular stimuli (seeing a flash or hearing a tone). They were both slower and less accurate than the control group. The accuracy and speed of another simple motor task were also poorer in individuals with dyslexia when the well-trained sequence was to be repeated after one night, indicating poorer consolidation (Nicolson et al., 2010).

Another type of task that has been used to explore this hypothesis is the serial reaction time task (SRT). Some studies used a classic version of the task that was first described by Nissen and Bullemer (1987). In this task, participants are exposed to a visual stimulus which appears in one of four locations on a screen and their task is to press a button (also one of four) that corresponds with the location on the computer display. The participants are instructed to press the button as quickly and as accurately as possible. Studies looking at healthy adults and children found that reaction times decrease over the duration of the task when the sequence is being repeated. Reaction times increase, on the other hand, when the sequence of stimuli does not follow any pattern. This indicates that implicit procedural learning of the sequence is taking place. A number of studies have reported significant differences between individuals with dyslexia and typical readers showing that the latter group had smaller differences in reaction times between the random and the sequence blocks than the control groups (Stoodley, Harrison, & Stein, 2006 (Harrison, & Stein, 2006; Jimenez-Fernandez, Vaquero, Jimenez, & Defior, 2011; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Stoodley, Stoodley, Ray, Jack, & Stein, 2008; Vicari, Marrota, Menghini, Molinari, & Petrosini, 2003; Vicari et al., 2005). Some studies, however, did not find support for this deficit (Bussy et al., 2011; Deroost et al., 2010; Gabay, Schiff, & Vakil, 2012; Kelly, Griffiths, & Frith, 2002; Menghini et al., 2010; Russeler et al., 2006; Yang & Hong-Yan, 2011). To clarify the effectiveness of this task at differentiating participants with and without dyslexia, Lum, Ullman, and Conti-Ramsden (2013) carried out a meta-analysis of 14 studies using the SRT. They found statistically significant differences between individuals with dyslexia and control group of medium effect size providing evidence for procedural memory impairment in dyslexia. However, in common with empirical explorations of other theories, a causal link could not be addressed as the studies used correlational designs.

2.2.2 Heritability and Genetics

There is a general agreement amongst researchers that dyslexia runs in families (Paracchini, Scerri, & Monaco, 2007). The level of heritability can be estimated from studies involving relatives of different degrees of genetic relatedness: monozygotic or dizygotic twins, siblings, and parents. Siblings living in the same family were shown to have similarity (shared variance) in reading ability as high as 80% (Reid, et al., 2008). In order to distinguish whether the found similarity is the effect of genetic heritability or the common environment, researchers conduct twin studies comparing dizygotic and monozygotic twins. Olson, Wise, Conners, Rack, and

Fulker (1989) showed that genes can explain around 60% of the familial variance in reading and the shared environment can explain about 20%. The estimates of dyslexia heritability being at least 60% have been found in many twin studies (Friend, DeFries, & Olson, 2008; Kirkpatrick, Legrand, Iacono, & McGue, 2011). The estimates, however, differ depending on the sample used. Particularly, the environmental backgrounds of the participants affect the results (Asbury & Plomin, 2013). Research suggests that environmental factors may affect transcription and translation of RNA and result in epigenetic effect (Cassiday, 2009). To date, such factors as teaching (Berninger & May, 2011), stress, and poverty have been recognized as related to changes in the epigenetic expression of genes. Epigenetic mechanisms whereby environment alters gene expressions in the context of reading disabilities is only emerging (Raskind, Peter, Richards, Eckert, & Berninger, 2013).

Linkage studies have been particularly useful in addressing the question of heritability in dyslexia as they involve looking at large families that are affected by dyslexia in several generations (Francks, Macphie, & Monaco, 2002). Candidate gene studies also provide evidence for associations between genes and reading disorder: these have identified several regions of the human genome that are likely to contain susceptible genes for dyslexia. Four candidate genes located within three of these linked chromosome regions have been identified: DYX1C1 on chromosome 15 (Taipale et al., 2003), ROBO1 on chromosome 3 (Hannula-Jouppi et al., 2005), KIAA0319 (Cope et al., 2005; Paracchini et al., 2006), DCDC2 on chromosome 6 (Meng et al., 2005; Schumacher et al., 2006) and CYP19A1 on chromosome 15 (Anthoni et al., 2012). For recent reviews of linkage and candidate gene studies see Newbury, Monaco, and Paracchini (2014), Paracchini et al. (2007) and Scerri and Schulte-Körne (2010).

Findings from various molecular genetics studies with humans and animal models demonstrate that dyslexia is a disorder with a number of pathways mildly disturbed in neuronal positioning or connectivity (Kere, 2014) which is consistent with the neuroanatomical findings of dysplasia and neuronal ectopias in the brains of people with dyslexia first found by Galaburda, Sherman, Rosen, Alboitiz and Geshwind (1985). The brain system and the genetic machinery may interact in more than one way leading to reading disorder (Pernet, Andersson, Paulesu, & Demonet, 2009; Grigorenko, 2009). As Paracchini et al. (2016) pointed out, the main drive for genetic studies is to expound the biology of dyslexia and provide a better understanding of its neurological basis. This could further help to fit biological data with the cognitive theories.

2.3 No one symptom and no one cause: the multifactorial nature of dyslexia

'Full understanding of dyslexia is likely to require many different small theories and a systems approach that considers multiple, interacting variables within individual brains and the external environment not described well by simple, linear, unidimensional causal mechanisms'

Berninger et al. (2006; p. 190)

Although it is well established that phonological aspects are important to learn to read and the phonological deficits often, not always though, occur in children with developmental dyslexia (Muter et al., 2004), these are not the only manifestations and causes of dyslexia. It has been argued that dyslexia occurs as a result of a combination of deficits in various areas (Pennington, 2006; Pennington et al., 2012). Fletcher et al. (2007) pointed out that the search for a single causal factor fully explaining dyslexia is outdated. Furthermore, an emphasis on the independence of dyslexia from other causes that could explain reading failure (i.e., low intelligence, socioeconomic disadvantage, inadequate schooling, or physical disability) seems to be superseded by theories embracing and acknowledging these factors (Lyon, 1995). Determining the causal role of any cognitive process proves to be problematic (Snowling et al., 2011). While the research community seems to generally agree that phonological deficit is fundamental problem for a majority of poor readers, it is still merely a symptom; the underlying causes are still debatable. This is a reason why the field shifted back its attention to the nature and role of fundamental auditory, visual and attentional aspects in reading (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Wallace, 2009).

The multiple-deficit cognitive model sees dyslexia as a result of an interaction between multiple risk and protective factors. These can be of environmental or biological nature (Pennington, 2006; 2009). This idea is in line with Elliott and Grigorenko's (2014) suggestion that no one factor is either sufficient or necessary for dyslexia to emerge. Furthermore, comorbidity of dyslexia with other disorders is to be expected due to common aetiology and shared risk factors. Pennington's (2009) approach to dyslexia, therefore, is that this disorder cannot be understood in categorical sense, but it must be seen as a continuum of difficulties.

Pennington et al. (2012) contrasted different theoretical explanations for reading difficulties at an individual level. The researchers found that one-third of their sample of children with dyslexia displayed multiple deficits, while 26% showed a single deficit. The remaining 40% of children did not fit either of the above models perfectly. These findings suggest that it is unlikely to pinpoint a single cause of dyslexia that would explain all cases. Therefore, thinking of dyslexia causes more in probabilistic terms seems more reasonable. A more recent study by Carroll et al. (2016) focused on pre-reading children who were followed up one up to four times. The findings were similar to these showed by Pennington et al. (2012) and indicated that there is no one single deficit that would characterise all of the poor readers.

The above mentioned behavioural studies provide evidence for the multifactorial nature of dyslexia that is also reflected in genetical and biological investigations. However, despite progress in understanding the neurogenetics of developmental dyslexia, there is still no good understanding of the molecular etiological pathways fundamental to the development of reading problems (Mascheretti et al., 2017). Mascheretti and colleagues (2017) therefore argue that an interdisciplinary approach including both the brain imaging and genetic studies is crucial for bridging the role of genes with reading impairment.

2.4 Challenges in dyslexia research: gaps in the literature and how this thesis will address them.

The current chapter discussed behavioural, cognitive, and biological approaches to reading disorders and provided a discussion of current understandings of dyslexia. From this synthesis of the literature, it is clear that reading involves a complex set of cognitive processes underpinned by a large number of brain areas. Some theories are able to explain the symptoms and causes of dyslexia better than others. However, it seems that there are no simple, uni-dimensional explanations and that dyslexia needs to be investigated from different angles. The key struggle across all of the investigations is to establish a causal link between dyslexia and demonstrated symptoms. It is necessary to consider the differing types of studies that are best able to reveal these causal links. Three types of research designs have been identified: (1) studies investigating early indicators predicting reading level in children, especially those at familial risk of dyslexia; (2) longitudinal studies to address the issue of causality; and (3) intervention studies.

There are some methodological limitations that lead to a misconception and a lack of consensus within the field. Previous research has tended to focus on comparing relatively small samples of children deemed to be at high or low risk of dyslexia based on family history, rather than on symptoms of dyslexia. Although there is evidence for the genetic component of dyslexia, it does not mean that everyone who has a member of family with dyslexia will also develop this disorder. Also, studies using this design vary in the way in which they recruit risk families: some use children who have at least one parent with dyslexia; other studies recruit children with dyslexic siblings; and, in some cases, family members self-report that they have dyslexia which is not confirmed by a professional diagnosis. Leavett, Nash, and Snowling (2014) also suggested that the awareness of dyslexia of parents who volunteer their children to take part in studies may mean that they may be highly motivated to support their children and promote reading also at home. Furthermore, selecting such samples does not ensure their representativeness. **Therefore, in the**

current thesis, an unselected, representative of the general population, a large cross-sectional sample is used. Such a design is also free of bias as the researcher is not aware of participants' familial risks and educational achievements.

Furthermore, most previous studies have used correlational designs, which cannot inform of the possible causes of dyslexia. **Here, a prospective study is conducted with a subset of children at a pre-reading age which will enable the author to discuss the causes and core deficits predicting later reading performance**. Although the correlational analysis is also conducted in the proceeding research chapters, the pivotal interest is on the prospective investigation and on group differences.

Another methodological problem identified within the dyslexia field is the use of different operational definitions by applying different cut-off points to identify poor readers. **The current research investigates the patterns of difficulties for poor readers who are identified using three different cut-off points. This will help disentangle the methodological problems from the theoretical ones.**

Some of the major issues raised in literature are whether there is a single or multiple core deficits in children with dyslexia. It is argued that if low-level, sensorimotor and motor deficits underlie developmental dyslexia, these deficits should be apparent in children even before they learn to read. If so, it should be possible to develop a screening tool that assesses basic visual and motor skills in young children. The current thesis seeks to investigate whether performance on the 'dot-to-dot' task:

(1) is associated with motor control, phonological processing, rapid automatized naming and short term memory in a cross-section of children and adults;

(2) can distinguish between children at low, medium and high risk of dyslexia as assessed by existing screening tool;

(3) can distinguish between poor and typical readers as assessed by reading tests prospectively;

(4) can predict later reading difficulties in pre-reading and in older children;

(5) is related to magnocellular and dorsal functioning;

(6) is compromised in adults with identified dyslexia.

In addition, the thesis aims to address a number of some broader questions:

(1) What deficits do poor readers display? Will these overlap? Will patterns of difficulties differ depending on the cut-off point used?

(2) What is the best predictor of reading problems?

(3) Are socioeconomic background and gender associated with reading problems?

The major theories of dyslexia propose different models explaining the origins of this developmental disorder. Clearly, this has an impact on theoretical and practical considerations within research. The lack of cohesion in the understanding of dyslexia negatively affects those who struggle with reading, as often they do not receive a much-needed intervention, or if they do, it may not be suitable for their specific requirements. This thesis provides an opportunity to discuss these issues and adds both to the practical perspective by investigating a novel test that has potential to help identifying dyslexia and to the theoretical aspects still debated within the literature by adopting a large-scale, cross-sectional sampling approach, and by conducting a prospective investigation of performance on the said novel task alongside the various standardized psychometric measures and existing dyslexia screening tools.

Chapter 3
General methods

This chapter provides a general overview of the methods adopted in the four studies presented in this thesis. A description of the novel visual-motor "Dot to Dot" task, which was used in every study, in addition to dyslexia screening tests and intelligence tests used in the studies with children (chapters 4-6) are provided here; details of measures specific to individual studies are reported in the corresponding chapters.

3.1 Ethical considerations

Each study was granted ethical approval by the School of Applied Sciences' Research Integrity Committee at Edinburgh Napier University. In the case of studies involving children within schools, ethical approvals were also granted by the City of Edinburgh Council. Having obtained an informed consent to participate *in loco parentis*, on behalf of the parents by the Head Teachers, letters informing of the research, as well as consent forms, were given to parents. Parents were provided with an option to opt their child out of the research. Children were informed verbally about the aim and the procedure of the study in age-appropriate terms, using a participant information sheet developed in accordance with the World Health Organization's *Informed Assent for Minors* template. Adult participants were given a brief outline regarding the purpose of the study and were instructed to read a standardised information sheet detailing the rationale behind the present research (see Appendix A for all relevant documentation).

3.2 Design

The main types of designs used across the studies were: (1) a correlational design with co-variates including the DtD measures and a range of cognitive and dyslexia-sensitive tests in children and adults; (2) between-groups comparisons, with the independent variables including risk of dyslexia, reader type for child samples, and dyslexia diagnosis in the adult sample; and (3) predicting reading ability using the DtD measures and other established tests.

Correlation tests were conducted to investigate the relationship between performance on the novel task (described in section 3.5.1) and age-standardised scores on a range of cognitive and perceptual tasks using a cross-sectional, unselected sample of children and a selected sample of adults. The use of a large cross-sectional sample of unselected sample of children was particularly important as it provided a representative sample, which is rarely achieved in dyslexia research.

The between-groups independent variables in children studies were **dyslexia risk** level (three levels: high, medium and low) as determined using an existing, commercially-available screening tool; **school** (three levels: school located in high, medium and low SES as determined using the government statistics on the schools' catchment areas' socioeconomic profiles and free school lunch rates; details in section 3.4.1.1); and **reading level** (poor vs. typical readers) as determined by two readings tests administered at the follow-up session. Dyslexia diagnosis (dyslexic vs non-dyslexic) was used as a between-groups independent variable in a study involving adult participants. The dependent variables included performance on the DtD task, performance on phonological processing tests, verbal short term memory tests, and motor tests, in addition to performance on reasoning measures. Sensitivity to psychophysical stimuli designed to preferentially activate the magnocellular/parvocellular and dorsal/ventral visual processing streams was also measured in the child sample.

The prospective investigation was used only with a sample of children. Here, regression analyses were conducted. Performance on the DtD task and on tasks derived from dyslexia screening tests were used as predictors. The outcomes (predicted scores) were reading tests (one-minute reading and nonsense passage reading) administered to children one, two or three years after the first tests scores were obtained.

3.3 Participants

Adequate sample sizes for the planned studies were not calculated prospectively as the data collection was very much dependent on the access to schools and availability of the participants. The power analyses however were calculated retrospectively (post-hoc power analysis) and presented in the relevant chapters. Providing these calculations is encouraged by some researchers (e.g, Fagley, 1985; Hallahan and Rosenthal, 1996; Onwuegbuzie and Leech, 2004) but discouraged by others (e.g., Lenth, 2007). Hence it was decided that the post-hoc analyses will be only provided for non-significant results with relatively small samples using medium effect sizes (not the actual effect size achieved) to hint the reader what power could be achieved with such a sample.

3.3.1 Children

Overall, 457 children took part in the baseline study (Chapter 4) with their mean age of 6.6 years old. Forty-eight percent of the sample was female. Sixty-one per cent of the original sample was followed up with reading tests (Chapter 5) and 37% with vision tests (Chapter 6). Children of pre-reading age (nursery class and the beginning of Primary 1; aged between 4 and 5 y.o.; n = 280 at baseline) were of particular interest in the study as deficits found in children before they start the formal reading instructions could be indicative of the causal links. It was also desired to explore how children of other ages performed and engaged with the novel DtD task, in case it could be used to help screen for dyslexia among children of all ages. Obtaining data from children of various ages was also necessary to develop the means and SDs of different age groups for standardising purposes of the DtD task. Therefore, children within Primaries 3 (aged between 7 and 8 y.o.) and 5 (aged between 9 and 10 y.o.) were also included.

The three cohorts correspond to three stages of literacy development (Frith, 1986). The first stage (pre-literacy) is before formal literacy training in school. At this stage, a child cannot read individual letters or words, but he or she recognises shapes of words, such as logos. In the emergent stage, formal reading instructions are delivered in school: letters, grapheme-phoneme correspondence are taught. The last stage is called the literacy stage. At this stage, reading is or should be, automatized.

Other inclusion criteria were normal, or corrected to normal vision. The detailed information on the number of participants and their age and gender are provided in the relevant chapters (Chapters 4 and 5). Here, however, a detailed description of the schools and a rationale behind their choice is provided.

3.3.1.1 Primary schools: characteristics

To ensure that the sample was representative of the larger population, three schools whose catchment areas were associated with low, medium, and high levels of multiple deprivations (The Scottish Government, 2013) within the same city were selected to take part in the study. This was particularly important because previous research tended not to use cross-sectional designs with large numbers of participants, which has made the generalisation of their findings difficult. Additionally, the schools' considerable socioeconomic differences allowed the exploration of the impact the environment has on children's reading performance. Chudgar and Luschei (2009) showed that variations of student performance could often be explained by family background, rather than schools. Nevertheless, schools do play an important role, especially when it comes to unequal or deprived communities. Therefore, it would be counterintuitive if the environment surrounding the children, both inside as well as outside the school, was not discussed and considered when carrying out research on dyslexia with school age children.

The choice of schools was based on the City of Edinburgh Council's recommendations as to how representative of Edinburgh's children population these schools were as well as on the schools' distinct socioeconomic characteristics derived from the government statistics of the catchment areas.

Information gathered for the purpose of these schools' profiles was taken from the Scottish Neighbourhood Statistics (2014 a, b, c), which is an on-going programme under the supervision of the Scottish Government which provides consistent and accessible statistics in small areas in Scotland. The Scottish Index of Multiple Deprivation (SIMD) provides important information about deprivation rank for each of the data zones in Scotland. This is based on a combination of data in the domains of current income, housing, health, education, skills and training, employment, geographic access and crime. The ranks range from 1 (most deprived) to 6,505 (least deprived), while deciles split the dataset into ten groups, each containing 10% of the data (Scottish Government, 2013).

Another widely used indicator of deprivation is registration for free meals in schools. Pupils who are entitled to free meals provided by the schools are those from families receiving Income Support (IS), Income-based Job Seekers Allowance (IBISA), Child Tax Credit or have low annual income (specified in detail in each year). Children from families supported under the Immigration and Asylum Act 1999 are also entitled.

In terms of school performance, Edinburgh City Council's inspections of the main criteria - curriculum, improvements in performance, learners' experience, improvement through self-evaluation and meeting learning needs - are reported here. Unfortunately, no statistics exist to define the proportion of pupils for whom English is a second language.

Table 3.1 presents all of the characteristics of the catchment areas of the three schools, and more detailed information on the deprivation indices and free meals are presented in Figures 3.1 and 3.2.

Table 3.1.
Socio-economic and school performance for each of the primary school

Indicators	School		
	1	2	3
SIMD rank (decile)	125 (1)	2868 (5)	5688 (9)
Unemployment[a]	33%	12%	5%

Anxiety/depression/psychosis prescription drugs	12%	7%	7%
Free school meals (P1-P3)	65%	35%	10%
Schools' evaluation[b]			
Curriculum	excellent	very good	good
Improvement in performance	excellent	good	good

Note. [a] Unemployment rate for Scottish population estimated for 6.9% (The Scottish Government, 2014b) [b] Based on Edinburgh City Council audits (HMIE, 2006, 2007, 2011).

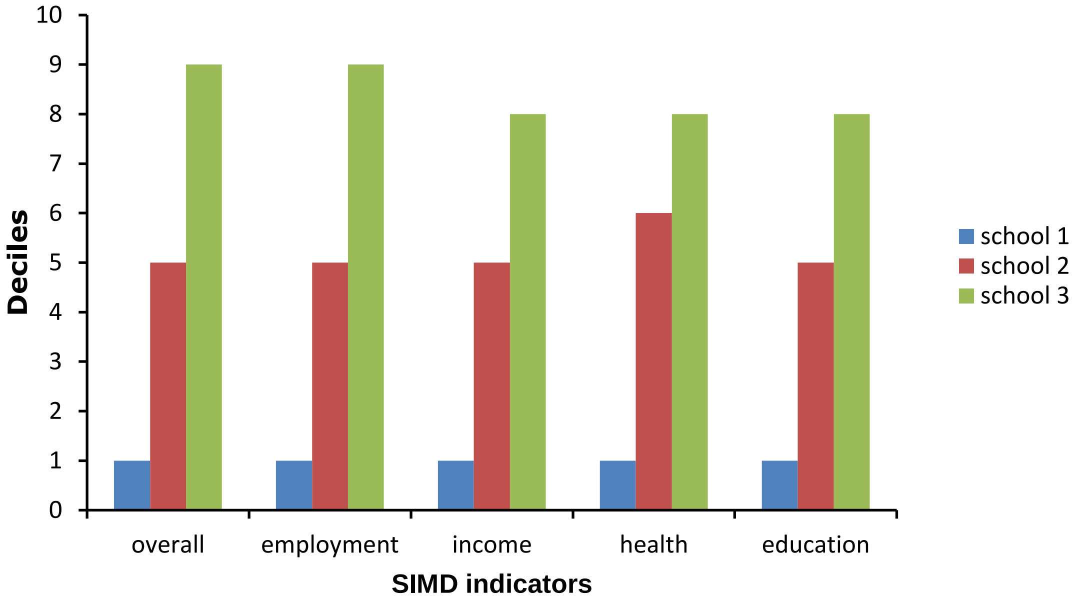

Figure 3.1. The Scottish Index of Multiple Deprivation (SIMD). Decile 1 indicates the most deprived 10% and decile 10 is the least deprived 10% of data zones in Scotland (Scottish Government, 2013).

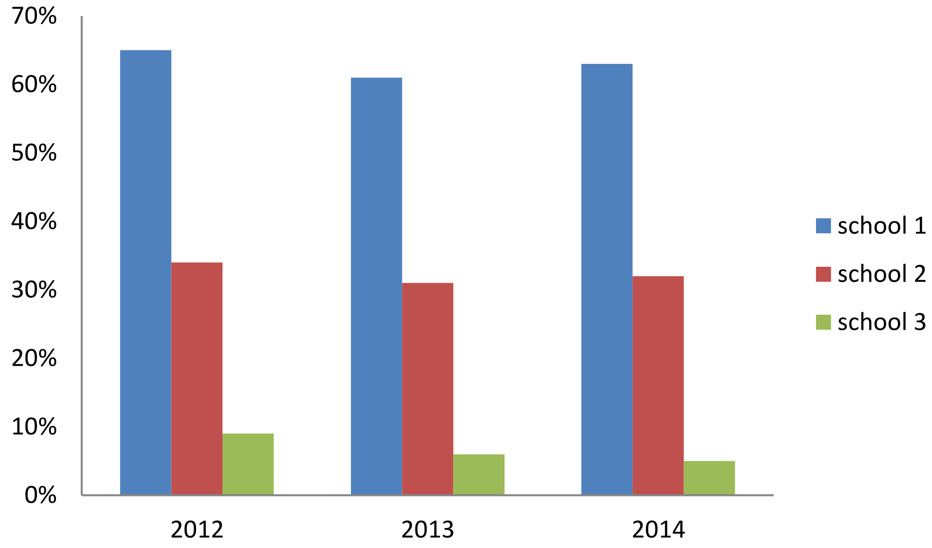

Figure 3.2. Percentage of pupils entitled to free school meals across the years.

From the characteristics of the schools' profiles and the Figures 3.1 to 3.2, it is apparent that the three schools that were chosen to participate in the study represent distinguishably different populations in terms of their socioeconomic backgrounds. However, the schools' performances, as audited by the HM Inspectorate of Education, are comparable. All of the schools achieved 'good' or higher qualitative codes for all of the components considered during the inspections.

3.3.2. Adults

Participants included students and staff members at Edinburgh Napier University, and members of the general public (*n* = 111; age ranged from 17 to 66 y.o., mean age = 27.36 y.o; 72% females). Participants were recruited via email and word of mouth, using a snowball sampling technique. Participants were not paid, or informed that they would be paid, in advance of their participation; however, they received high street vouchers worth £10 to compensate for their travel and time.

Thirty-seven participants had previously been identified as having dyslexia by the University's specialist dyslexia team or an educational psychologist, and the remaining participants reported having no language / reading or motor impairments. Eleven participants were not professionally diagnosed with dyslexia, however, they self-reported a possibility of having dyslexia.

3.4 Materials

The summary of all the variables together with the test batteries they were derived from is presented in Table 3.2. The detailed descriptions of the measures that were discussed in more than one chapter are provided in the following sections.

Table 3.2
Summary of all the tests used at the baseline and the follow-up testing sessions with indication of age groups taking the tests

Skill	**Task/measure**	**Age**	**Test Set**
Baseline			
DtD	DtD: First Sector Max Error (FSME); Total Error (TE), Time (T), SD2, Direction Ratio (DR), TimeTotal (TT)[a]	all	Dot-to-Dot
Phonological Processing (PP)	Rhymes & Alliteration	4:00-7:11	Lucid-Rapid
	Word Chopping	8:00-15:11	Lucid-Rapid
	Rhyme & Alliteration	4:6-6:6	DEST-2
	Phonemic Segmentation	6:6-11:00	DST-J
Auditory Sequential Memory (ASM)	Races	4:00-7:11	Lucid-Rapid
	Mobile Phone	8:00-15:11	Lucid-Rapid
Visual Memory Phonic Skills (VM/PS)	Zoid's Friends	4:00-7:11	Lucid-Rapid
	Funny Words	8:00-15:11	Lucid-Rapid
Processing speed and lexical access (RAN)	Rapid automated naming	all	DEST-2 or DST-J
Digit Span (DS)	Forwards Digit Span	4:6-6:6	DEST-2
	Forward and backward Digit Span	6:6-11:00	DST-J
Motor Skills (MS)	Bead threading	all	DEST-2 or DST-J
Perceptual Reasoning (BD)	Block Design	all	WPPSI-IV or WISC-IV
Perceptual Reasoning (MR)	Matrix Reasoning	all	WPPSI-IV or WISC-IV
Verbal Reasoning (VR)	Similarities	all	WPPSI-IV or WISC-IV
Follow-up			
Nonsense Reading (NR)	Nonsense Passage Reading	6:6-11:00	DST-J
Speeded Reading (SR)	One Minute Reading	6:6-11:00	DST-J

Note. [a] measures for dominant hand (DH) and non-dominant hand (NDH) and for FirstUp and FirstDown patterns.

3.4.1 The Dot-to-Dot (DtD) Task

3.4.1.1 DtD task: Etiology

The Dot-to-Dot task developed serendipitously from other activities initiated by Professor Jon M. Kerridge (School of Computing at Edinburgh Napier University). As part of a public engagement at the Edinburgh Science Festival in 2006, Prof. Kerridge created a system using infrared detectors of movement to follow young children as they tried to 'walk their name' (see Figure 3.3). This was inspired by the Watching Walkers project, in which Prof. Kerridge was already involved [1]. Volunteers were asked to write their name on a piece of paper, without lifting the pencil from the paper using joined-up-writing. They were then asked to walk in the area covered by the detectors using their name as a pattern for their walk. At the end of their name, they left the area and a label was printed for volunteers to take away. During the 10-day festival, 5000 labels were printed, some of them showing interesting patterns. In discussion with some of the children, he discovered that those who found the task difficult often also had problems with reading, writing, and/or spelling.

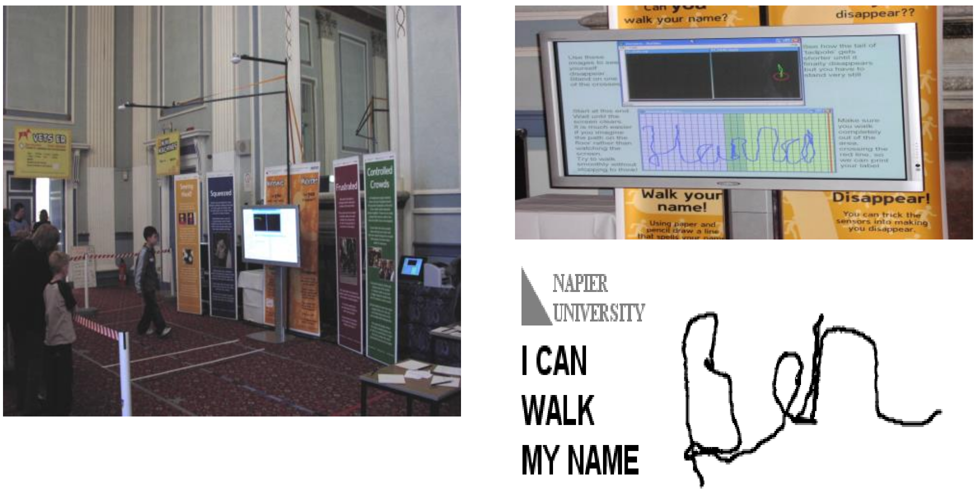

Figure 3.3 The walking area with the sensors mounted 3 meters above the floor. On the left are presented examples of two of the children's 'walked' names

From these observations, it was hypothesised that measuring a series of dots being traced or drawn by an individual could be informative of potential visual and motor problems. The DtD task is an entirely new task that may be related to motor skills as well as to high level processing. It is believed that the difficulty to fixate one's eyes on the screen while moving the stylus on the tablet distinguishes this task from

[1] More information on the project on http://www.iidi.napier.ac.uk/c/grants/grantid/11014065

standard drawing tasks where the eyes gaze just ahead of the hand holding a pen. This ability to dissociate the gaze and the hand may be related to divided attention. As such it is likely to reveal any developmental delay in control of sensorimotor processing, which as discussed earlier in chapter 2 may be compromised in individuals with dyslexia. It was proposed then that one could use this technology to identify possible dyslexia, which is believed to be underpinned by sensorimotor deficits. It is important to emphasise that the task is not related to any language and phonological processing therefore it is unlikely to be interpreted under phonological deficit theory. A feasibility study was conducted in one of the primary schools (School 1), where all of the children were assessed on the prototype of the DtD task. Then, Prof. Kerridge spoke to the class teachers. There was 84% agreement between the data collected (observations of the patterns) and the teachers' informal appraisal of children's reading and / or writing skills.

Further investigation was undertaken using university students diagnosed with dyslexia and those who self-reported no reading problems. At that point no other information regarding the participants, for instance their age, was collected. Forty-six participants took part. This time, basic quantitative scores were generated by the software. Table 3.3 presenting the group comparison is provided on the next page.

Table 3.3

Group comparisons from the pilot study

	Dyslexic	N	Mean	SD	t-test
Dominant Hand:					
Time	No	27	15.541	5.465	*t*(44)=.724,
	Yes	19	14.300	6.081	p=.473
First sector max. error	No	27	12.333	4.625	***t*(44)=2.620,**
	Yes	19	16.437	5.999	***p*=.012***
Total error	No	27	5943.985	1811.307	*t*(44)=1.076,
	Yes	19	6519.163	1745.058	*p*=.288
SD2	No	27	135.422	60.423	t(44)=-.858,
	Yes	19	152.205	71.797	*p*=.395
Non-dominant hand:					
Time	No	27	15.244	5.958	*t*(44)=.705,
	Yes	19	16.047	7.218	*p*=.485
First sector max. error	No	27	13.967	4.709	*t*(23.96)=1.718,
	Yes	19	18.111	9.742	*p*=.099
Total error	No	27	6427.959	1819.020	*t*(44)=-.683,
	Yes	19	6827.600	2135.028	*p*=.498
SD2	No	27	152.270	60.922	*t*(44)=-.126,
	Yes	19	154.947	83.195	*p*=.900

Note. *p<.05. SD2 = points over two standard deviations

Anecdotal evidence and early pilot studies appeared to suggest that the DtD task could distinguish between adults with and without dyslexia and between children with reading problems as reported by their teachers. However, more controlled research was needed in order to: (1) see if the DtD task could objectively and reliably indicate and predict a risk of dyslexia; and (2) identify the cognitive and perceptual factors associated with performance on the DtD task. These are the core purposes of the current thesis.

3.4.1.2 The DtD task: Apparatus

The equipment used for the DtD task comprises a PC display monitor connected to a laptop computer system. Participants use a stylus to “draw” a line on a graphics tablet connected to the laptop (Figure 3.4).

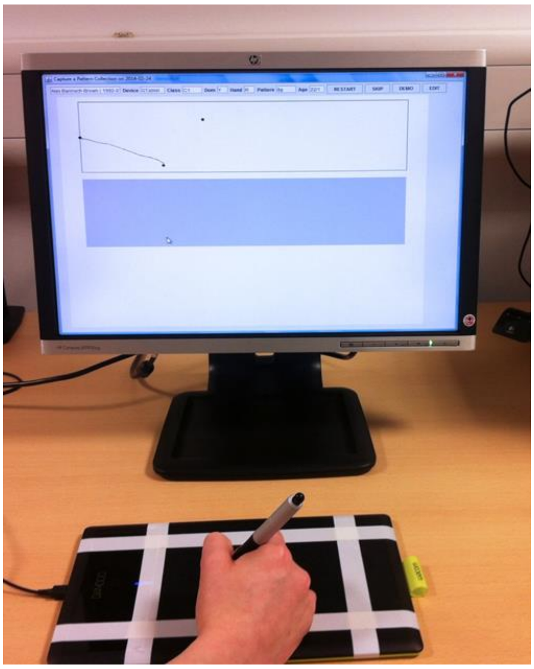

Figure 3.4 Experimental set up for the "Dot to Dot" task showing the display monitor, touch-screen tablet, and a stylus.

The person administering the DtD task uses the laptop to navigate around the software. The monitor displays two specific areas of which the participant has to be aware. The upper area shows the pattern as it is currently drawn. The lower grey area shows the position of the stylus on the graphics tablet (see Figure 3.5).

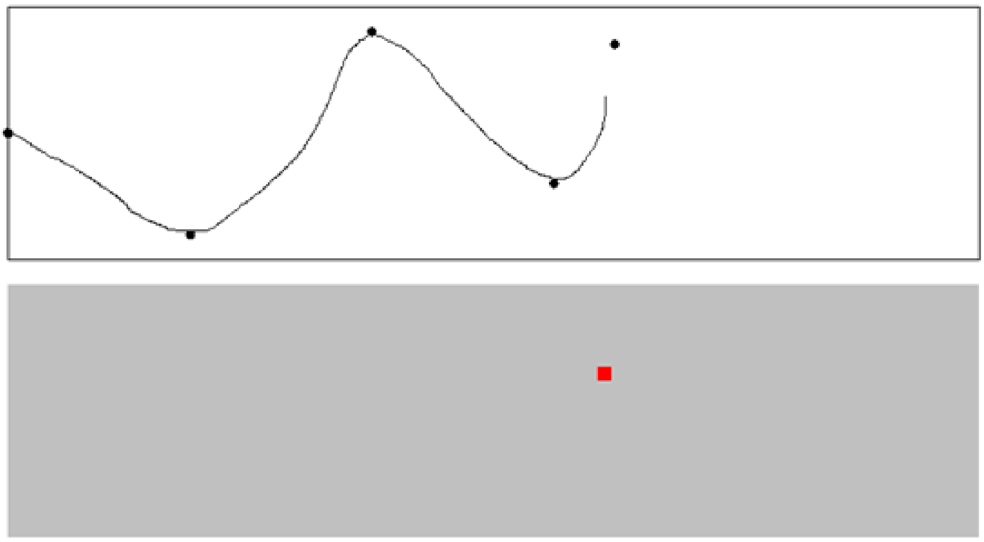

Figure 3.5 Example of a display screen during a trial.

As the stylus was moved, the red square changes to a black dot and the movement of the stylus was shown in the upper area. If the participant lifted the stylus from the surface of the graphics tablet the red square appeared to allow them to replace the stylus in the correct place.

3.4.1.3 DtD task: Description of the task

Participants were asked to look at a sequence of dots on a monitor and draw a line as quickly and accurately as possible between the dots using the graphics tablet and stylus. Initially, only the first two dots in the pattern were shown with no line joining them. The participant placed the stylus on the red square and moved the stylus towards the first dot. This part of the line was not captured. The participant moved the stylus towards the second dot and as soon as they were close enough to that dot the next dot appeared and so on until the stylus moved to the final dot at the centre of the right-hand edge. The system stops the participant from moving the dot outside the grey area. If the participant moved the stylus beyond a point and the next point did not appear because they were insufficiently close to the target dot then they would have to retrace their steps so that they get close enough for the next dot to appear. Participants always started the task with their dominant hand which was determined before the task was started. The testing session started with researcher's explanation and demonstration of the task followed with one practice trial. Participants then completed three trials for each of FirstUp (joining 9 dots) and FirstDown (8 dots) patterns. The sequence of trials was randomized by the software. The whole process was then repeated for the non-dominant hand.

Once a trial was completed, the points that make up the drawn line were sent to the software system. Typically, it took a participant between 10 to 20 seconds to complete a trial during which time about 1000-1500 data points were captured. The system detects movements of the stylus and records each movement as a new point denoting the end of the movement.

The software system then created a canonic version of the drawn pattern to enable further analysis. The drawing area is 800 pixels wide (x – direction) and 200 pixels high (y – direction). For each value of x the software determined the average value of the corresponding y-values and recorded that value. If there were no y-values for a particular value of x the system interpolated a y-value based on the closest x-values either side that had a y-value. The missing y-values were created assuming a straight line between the interpolation points. The canonic pattern thus comprises a set of 800 points in the x-direction each with a single y-value. An x-value may have several y-values if the participant did move the stylus sufficiently or if for example they created a loop or retraced the line to return to a dot that they had missed. A simplified diagram is presented in Figure 3.6.

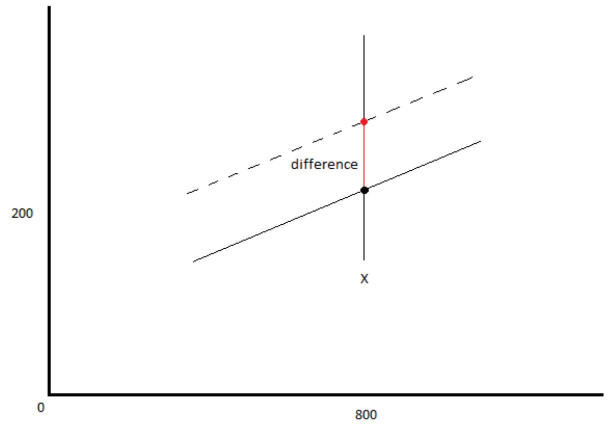

Figure 3.6 Simplified diagram of the drawing area showing how the y values are derived if the drawn line is away from the target dot (black dot).

A large number of different values that capture aspects of each line were calculated by the software. These values were calculated relative to the line of perfect fit (straight line joining two dots with the fewest number of pixels coloured), calculated automatically by the software (see Figure 3.7).

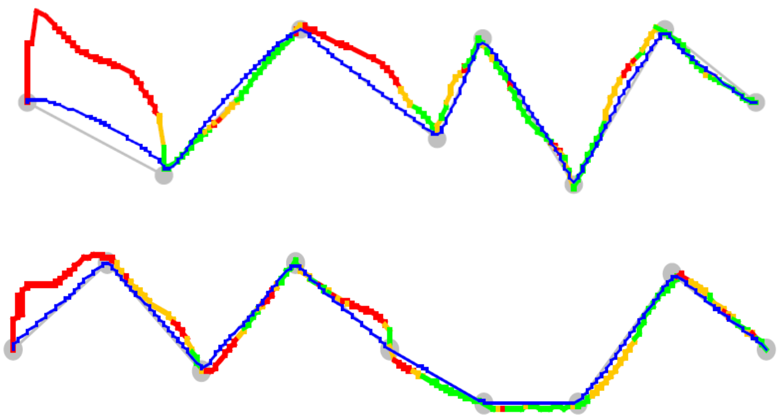

Figure 3.7 Example of the output from a single trial for FirstDown (top picture) and FirstUp (bottom) patterns. The grey line shows the line of best fit calculated by the software. The coloured line shows the line drawn by the participant: The blue line shows the resultant line taking the values from all the participants in a particular age (in three months categories) group. The multi-coloured line shows the line drawn by the participant. The green, yellow and red sections of the line indicate that the points fell within 1, beyond 1 and 2 SD of the mean, respectively, for the sample as a whole based upon the standard deviation derived from the analysis of the participant's line compared with the straight line joining the points. Note that in these examples, the **first sector max errors (FSME)** are very large as indicated by red lines. In the top pattern also the error is in the wrong **direction** (opposite to the target dot).

The following are the detailed DtD measures used in the studies:

(1) *Time* (T) in seconds taken to draw the pattern;

(2) *Total error (TE)* the sum of all the errors (deviations from the perfect fit line) over the whole pattern. The smaller the value the better the performance;

(3) *First sector maximum error (FSME)* maximum error (deviation from the perfect fit line) between the first two dots measured as the vertical distance between the line drawn and the straight line joining the two dots. The smaller the value the better the performance;

(4) *SD2* the count of the points over 2 standard deviations (red line);

(5) *Time total (TT)* a score combining the time and total error in order to account for the effect of time that participants took to complete the task and the accuracy (speed and accuracy trade-off);

(6) *Direction Ratio (DR)* direction of the first sector max error (see explanation below).

The above measures were generated by the software for the entire task (all trials averaged) for both dominant and non-dominant hand, but the average values are also calculated separately for each type of pattern: FirstUp and FirstDown. For the FirstUp and FirstDown patterns, only the first section measures (First sector maximum error and direction ratio) were of interest and only these were included in the analyses.

Direction of the first line

As half of the patterns always started from the first dot located below the starting point (FirstDown) and the other half above it (FirstUp), it was noticed during data collection that some children tended to move their stylus towards the top of the screen where the panel containing the dots and lines was located. Therefore, it was decided to investigate the direction of the first drawn line, and whether children confused the direction in any systematic way. To do this, a measure called the *Direction Ratio* was calculated. This variable indicated whether the maximum error in the first sector (between the first two dots) was in the same direction as the target dot. For instance, in Figure 3.7 in the top pattern (FirstDown) the maximum error is towards the top of the drawing area although the dot which needs to be joined is below the initial/starting dot. It indicates that the participant drawing the first line drew it in the opposite direction to the target dot. The bottom example in Figure 3.7, on the other hand, shows that the maximum error was towards the target dot. In this example, the participant struggled to draw a straight line but did not confuse the directions and aimed towards the target dot.

The ratio was derived from four different codes: two of them indicated that the participant drew the first line in the same direction as the first dot (correct direction) and the other two codes indicated the opposite direction (wrong direction). The ratio was calculated by dividing the number of completed patterns by the number of correct direction patterns. Thus a perfect score would be 1 (all patterns with correct direction) and the lowest score would be 0 (all wrong direction). The feature of calculating the direction ratio measure was added to the software in the middle of data collection; therefore, not all participants will have this measure calculated.

3.4.2 Dyslexia sensitive (screening) tests

The screening tools for dyslexia as well as the Wechsler's intelligence subtests (details in the next section) were chosen due to a wide age-range applicability, which allowed the researcher to compare the same skills and abilities of participants in a wide range of ages. The tasks were chosen based on their high validity. All subtests were administered under strict guidelines from the accompanying administration manuals.

3.4.2.1 Computer-based dyslexia screening: general information

Lucid Rapid is a computer-based dyslexia screening tool for children between 4-15 years (Singleton, 2009; Lucid Research Ltd). The program comprises three separate tasks, lasting approximately five minutes each. The tests varied depending on the child's age. The completion of all three tests allowed researchers to obtain a risk of dyslexia estimate classifying them into four different risk categories: very high, high, moderate and low. Table 3.4. shows the breakdown of the categories and corresponding centiles, performance and chance of risk percentages.

Table 3.4

Lucid Rapid Dyslexia scoring system

Score	1	2	3	4	5	6	7
Centile range	<5	5-19	20-34	35-64	65-79	80-94	>95
Performance	Very low	Low	Below average	Average	Above average	High	Very high
Risk category	Very high	High	Medium	Low			
Chance of having dyslexia	95%	90%	75%	10%			

The individual tests in Lucid Rapid that were selected from CoPs (Cognitive Profiling System), and LASS (Lucid Assessment Systems for Schools) Junior and Secondary, were validated and normed on 2000 children in the UK (Lucid Research Fact Sheet 4, 2007). Brookes, Ng, Lim, Tan, and Lukito (2011) reported that the sensitivity[2] of Lucid Rapid in identifying dyslexia was 81.9%, specificity[3] of 45.5%, a positive predictive value[4] of 81.1% and a negative predictive value[5] of 46.9%.

Lads (Lucid Adult Dyslexia Screening) is a set of computer-based tasks for people over 15 years old. The system was released in 2002 following three years of research at the University of Hull. The test comprises four tasks taking up to 30 minutes. Lads provides a categorisation into four groups: low probability of dyslexia, borderline, moderate, and high probability of dyslexia. Singleton, Horne and Simmons (2009) showed that LADS demonstrates a sensitivity rate of 90.6% and a specificity rate of 90%.

The details of the tasks administered to adults are provided in the relevant chapter (Chapter 7); here detailed descriptions of the tasks administered only to children are provided.

3.4.2.1.1 Lucid Rapid: description of tasks administred to children

Performance of children on the following tasks was analysed in Chapters 4, 5 and 6. In order to avoid repetition, the detailed descriptions of the tasks are provided here.

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[2] ***sensitivity*** is a percentage of cases who were correctly identified as poor readers (true positives)
[3] ***specificity*** is a percentage of cases who were not poor readers and were correctly identified as such (true negatives)
[4] ***positive predictive value*** is the percentage of correctly predicted cases with the observed characteristic compared to the total number of cases predicted as having the characteristic.
[5] ***negative predictive value*** is the percentage of correctly predicted cases who are good readers

The Lucid Rapid Dyslexia Screening system includes three subtests based on the Phonological Deficit model (Snowling, 2000). The content of each of these tests varies according to the age of the child. The test assessed the following cognitive areas:

(1) *Phonological processing (PP-L*[6]*).* Younger children (4:0 – 7:11) were given a test that assessed the skills of rhyming and alliteration (see Figure 3.8), whereas older children (8:0 – 15:11) were given a test that requires them to segment words into syllables and phonemes (see Figure 3.9). All test scores are based on the accuracy of the child's responses; however, in order to increase the sensitivity of the rhyming and alliteration test for children in the 5:0 – 7:11 age range, the speed of the child's responses has also been taken into account when calculating results.

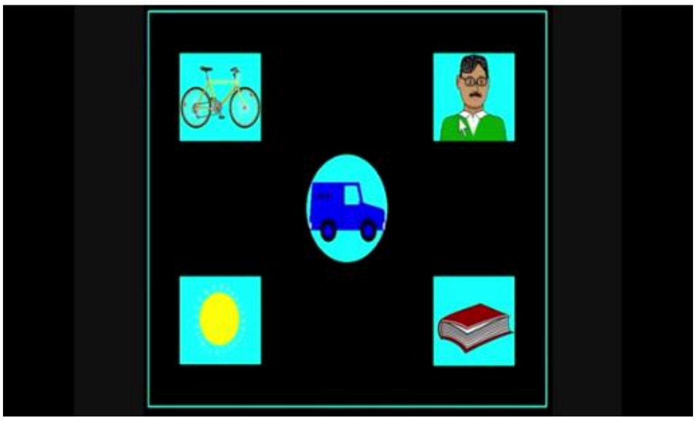

Figure 3.8. Example screen from the Lucid Rapid Rhymes test. Children are introduced to the five words and then asked to indicate which of the words on the outside (*bike, man, book, sun*) rhymes with the word in the middle: *van*.

[6] '*L*' indicated that the test was derived from the Lucid Rapid test. It used to distinguish this test from a phonological processing test derived from DEST-2 and DEST-J

Figure 3.9 Example screen from the Lucid Rapid Word Chopping test; the question posed is: *If we cut DOOR out of DOORWAY what do we have left?* Each of the four speakers gives a possible answer.

(2) *Auditory sequential memory (ASM)*. The first task was designed for children younger than eight years. They were given a test that required them to remember sequences of animals (see Figure 3.10). Older children were given the second test that required them to recall sequences of digits (see Figure 3.11).

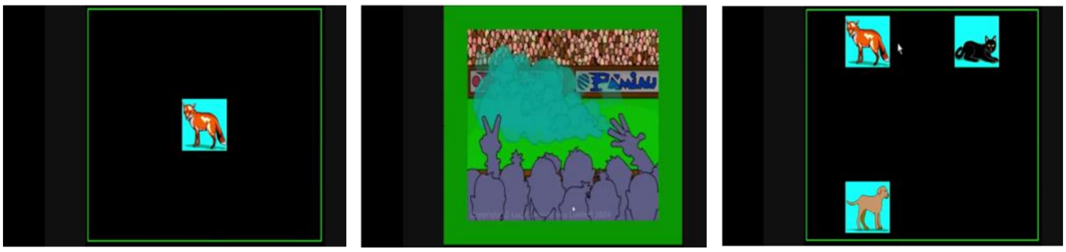

Figure 3.10 Example screen from the Lucid Rapid Races test. From the left: children are introduced to various animals, then they can see animation of a race (middle), at this stage the animals are not visible, but the order of animals reaching the finish line is presented verbally. Finally, children need to click on the animals in the same order in which they reached the finish line

Figure 3.11 Example screen from the Lucid Rapid Mobile Phone test. Here the children listen to the phone number and then they need to dial the same number on the phone.

(3) *Visual-verbal integration memory & phonic skills (VM/PS).* Children under the age of eight are tested for their ability to integrate visual and auditory information in a short-term memory task involving sequences of colours (see Figure 3.12). Children over the age of eight took the phonic skills test which relies upon decoding of nonsense words which the child will not have encountered before (see Figure 3.13).

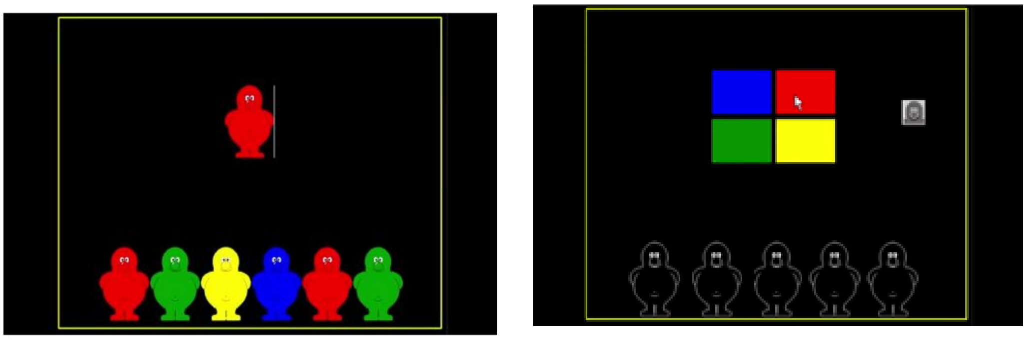

Figure 3.12 Example screen from the Lucid Rapid VM (Zoid's Friends) test. Children are presented with a number of coloured creatures presented in a particular order (left) then the creatures blank appear (right) and participants have to colour them, using a pallete of colours, in the same order as they were presented.

Figure 3.13 Example screen from the Lucid Rapid Phonic Skills test. Children are presented with a nonsense word visually (in this example: *onk*) and they have to pick the most accurate pronunciation: each speaker provides one option.

3.4.2.2 Paper-based dyslexia screening: general information

The Dyslexia Early Screening Test, second edition (DEST-2) was designed for use with children between 4.5 and 6.5 years (Fawcett & Nicolson, 1996), while the Dyslexia Screening Test-Junior (DST-J) was for children between 6.6 and 11 years old (Fawcett & Nicolson, 2004). Dyslexia Adult Screening Test (DAST) was designed for people aged 16 years and 5 months and older. The tests were designed by a team of researchers from the University of Sheffield, based on the research providing evidence for prevailing phonological skill (Bradley & Bryant, 1983), a mild cerebellar (Fawcett et al., 1996) as well as temporal order processing (Tallal et al., 1993) deficits in individuals with dyslexia.

The full version of the test consists twelve subtests. Each of these can be seen as an independent positive indicator of dyslexia. For the purpose of the current research, four subtests were used at a baseline and two at the follow-up. The choice of these subtests was motivated by a desire to test skills that may be related to the DtD task, such as motor skills and rapid naming. Two other component measuring phonological processing and short-term memory were included as these are seen as good predictors of dyslexia. As the study focused on a range of age groups, it was important to include the subtests that would be available across the age-appropriate versions of the test batteries (all four tasks were in the DEST-2 and DST-J test batteries). The following tests were chosen for both samples of children and adults: Phonological Processing, rapid automatized naming (RAN), Bead Threading and Digit Span. Children were also tested on two reading tests: speeded reading and nonsense passage reading. The following section provides detailed descriptions of the subtests completed by the child sample.

3.4.2.2.1 Dyslexia (Early) Screening test: description of tasks given to children

Phonological Processing (PP-D). The Rhyme/Alliteration task from the DEST-2 test was used as a measure of phonological awareness in the younger group of children. In this task, children were given two words (e.g., *bat cat*) and asked if they rhymed (rhyme task) or asked what was the first sound of a word, e.g., *ball* (alliteration task). The older group was given a Phonemic Segmentation task from the DST-J, where they had to repeat a word without an indicated phoneme, for example: 'say *marmalade*; say it again but without *mar*'.

Rapid Automatised Naming (RAN). In this task, participants were asked to name 40 outline drawings as fast as they could (see Figure 3.14). Practice with half of the pictures was given prior to the timed task. Scores were recorded in seconds. This task has been found to be a unique contributor to predicting reading problems that are independent of phonological processing (Wolf & Bowers, 1999). For more detailed discussion on RAN see Chapter 2.

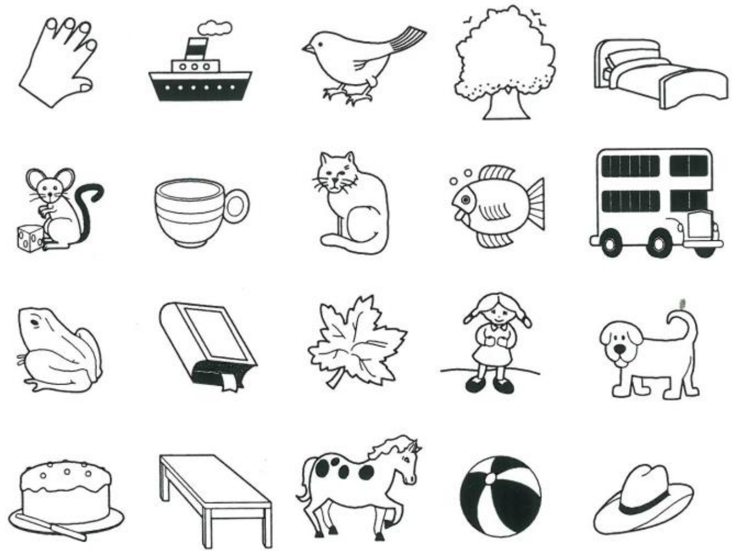

Figure 3.14 RAN test stimuli: half of the pictures that are shown to a participant during the test; a child is asked to name them as quickly as possible.

Bead Threading (BT). Round wooden beads (25mm in diameter with a hole of 6mm diameter in the centre) and a cord (40cm long and 3mm in diameter) were used. Participants were given 30 seconds to thread as many beads as they could. This acts as a measure of fine motor skills and also tests hand-eye co-ordination and manipulative skills.

Digit Span (DS). Test is composed of two parts: Digit Span Forward (repeating numbers in the same order; 16 items) and Digit Span Backward (repeating in the reverse order than presented by the examiner; 14 items). Younger children below the age of six years and six months were tested only on the first part of the test. Each item in the test has two trials with the same number of digits. The test was discontinued after two scores of zero within one item. This test is designed to measure auditory short-term memory, sequencing skills, attention and concentration. Specifically, the skills required for the first part of the test were rote learning and memory, attention, encoding and auditory processing, the second part involved working memory, a transformation of information, mental manipulation and visuospatial imaging.

The following two tests were used at the follow-up stage and were used to determine overall reading score of children. They were both derived from DST-J battery.

The DEST's validation was provided by Fawcett, Singleton and Peer (1998), who showed an accuracy of 90% in predicting reading at the age of eight. Nicolson and Fawcett (1997) reported the sensitivity reaching 94% and specificity of zero per cent. Simpson and Everatt (2005) found that individual subtests of the DEST were more predictive of literacy skills than the global screening test's score.

Speeded Reading (SR). The task is also referred to as the one-minute reading task. This test requires a child to produce a speeded and an accurate performance. The child is asked to read aloud a page of individual words, graded in difficulty. The score of the test was the number of words correctly read.

Nonsense Reading (NR). The Nonsense Reading task is one of the most sensitive to dyslexia tasks (Fawcett & Nicolson, 2004). It requires a child to read a passage with real and nonsense words. Both the accuracy and time are considered. For each correctly read real word and nonsense word, one and two points were awarded, respectively. Extra points were added if the passage was read in less than one minute. If a child took more than one minute points were subtracted. In accordance to previous data treatment, raw scores for both results were residualised for age.

Reading difficulty was operationally defined as reading performance on the Speeded and Nonsense readings tasks (both tasks normalised and then averaged), falling below 1 (def. 1), 1.5 (def. 2) and 2 (def. 3) standard deviations below the sample mean. This solution was considered as more appropriate, as opposed to using the norms provided by the manuals because:

(1) the current study attempted to be in line with previous research in the field (e.g., Carroll et al., 2016) that often uses reading passages as tests and considers those readers falling below a certain threshold as dyslexic;

(2) calculating the normalised total reading score allowed the researcher to use different thresholds (as mentioned above) and investigate how the patterns of difficulties change depending on the operational definition used; such level of detail would not be achieved if the norms provided by the manuals were used; (3) the performance on both tasks (Speeded and Nonsense Reading) could be combined and

the score represented overall reading score which can be seen as more sensitive a measure than only using one of the tests.

To analyse children's performance cross-sectionally on the tests derived from DEST-2 and DST-J, scores were residualised for age in months. This was also decided due to the fact that both of these tests used a slightly different age-normed scoring system (see Table 3.5) which made it difficult to compare performance across the age groups.

Table 3.5
'At risk' norms and corresponding percentiles for DEST-2 and DST-J screening tests

DEST-2		DST-J	
At risk	percentile	At risk	percentile
- -	Bottom 10%	- - -	Bottom 4%
-	11 – 25	- -	5 – 11
o	26 – 75	-	12 – 22
+	76 – 90	**o**	23 – 77
+ +	Top 10%	+	78 - 100

3.4.3 Intelligence Tests: Wechsler's scales

Wechsler's Preschool and Primary Scale of Intelligence, fourth edition (WPPSI-IV), was designed for children aged between 4-7 years (Wechsler, 2012). Wechsler's Intelligence Scale for Children (WISC-IV) was designed for children aged between 6-16 years (Wechsler, 2004). These are most commonly used tests for the assessment of intellectual abilities in children (Flanagan & Kaufman, 2009; Hale, Casey, & Ricciardi, 2014; Prifitera, Saklofske, & Weiss, 2008). Full Scale IQ is based on the total combined performance of the Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PRI), Working Memory Index (WMI) and Processing Speed index (PSI). Unfortunately, due to time constraints it was not possible to test the full scale IQ in the current studies and only selected subtests from the Verbal Comprehension and Perceptual Reasoning indices were used. Unfortunately, due to time contraints it was not possible to test the full scale IQ in the current studies.

From these scales, three subtests were used. The idea was to include some more general verbal tests, which may be difficult for those with dyslexia (the Similarities, a measure of verbal reasoning) and have been shown to correlate strongly with word reading (Wechsler, 2012) and with overall reading (Wechsler, 2003), and some tests that likely reflected more "general", non-verbal, fluid, or abstract intelligence (Block Design and Matrix Reasoning), which supposedly are independent of dyslexia and show weak correlations with reading (Wechsler, 2003; 2012). These were included to investigate whether the performance on the DtD test is related to reasoning skills too. Reliability coefficients for all three measures were at least .80 in typical and reading disorder samples (Wechsler, 2003; 2012).

Block Design (BD). Participants were asked to re-create a design using red-and-white blocks from a previously constructed model or a Stimulus Book within a specified time (see Figure 3.15). The task was designed to measure the ability to analyse and synthesise abstract visual stimuli. It involves nonverbal concept formation, visual perception and organisation, simultaneous processing, visual-motor integration, learning and the ability to separate figure and ground in visual stimuli.

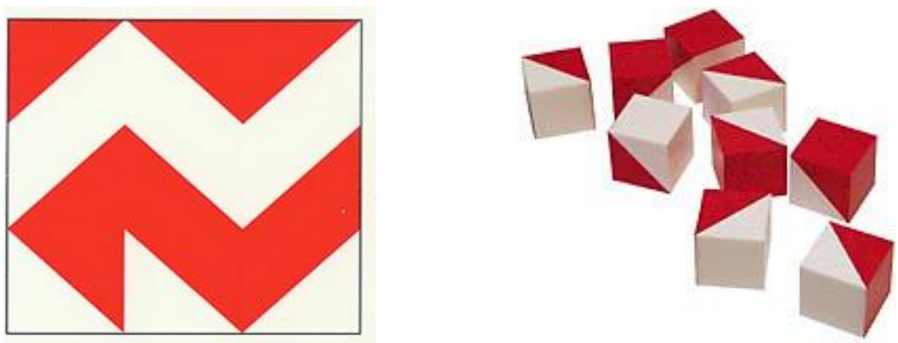

Figure 3.15 Block Design test: an example pattern (left) that was assembled from the white and red blocks (right).

Matrix Reasoning (MR). In this task, participants looked at an incomplete matrix and were asked to select the missing part from response options. This test was designed to measure visual information processing and abstract reasoning (i.e., continues and discrete pattern completion, classification, analogical reasoning and serial reasoning). The test is seen as a measure of fluid intelligence and general intellectual ability (see Figure 3.16).

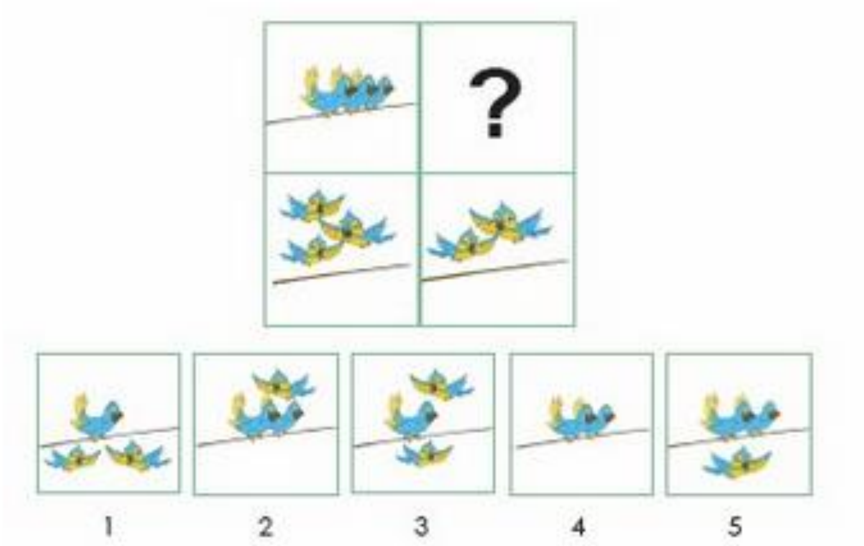

Figure 3.16 Example of Matrix Reasoning test. Children are shown coloured matrices or visual patterns with something missing. The child is asked to select the missing piece from a range of options.

Similarities: Verbal Reasoning (VR). In this task, two words representing common objects or concepts (e.g., *juice-milk* or *ears-noses*) were presented and a participant needed to explain in what way they were similar. Younger children were first shown pictures and were asked to identify the similarities. After completing four trials the concepts were presented verbally. Older children, over the age of six, were presented with the concepts only verbally. The test was discontinued after four consecutive scores of zero. The task was designed to measure verbal reasoning and concept formation. It also requires good auditory comprehension, memory, ability to distinguish between non-essential and essential features, and verbal expression.

3.4.4 Additional data

The researcher attempted to control for a number of factors that may have affected performance. She, therefore, observed closely and took notes during testing of details that could have influenced children's performance: time of the day, level of concentration, level of noise in the background, and any other pieces of information she found relevant. The level of children's English was noted and confirmed with the teachers if in doubt. Demographic questionnaires containing questions about the adult participants' age, occupation and history of reading difficulties in family as well as when they were diagnosed with developmental dyslexia were filled in by the adult participants.

3.5 Procedure

3.5.1 Children

Informed consent to participate was gained from participants after the procedures had been explained. Children were tested individually at their schools, in rooms assigned by their Head Teachers. Overall, children were approached three times: two times (two sessions) at baseline testing and one time at a follow up. Due to time constraints, the follow-up session was conducted **either one, two or three** years after the baseline. At the baseline, they were tested twice for up to 30 minutes to avoid fatigue. The two sessions were no longer than one month apart. The follow up session also lasted approximately 30 minutes. The details of tests used at the baseline and at the follow-up are provided in Table 3.6.

Table 3.6
Tests administred at the baseline and at the follow-up sessions

Baseline		Follow-up
Session one	Session two	
Lucid-Rapid Dyslexia Screening Test	Dyslexia (Early) Screening Test: subtests measuring speed of processing, motor and phonological skills and memory	Dyslexia Screening Test: Reading skills: One minute reading, nonsense passage reading
The Dot-to-dot	Cognitive abilities: Wechsler's subtests measuring perceptual reasoning and verbal comprehension	Visual tests: contrast sensitivity (magnocellular, parvocellular), coherent dot motion (dorsal), coherent form (ventral)

In the first session of the baseline tests, children completed the DtD task and the Lucid RAPID. The order of the tasks was randomized (155 children started with Lucid, 272 started with DtD; no significant differences were found between children's performance across the two order presentations) to control for order effects. Nursery children tended to get bored or tired more quickly; therefore only those who expressed willingness to participate were approached a second time. If a child was reluctant to complete the tests when approached the second time, he or she was not approached again. Ten children were re-approached out of the entire sample.

There is no evidence to suggest that the fact that some children were approached two times to do the tasks had any impact on the findings.

The second session consisted of Dyslexia Screening Tests' (DEST-2 or DST-J) subtests and Intelligence Scales' (WPPSI-IV or WISC-IV) subtests. The order of the subtests was fixed, in accordance with the manuals; however, the order of the tests was randomized with 225 children starting with the Dyslexia tests and 227 with the Wechsler's tests. Again, no significant differences were found between the two groups.

3.5.2. Adults

Informed consent to participate was gathered from participants after the procedures had been explained. Participants were tested individually in person in a private room at Edinburgh Napier University. Instructions for every task were given verbally with time allocated to ask questions if needed. All participants completed the DtD task in the first session and the remaining tasks in the follow-up session up to one year after. Following completion, participants were thanked and excused.

Chapter 4

Cross-sectional investigation of children's performance on the DtD task, dyslexia screening and reasoning tasks

Abstract

The current study investigated whether performance on the DtD task can feasibly help in identifying children at risk of dyslexia and which, if any, of the DtD measures seem to be most indicative. A cross-sectional, unselected sample of young children (*N* = 457; mean age = 6.6 years; *SD* = 1.9; 48% F) took part in the study. Key findings are: (i) the DtD is indeed within the scope of preschool and school children; and (ii) performance on DtD (especially the first sector error) demonstrated significant differences between children at high and low risk of dyslexia (as assessed by Lucid Rapid). This shows that the DtD measures have discriminative abilities and potential to predict dyslexia, as this will be explored in chapter 5. Irrespective of the adequacy of Lucid, it involves phonological processing and working memory, therefore has no obvious association with the DtD's first sector error which is also evidenced by lack of significant correlation between the DtD measures and phonology based measures. Children who were found to be at high risk of dyslexia showed poor performance on the DtD task and this indicates either a failure to inhibit so automatic actions or initial difficulty dissociating hand and gaze control. Consequently, this is inconsistent with the phonological deficit hypothesis and is more consistent with automatisation deficit. Further research should revisit the children and assess their reading level in order to verify the here estimated risk of dyslexia.

4.1 Introduction

As an extensive discussion of the relevant literature has already been presented and discussed in Chapters 1 and 2, the introduction section within this chapter, and proceeding research-based chapters, will not repeat these discussions. It will instead reiterate the key areas of literature and theoretical arguments as relevant to the current chapter's specific research within the introduction section and will place core focus on the relevance of these to the current research being discussed. In particular, the importance of exploring the possibility of a screening measure for pre-reading age children will be discussed here.

The current research chapter offers a cross-sectional perspective on understanding various aspects of developmental dyslexia in primary-aged children across three schools located within different socioeconomic environments. This study aimed to investigate the practical value of the novel tool, the DtD task, as a measure of skills compromised in some individuals at risk of developmental dyslexia. The performance on the DtD task and other already established tests associated with core deficits of dyslexia, such as phonological processing, memory and rapid naming was assessed. These three measures have been previously shown to be good predictors of dyslexia (Hulme & Snowling, 2009; Vellution et al., 2004). Reasoning abilities were also included within the test battery. The investigation of differences in DtD performance between children at high, medium and low risk of dyslexia was a crucial part of this study.

As the DtD software generates various measures (Chapter 3 provides details), which putatively reflect different skills, it is imperative to investigate which measures from this tool may be related to dyslexia-sensitive and intelligence tests. Thanks to this, it will be possible to evaluate the type of skills associated with the DtD test. This will help to verify empirically whether children performing poorly on the DtD test also show difficulties in motor, phonological, memory and/or cognitive tasks.

As discussed in Chapter 1, the role of intelligence in dyslexia has been long debated in the literature, and the classical definition of dyslexia included an IQ - reading level discrepancy. This means that a child with dyslexia would have to have a reading level significantly lower than the level expected of their intelligence (BPS, 1999). However, research has since shown that children who would fit into this IQ – reading level discrepancy category and those who would not, do not differ qualitatively (Carroll et al., 2016; Share & Shalev, 2004; Stanovich & Siegel, 1994). The current study will also provide an opportunity to examine reasoning levels of children at risk of dyslexia to see if those at high risk perform poorer on these tasks. However, the discrepancy definition will not be used in the current study.

The present study involves an unselected sample of children. This provides a more representative sample than has been used in most previous studies in this area. Previous studies have tended to use sets of children at familial risk of dyslexia and matched control groups (e.g., Kevan & Pammer, 2009) or have excluded borderline cases (Le Jan et al., 2011). However, such an approach is prone to sampling biases as recruitment of risk families differs across studies: for example, some use children who have at least one parent with dyslexia, and others recruit children with dyslexic siblings. Often, this is based on self-report of family members; parents' awareness of dyslexia may also be related to more motivated volunteers taking part in studies. Therefore, the choice of an unselected sample may minimize these biases which will strengthen the validity of results.

Similarly, the existent literature is unable to provide a clear picture of gender differences in those with developmental dyslexia. Although many studies have reported that males tend to be identified with dyslexia more often than females (e.g., Rutter et al., 2004), others point out that it may depend on who conducts the assessment, and that boys may be more likely to receive a diagnosis due to their misbehaving (Shaywitz, 1996). To address this gap in understanding, the current research will explore performance on the tasks and dyslexia risk across genders.

Previous research has further indicated that low socioeconomic status may be linked to poor phonological awareness (Nittrouer, 1996). It has been shown that children from families with higher socioeconomic status, with access to more resources and educated parents, tend to outperform other children (Buchmann & Hannum, 2001) and are less likely to develop reading difficulties (Chaney, 2008; Whitehurst & Lonigan, 1998). A more detailed discussion on the impact of SES on reading abilities and disabilities was provided in Chapter 1. The current study's sample comprises children attending three different primary schools, associated with different socioeconomic backgrounds. The purpose of including children from different backgrounds was to assure the representativeness of the sample. However, it also provided an opportunity to explore differences in performance among children attending different schools. The present study also focuses on primary school aged children in three different age cohorts as already discussed in Chapter 3. The youngest cohort comprises pre-reading children, which minimizes the reciprocal effect of reading on related cognitive skills (Castles & Coltheart, 2004). The inclusion of children who have not experienced formal reading instructions and were not explicitly exposed to reading is crucial as deficits present in these children could be interpreted as causal to reading problems. An investigation of such pre-reading cohorts' deficits minimises internal validity concerns as, in opposition to deficits found in older children, they cannot be seen as a consequence of poor reading instruction or lack of practice.

Currently, there is a good understanding within the filed that phonological processing deficits are key in dyslexia (Snowling, 2000). However, these may be seen as proximal causes of reading problems, with cerebellar (Fawcett et al., 1996) and visual pathways deficits (Stein, 2001) seen as distal, brain-based, underlying explanations. It is argued that if these deficits underlie developmental dyslexia, they should be apparent in children even before they learn to read. This assumption provides a great opportunity to develop a screening tool that would measure motor and visual processes that could predict reading but are not related to phonological and language knowledge. This is of particular importance as often the formal identification of reading problems occurs late (Singleton, 2009). Late identification leads to late interventions and is often related to a negative cycle of educational and life achievement (Stanovich, 1986). The identification of dyslexia is particularly difficult in EAL children for whom assessments designed for English native speakers are not appropriate (Everatt et al., 2004).

Non-linguistic screening tasks do currently exist however they are never used as stand-alone tests and they present a number of challenges. Two such tests are part of the DEST/DST/DAST screening batteries by the Sheffield group. These are Bead Threading (also used in the current study) and postural stability tests. Although studies fairly consistently show significant differences in performance on these tasks between dyslexic and control groups (Fawcett et al., 1996; Ramus et al., 2003), such tasks generally appear poor at predicting reading performance (Simpson & Everatt, 2005). This possibly indicates that such tasks are not a good proxy for cerebellum function. Similarly, psychophysical tasks associated to visual pathways processing tend to be controversial and their construct validity has been questioned (Skottun, 2013). Also, some of the tasks require specialized, not portable and expensive equipment (e.g., Goulème, Villeneuve, Gérard, & Bucci, 2017; Kevan & Pammer, 2009). Furthermore, none of the existing tests measure a combination of skills believed to be compromised in dyslexia. The novel dot-to-dot task has a potential to address some of these issues. It is easy to use and requires relatively inexpensive equipment (laptop and a graphics tablet). It only takes up to ten minutes to complete the task. The DtD task presumably involves a broad range of motor, visual, and attentional skills; it requires no phonological processing and minimal language reasoning (to understand instructions).

4.1.1 Research aims and hypotheses

This study aimed to investigate whether performance on the DtD task can reliably distinguish between those children who were at high, medium or low risk of dyslexia as assessed by an existing screening tool – the Lucid Rapid (see Chapter 3 for details). As the DtD is a new test under investigation, it was important to investigate which of its measures, if any, were related to children's performance on dyslexia sensitive and reasoning tests. Differences in the range of dyslexia-sensitive and reasoning tests between different risk groups were investigated, and school and gender effects were also explored.

The following hypotheses were formulated:

(1) Performance on the DtD task, the established dyslexia screening tests, and verbal (Similarities) and non-verbal reasoning (Matrix Reasoning and Block Design) tests will significantly differ between children at high, medium and low risk of dyslexia as assessed by Lucid Rapid.

(2) Performance on the DtD task will be related to the performance on some of the dyslexia-sensitive tasks (Phonological Processing, RAN, memory and motor tasks), to motor task and to verbal and non-verbal reasoning.

It was also aimed to examine whether school (socioeconomic background) and gender had any effect on children's performance on dyslexia screening tests, reasoning tests and the DtD task.

4.2 Methods

4.2.1 Design

The research used a between-subjects design within a quasi-experimental framework, with dyslexia risk as one independent variable with three conditions (low, moderate, and high risk of dyslexia), the school as the second independent variable (three schools: school 1 - low SES, school 2 - medium, school 3 - high) and gender (males and females) as a third. The dependent variables were the participants' scores on established dyslexia screening tests (Phonological Processing, RAN, Digit Span and Bead Threading), verbal (Similarities) and non-verbal reasoning (Matrix Reasoning and Block Design) tests and the DtD task.

Correlational analyses were also conducted to determine whether the variables which theoretically should be assessing different skills were related. Associations between dyslexia risk and gender, as well differences in performance among children from different schools were examined.

4.2.2 Participants

Overall, 457 children (mean age = 6.6 years; *SD* = 1.9; 48% F) participated in the study. The inclusion criteria were normal, or corrected-to-normal, vision and no history of neurological impairment. Participants were recruited from three different schools, each located within a different catchment area (for details see Chapter 3). Seventeen of the 474 children registered in the chosen classes were excluded from the study due to reluctance to take part (*n* = 7) or parental opt-out (*n* = 10). The study focused on three cohorts: children in Nursery and Primary 1 (pre-readers), Primary 3, and Primary 5. Some of the children opted out of some of the tests, so the number of participants for each measure fluctuates. Table 4.1 presents the number of children across three schools and the classes they were in at the time of testing.

Table 4.1.
Number of children tested in all schools broken down according to the school year (mean age in brackets).

		School			Total
		1	2	3	
School year (mean age in years)	Nursery (4.13)	24	0	0	24
	P1 (4.79)	80	70	106	256
	P3 (7.23)	32	21	34	87
	P5 (9.19)	36	26	28	90
Total (6.34)		172	117	168	457

4.2.3 Materials

A summary of all the measures used in the study, together with the test batteries that they were derived from, is presented in Chapter 3 (see *Baseline measures* in Table 3.6).

4.2.4 Procedure

Informed consent to participate was obtained after the procedures were explained. Children were tested in their schools, in rooms assigned by their Head Teachers. The children were tested over two sessions each lasting approximately 30 minutes. Details of the procedure were described fully in Chapter 3.

4.3 Results

This section is structured as follows. First, a description of the treatment of the data will be presented. The data collected were complex, using multiple tasks and a large sample of children, some of whom did not complete every task, as detailed in the Method section previously. Because of this, it is important to be clear and transparent about the ways in which the data were handled, including handling of missing data and standardising scores on different tasks prior to discussing the actual findings. This will be followed by a section describing the analysis of differences between dyslexia risk groups on the novel and the established measures investigated. Dyslexia risk in this analysis was estimated by the computerised dyslexia screening tool, the Lucid Rapid. Further, the analyses of the relationships between variables will be provided, and school and gender effects will be further analysed. Separate univariate ANOVAs were conducted for the two independent variables (dyslexia risk and school) and a test of association for gender and dyslexia risk as the three-way ANOVA was not suitable due to a small number of children at high risk of dyslexia in school 3 (n= 10) was also carried out. Therefore, the interaction between dyslexia risk, school and gender could not be investigated directly.

4.3.1 Data treatment

4.3.1.1 Missing data

Due to the nature of the study, which involved testing children over fairly long sessions, there were missing scores on various tasks. Children were happy to complete some tests but not the others. Also, some of the DtD measures were added in due course. The percentage of missing data points for each task ranged from 6 to 34% (details are provided in Appendix B Tables B-1 and B-2). It was, therefore, important to investigate whether there were any patterns to the missing values prior to data analysis. Little's MCAR test, as a part of the missing values analysis, was conducted to investigate if these values were missing completely at random (MCAR). The test was statistically non-significant (χ^2 = 2298.184, df = 2438, p = .979), which indicated that the missing data were missing at random. It was decided that the best method of dealing with missing data was to use the pairwise deletion method because it allows using as many cases as possible for each analysis. Listwise deletion was considered but rejected (unless otherwise specified) as it would reduce the statistical power by lowering the number of participants included in the analysis, as it would not use all of the available information. Imputation methods were also considered but again rejected due to possible reduction in the variability of the scores (in case of the mean substitution method), biased estimates (if dummy variable adjustments method was used), or overestimated model fit and correlation estimates (regression imputation) (Enders & Craig, 2010; Little, Roderick, & Rubin 2002; Paul, 2001; Schafer & Graham 2002).

4.3.1.2 Standardising, deleting and combining scores

To analyse children's performance on all of the tests, the scores were residualised for age in months; a method used in previous research (e.g., Carroll et al., 2016). Interpretation of residualised scores is comparable to interpretation of z-scores. The residual score for each raw score was calculated as the difference between the observed value of each dependent variable (the raw score on DtD, cognitive, and dyslexia screening tests) and the value predicted on the basis of the age in months. This assured control of the results for age. This also allowed an interpretation of the findings and the comparisons across different age samples.

Another aspect that was taken into account before commencing with the inferential analyses was the number of DtD trials completed by the participants. This was particularly important to consider as the values calculated by the DtD software provide the mean scores from all of the trials. Therefore, the mean scores of less than six trials (full set) would generate a mean that would not give a fair representation of the child's performance on the task. The performance naturally should get better from trial one to trial six due to practice effects, so if a child completed only three trials, their performance could appear to be worse than if they had completed all six trials. To illustrate this point, an independent t-test was conducted to investigate differences in DtD measures for non-dominant hand between children who completed one trial (n = 22) and those who completed all trials (n = 317). The differences in three main measures, time, first sector max. error and total error were statistically significant (p = .005; p = .018; p = .014; respectively)[7]. Also, there was a great variability of the number of completed trials across children (details provided in Table

4.2), especially in terms of the non-dominant hand. For the following analyses, only children who completed all the trials were included.

[7] Other comparisons (e.g., between 3 and 6 trials) were not conducted due to small number of participants in in-complete trials groups which can be seen in Table 4.2.

Table 4.2
Number of DtD trials completed by the participants for dominant and non-dominant hand

No of completed trials	Dominant hand		Non-dominant hand	
	Frequency	%	Frequency	%
1 of 6	4	0.9	22	6
2 of 6	12	2.7	8	2.2
3 of 6	12	2.7	6	1.6
4 of 6	5	1.1	10	2.7
5 of 6	7	1.6	4	1.1
6 of 6	406	91	315	86.3
Total	446	100	365	100

Before conducting the analyses of differences and relationships, consideration was given as to whether some of the measures should be combined due to the common skills that they were deemed to test.

A principal component analysis (PCA) was run on a seven-item battery of tests that measured dyslexia-sensitive skills. The suitability of PCA was assessed prior to the analysis and it has been noticed that the data violated the assumption of normality. However, due to no alternative test available, the PCA was conducted with caution during interpretation. Inspection of the correlation matrix showed that all variables had at least one correlation coefficient greater than 0.3. The overall Kaiser-Meyer-Olkin (KMO) measure was .801, Bartlett's Test of Sphericity was statistically significant ($p < .001$), indicating that the data was likely factorizable.

PCA revealed four components that had Eigenvalues greater than one and which explained 40.32%, 13.62%, 13.48% and 10.38% of the total variance, respectively (see Table 4.3). The four-component solution explained 77.8% of the total variance. The interpretation of the data was fairly consistent with the pre-existing assumption of the skills measured within the tests with strong loadings of phonological items on Component 1, memory-related items on Component 2, rapid naming items on Component 3, and a motor item on Component 4. Visual inspection of the scree plot indicated that four components should be retained (Cattell, 1966). Component loadings and commonalities of the rotated solution are presented in Table 4.3.

Table 4.3

Principal Component Analysis (PCA) for dyslexia screening test battery

	component			
	1	2	3	4
Phonological processing (DEST)	.945			
Phonological processing (Lucid)	.810			
Auditory sequential memory	.538			
Digit span		.908		
Visual memory/phonic skill		.715		
Rapid automatised naming			.983	
Bead threading				.961

Note. Loadings below .3 are supressed

Component 1 is interesting as it shows that auditory sequential memory (ASM) from Lucid Rapid loaded with the phonology-based tasks rather than the other two memory measures (digit span and visual memory). The loading of the ASM measure was, however, lower (.538) than the phonological components (> .800). As the analysis did not yield entirely logical components in terms of underpinning task-theoretical links (e.g., phonological and memory tasks loading to the same component), and with three of the four components containing fewer than three loading items, the analysis was not used to inform the combination of items. Instead, their theoretical underpinnings were considered for this task, as detailed next.

In order to reduce the number of variables, it was decided that the two phonological measures (PP-D and PP-L) would be combined by adding and averaging their two scores for the analyses and this was named *Phonological Processing* (PP). The VM/PS scores need to be considered with caution as they comprise two tasks administered to the participants depending on the children's age. Younger children (< 8 y.o.) did a visual memory task (*n* = 242), whilst older children did a phonic coding task (*n* = 106). Probably due to a greater number of participants completing the visual memory test, this variable loaded into the second component. Therefore, there is no good reason to combine the two tasks. The Lucid Rapid authors argue that the use of these two different tasks aids better estimation of risk at different ages; in older children, a test of visual memory would be more indicative of reading problems than the phonic skills. That, however, in no way indicates that these two subtests test the same skill.

To explore the possibility of reducing the number of DtD variables that may be relevant to identifying dyslexia, a principal component analysis was carried out on the ten main measures derived from the DtD software. It was not possible to conduct the PCA on all measures as there were linear dependencies between some measures (e.g., Direction ratio was an aggregate variable combining direction ratios for FirstUp and FirstDown patterns) which was evidenced by correlation matrix indicated as nonpositive definite in SPSS. The suitability of PCA was assessed prior to analysis, and it also showed that the data violated the assumption of normality. Inspection of the correlation matrix showed that all variables had at least one correlation coefficient greater than 0.3. The overall Kaiser-Meyer-Olkin (KMO) measure was .630 which is considered as 'mediocre' indicating that the sampling was barely acceptable (Kaiser & Rice, 1974). Bartlett's Test of Sphericity was statistically significant ($p < .001$), indicating that the data were likely factorizable.

PCA revealed four components that had Eigenvalues greater than one and which explained 39.7%, 15.5%, 13.0% and 8.6% of the total variance, respectively. The four-component solution explained 76.8% of the total variance. The interpretation of the data was fairly consistent with the pre-existing assumption of the skills measured by the tests with strong loadings of accuracy-related items mostly for the non-dominant hand on Component 1 (although the FSME for dominant hand also loaded onto this component and on component 2), accuracy-related items for dominant hand loaded on Component 2, speed items for both hands on Component 3 and a direction-related item also for both hands on Component 4. Component loadings and communalities of the rotated solution are presented in Table 4.4.

Table 4.4
Principal component analysis for the DtD measures

	component			
	1	2	3	4
NDH First sector max.err	1.000			
NDH Total error	.960			

NDH SD2	.575			
DH First sector max.err	.516	.406		
DH SD2		1.025		
DH Total error		.734		
NDH Time			.875	
DH Time			.852	
NDH Direction ratio				.798
DH Direction ratio				.789

Note. Loadings below .3 are supressed. NDH=non-dominant hand; DH=dominant hand.

Due to the KMO measure being quite low and the fact that the normality assumption was violated, the results need to be interpreted carefully. It was particularly noticeable that some of the measures (Time and Direction Ratios) from two hands loaded into one component. Clustering measures obtained from dominant and non-dominant hands could possibly lower the sensitivity of the measures; therefore, it was decided to keep them as separate variables.

From the above dimension reduction analysis, it was concluded that the DtD measures should not be clustered as reducing and collapsing some measures would be possibly misleading and against the sole purpose of the current study which was to find out which measures were indicative of dyslexia risk.

4.3.1.3 English level comparisons

There were 71.2% of children for whom English was a native tongue, 22.7% of children had English as a second language who spoke *good* English, according to the observations made during testing, and 6.1% of children whose English was *poor*. Poor English was indicated when a child struggled to understand the instructions or answer simple questions. These levels were also confirmed by the teachers. As some of the tests heavily rely on language skills, which could have affected the results, a comparison of the performance between the groups was employed first. Second, a test of association was conducted to investigate whether children with a poor level of English would be more likely to be flagged as being at risk of dyslexia.

A Kruskal-Wallis H test was conducted, as preliminary assumption checking revealed that data were not normally distributed (assessed by investigation of skewness and kurtosis; scores within the range of -1 to 1 were considered as normal), to determine whether there were differences in various dyslexia sensitive and reasoning scores between groups that differed in their level of English: the "native", "non-native-good" and "non-native-poor". Distributions of the scores were similar for all groups, as assessed by visual inspection of a boxplot. Table 4.5 presents median scores for all groups and Table 4.6 presents Kruskal-Wallis H test results. Pairwise comparisons were performed using Dunn's (1964) procedure. A Bonferroni correction for multiple comparisons was carried out with statistical significance accepted at the p < .017 level (0.05 divided by 3).

Table 4.5

Median scores for three English level groups

	Level of English					
	native		non-native-good		non-native-poor	
Test	N	Median	N	Median	N	Median
Phonological Proc.	302	35	93	35	21	4
Auditory Seq. Memory	299	41	91	20	21	24
Visual Memory/Phonic S.	265	30	81	34	21	20
Block design	317	8	102	9	28	7
Matrix Reasoning	316	8	102	8	28	9
Verbal reasoning	310	11	100	10	22	8
Digit Span	312	.17	100	-.06	24	-.55
RAN	306	-.12	96	.06	24	.19
Bead Threading	315	.48	101	.48	29	.48

Note. RAN=Random Automatised Naming.

Table 4.6

Kruskal-Wallis T test and pairwise comparisons across three English level groups

	Kruskal-Wallis H	*p*	Group comparison	*p*
PP	$\chi^2(2) = 16.562$	< **.001***	NN poor vs. NN good	**.009***
			NN poor vs. N	< **.001***
			NN good vs. N	.145
ASM	$\chi^2(2) = 15.346$	< **.001***	NN poor vs. NN good	.733
			NN poor vs. N	**.013***
			NN good vs. N	**.008***
BD	$\chi^2(2) = 6.825$	**.013***	NN poor vs. NN good	**.048***
			NN poor vs. N	.393
			NN good vs. N	.173
VC	$\chi^2(2) = 14.530$	**.001***	NN poor vs. NN good	.088
			NN poor vs. N	**.002***
			NN good vs. N	.106
DS	$\chi^2(2) = 13.196$	**.001***	NN poor vs. NN good	.121
			NN poor vs. N	**.003***
			NN good vs. N	.141
RAN	$\chi^2(2) = 9.230$	**.010***	NN poor vs. NN good	.157
			NN poor vs. N	**.013***
			NN good vs. N	.488
VM/PS	$\chi^2(2) = 1.432$	.489		
MR	$\chi^2(2) = .122$	.941		
BT	$\chi^2(2) = 3.069$	.216		

Note. N = native; NN = non-native; PP = Phonological Processing-Lucid; ASM = Auditory Sequential Memory; VM/PC = Visual Memory/Phonic Coding; BD = Block design; MR = Matrix Reasoning; S = Similarities; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; * statistically significant result.

There were significant differences in the tasks that required a good level of English: Phonological Processing, Digit Span and RAN. Children with native English performed significantly better than the non-native poor English pupils. Significant differences were also found in auditory sequential memory (ASM) task, which relies heavily on listening skills, between all three groups; non-native children with poor and good English were significantly poorer than native English children.

A Kruskal-Wallis test for the DtD measures revealed no differences (all *ps* > .05) between the three English level groups.

A Chi-square test of association was conducted between English level and dyslexia risk (Lucid Rapid). Expected and observed frequencies are presented in Table 4.7. There was a statistically significant association between English level and dyslexia risk ($\chi^2(6) = 15.843$, $p = .015$; Cramer's V = .472) with a higher frequency of children with poor English being flagged as at high risk of dyslexia than would have been expected.

Table 4.7
Contingency table of dyslexia risk and level of English.

English	N	Dyslexia risk[a] very high	high	moderate	low	Total
Native	observed	24	39	94	96	253
	expected	30.6	41.6	91.1	89.7	253
Non-native good	observed	12	13	27	25	77
	expected	9.3	12.6	27.7	27.3	77
Non-native poor	observed	6	5	4	2	17
	expected	2.1	2.8	6.1	6.0	17

Note. [a] based on Lucid Rapid Screening test

These results indicate that level of English may be a confounding variable affecting subsequent analyses. Due to these findings, the analyses in the following sections involving the aforementioned tests excluded non-native children with poor English.

4.3.1.4 Multiple testing

While there are a number of approaches to overcoming problems related to multiple testing, they all attempt to assign an adjusted p-value to each test or reduce the p-value threshold from 5% to a more reasonable value. Many traditional techniques such as the Bonferroni correction seem to be too conservative (Bland & Altman, 1995). Although they reduce the number of Type 1 errors, they may also reduce the number of true discoveries (i.e. increase the proportion of Type 2 errors). The False Discovery Rate approach was therefore used. This approach also determines adjusted p-values for each test, but controls for the number of false discoveries in those tests that result in a true discovery (i.e. a significant result). Because of this, it is less conservative than the Bonferroni approach and has greater ability to find truly significant results. In the current study, the Benjamini and Hochberg (B-H)

Procedure (Benjamini & Hochberg, 1995) was used for multiple tests by calculating a q value. The procedure is following:

1. Individual p-values are organised in ascending order and ranked (the smallest p-value is assigned rank 1, etc.)
2. For each p-value a q value is calculated using the **(j/m) Q** formula, where:
   j = rank assigned to the individual p-value;
   m = total number of tests;
   Q = the false discovery rate (FDR) at the 5% level.

An FDR adjusted p-value (or q-value) of 0.05 implies that 5% of significant tests will result in false positives. This value is rather arbitrary, and there are no clear guidelines indicating the appropriate magnitude of this value. Thus it should be based on researchers' judgements. In literature, values from .05 up to .25 can be found.

Detailed calculations relevant to the multiple analyses in the following sections within the thesis are provided when necessary. Where there is no difference between B-H and Bonferroni corrections, the latter is reported for simplicity.

4.3.2. Descriptive statistics

Following the above-mentioned exclusions of participants, the final sample comprised of 432 children (49.5% females) with a mean age of 6.14 years (*SD* = 1.90); ages ranging from 4 to 11 years old. Thirty-seven per cent of children were in School 1 (low SES), 25% in School 2 (medium SES), and 38% in School 3 (high SES). The tables below present minimum and maximum scores on the dyslexia and IQ measures (Table 4.8) and on the DtD measures (Table 4.9). As all the scores were standardised by residualising them for age, the means were close to zero, and the standard deviations were close to one; thus they are not reported in the tables.

Table 4.8
Descriptive statistics showing residualied minimum and maximum scores dyslexia-sensitive and reasoning measures

	N	Min	Max
Phonological Processing	362	-2.100	1.656
Auditory Sequential Memory	382	-2.034	2.003
Visual Memory/Phonic Skill	348	-1.987	2.491
Digit Span	397	-5.086	3.556
Random Automatised Naming	390	-2.966	7.571
Bead Threading	404	-2.470	2.994
Block Design	407	-3.320	3.190
Matrix Reasoning	407	-3.031	2.786
Verbal Reasoning	398	-2.355	2.510

Note. N = number of participants

Table 4.9
Descriptive statistics showing residualied minimum and maximum scores for the DtD measures

	N	Min	Max
DH Time	369	-1.621	5.280
DH First sector max.err.	369	-1.898	3.900
DH Total err.	369	-1.894	6.479
DH SD2	369	-2.513	4.031
DH Direction ratio	370	-1.966	3.159
DH FirstDown First sector max.err.	369	-1.801	3.726
DH FirstDown Direction ratio	360	-0.921	3.289
DH FirstUp First sector max.err.	369	-1.739	6.486
DH FirstUp Direction ratio	247	-1.823	1.065
DH TimeTotal	369	-1.518	5.855
NDH Time	287	-1.503	4.700
NDH First sector max.err.	287	-2.021	4.826
NDH Total err.	287	-1.744	4.421
NDH SD2	287	-2.255	3.281

NDH Direction ratio	287	-1.850	2.958
NDH FirstDown First sector max.err.	292	-1.587	4.246
NDH FirstDown Direction ratio	280	-1.667	2.395
NDH FirstUp First sector max.err.	287	-1.973	7.837
NDH FirstUp Direction ratio	245	-1.308	1.281
NDH TimeTotal	287	-1.378	3.507

Note. N = number of participants SD2 = points over 2 SD; FirstUp = pattern with the first dot located above the starting point; FirstDown: pattern with the first dot located below the starting point; NDH = non-dominant hand; DH = dominant hand.

Due to the complexity of the analyses presented in the following sections and a large number of variables used within the study, more detailed descriptive statistics relevant to the particular type of analysis are provided in the relevant sections together with the inferential statistics.

4.3.3 Risk of dyslexia

The Lucid-Rapid dyslexia screening tool was used to evaluate dyslexia risk in the cross-section of children. Cronbach's alpha for the set of the three Lucid-Rapid subtests was .717, which indicates acceptable internal reliability. Overall, 26.7% of children did not complete all three tasks, therefore their risk of dyslexia could not be established based on the Lucid Rapid test. From the children who completed all tasks, 12.4% were indicated as at very high risk of dyslexia, 16.4% at high risk, 36.9% at moderate and 35.3% at low risk of dyslexia. The number and percentage of children in risk groups across the three schools are presented in Table 4.10.

Table 4.10
Number and percentage of children in dyslexia risk groups from across the three primary schools.

	Dyslexia Risk[a]				
School[b]	very high	high	moderate	low	Total
1	26	33	50	33	142
	18.3%	23.2%	35.2%	23.2%	100%
2	13	17	32	22	84
	15.5%	20.2%	38.1%	26.2%	100%
3	4	7	43	67	121
	3.3%	5.8%	35.5%	55.4%	100%
Total	43	57	125	122	347
	12.4%	16.4%	36%	35.2%	100%

Note. [a] assessed by Lucid Rapid. [b] School 1 was located in low SES area, school 2 in medium and school 3 in high.

For the purpose of further analysis, and due to the small number of children in the "very high" risk category in the school 3, the very high risk group was combined with the high risk of dyslexia creating the new category called "high risk" of dyslexia (n = 100).

4.3.4 Investigating dyslexia risk groups differences

4.3.4.1 The Dot-to-Dot Task

A number of univariate analyses of variance (ANOVAs) was carried out to determine the effect of pupils' dyslexia risk (high, medium, or low) on their performance on the DtD task. The use of MANOVA was considered unsuitable due to the presence of missing data for different combinations of tasks (the MANOVA analyses only complete scores of included variables). Exploration of data showed some normality violation but only where there was a difference in results between ANOVA and a nonparametric equivalent (Kruskal-Wallis H test), the result from the latter one is presented. B-H correction was used [8]. Descriptive statistics together with the ANOVAs' results for the DtD measures for the dominant hand are provided in Table B-3 in Appendix B. Only two of the measures could significantly distinguish between risk groups

Two of the DtD measures, the First Sector Maximum Error and Direction Ratio, both for the FirstUp pattern for dominant hand, yielded statistically significant results with small effect sizes. Tukey's post-hoc tests indicated that children at high risk of dyslexia made significantly greater maximum errors while drawing the line within the first sector, on average, than children at low risk (p = .009). Children at high risk and those at medium risk did not differ in their performance (p = .117), nor did children at medium and low risk (p = .529). In terms of the direction ratio, again, pairwise comparisons showed that this measure could distinguish between high and low dyslexia risk groups (p = .011) but not between medium and high (p = .144) or

[8] B-H correction was used to the calculated q value for all of the 29 univariate ANOVAs (all DtD, dyslexia screening and cognitive tests)

medium and low (p = .809). These results are presented graphically in Figures 4.1 and 4.2.

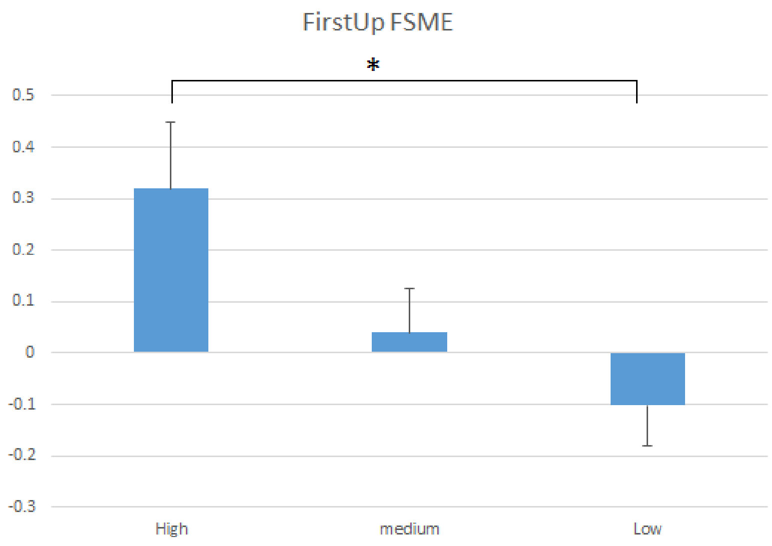

Figure 4.1 Dyslexia risk (estimated by Lucid Rapid) group differences in DtD FirstUp First Sector Maximum Error (FSME) measure for dominant hand.

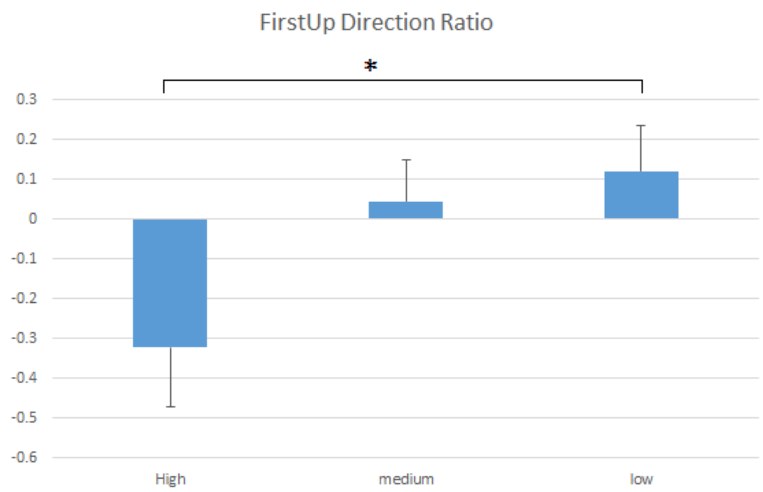

Figure 4.2 Dyslexia risk (estimated by Lucid Rapid) group differences in DtD FirstUp Direction Ratio measure for non-dominant hand.

On order to see if the language played a role in children's performance on the DtD task, data were analysed again using ANCOVA. After controlling for verbal reasoning, difference in group variances for the DtD FirstUp First Sector Maximum Error measure disappeared (F(2, 284) = 1.082; p = .340). Similarly, the group effect in the FirstUp Direction Ration measure did not remain statistically significant after controlling for verbal reasoning (F(2, 184) = 1.648; p = .195).

None of the DtD measures for non-dominant hand showed statistically significant differences. Table B-4 in Appendix B presents descriptive statistics together with the findings of the ANOVAs for the DtD measures for non-dominant hand.

4.3.4.2 Dyslexia-sensitive and intelligence tests

This section presents further univariate ANOVAs that were run to determine the effect of pupils' dyslexia risk on dyslexia-sensitive measures (DS, RAN, BT, PP, ASM, VM/PS) and reasoning (BD, MR, VC) measures. Descriptive statistics together with the findings of the ANOVAs are provided in Table 4.11.

Table 4.11

Dyslexia risk group differences on the dyslexia sensitive measures

DtD	DD risk	*N*	*M*	*SD*	*F (df)*	*p (q); η²*
Phonological Processing	high	75	-0.737	0.669	**104.171**	<0.001* *(<0.014)*
	medium	116	0.003	0.719	(2, 298)	η^2=.411
	low	110	0.613	0.470		
Digit Span	high	79	-0.639	0.971	**40.057**	<0.001* *(<0.014))*
	medium	117	-0.030	0.800	(2, 303)	η^2=.209
	low	110	0.603	1.067		
RAN	high	75	0.416	1.246	**15.672**	<0.001* *(<0.014)*
	medium	115	-0.133	0.675	(2, 295)	η^2=.096
	low	108	-0.265	0.616		
Bead Threading	high	79	-0.333	0.817	**4.925**	0.008* (*0.016)*
	medium	117	0.058	1.047	(2, 303)	η^2=.031
	low	110	0.080	1.015		
Auditory Sequential Memory	high	86	-0.936	0.411	**146.280**	<0.001* *(<0.014)*
	medium	118	-0.034	0.814	(2, 315)	η^2=.482
	low	114	0.810	0.782		
Visual Memory/Phonic Skill	high	86	-0.649	0.522	**93.797**	<0.001* *(<0.014)*
	medium	118	-0.105	0.759	(2, 315)	η^2=.373
	low	114	0.812	0.920		
Block Design	high	80	-0.429	0.962	**23.448**	<0.001* *(<0.014)*
	medium	117	-0.140	0.943	(2, 305)	η^2=.133
	low	111	0.522	1.084		
Matrix reasoning	high	80	-0.365	0.974	**17.916**	<0.001* *(<0.014)*
	medium	117	-0.109	1.022	(2, 305)	η^2=.105
	low	111	0.449	0.931		
Verbal Reasoning	high	78	-0.614	0.930	**38.798**	<0.001* *(<0.014))*
	medium	115	-0.040	0.990	(2, 301)	η^2=.205
	low	111	0.531	0.722		

Note. * significance at the B-H adjusted level *critical q values provided for the p values.*

Tukey's post hoc pairwise comparisons tests are provided in Table 4.12.

Table 4.12
Pairwise comparisons between dyslexia risk levels

			Mean difference	*p*	95% CI Lower bound	95% CI Upper bound
VM/PS	high	medium	**-0.523**	<0.001*	-0.795	-0.251
		low	**-1.469**	<0.001*	-1.743	-1.194
	medium	low	**-0.945**	<0.001*	-1.188	-0.702
DS	high	medium	**-0.611**	<0.001*	-0.950	-0.271
		low	**-1.259**	<0.001*	-1.600	-0.917
	medium	low	**-0.648**	<0.001*	-0.951	-0.345
ASM	high	medium	**-0.902**	<0.001*	-1.156	-0.648
		low	**-1.756**	<0.001*	-2.012	-1.500
	medium	low	**-0.853**	<0.001*	-1.080	-0.626
RAN	high	medium	**0.513**	<0.001*	0.216	0.811
		low	**0.646**	<0.001*	0.347	0.946
	medium	low	0.133	0.470	-0.133	0.398
BT	high	medium	-0.390	0.018	-0.745	-0.036
		low	**-0.428**	0.013*	-0.785	-0.071
	medium	low	-0.038	0.983	-0.354	0.279
PP	high	medium	**-0.739**	<0.001*	-0.964	-0.515
		low	**-1.365**	<0.001*	-1.592	-1.139
	medium	low	**-0.626**	<0.001*	-0.827	-0.426
BD	high	medium	-0.313	0.117	-0.673	0.046
		low	**-1.016**	<0.001*	-1.377	-0.654
	medium	low	**-0.702**	<0.001*	-1.023	-0.382
MR	high	medium	-0.257	0.168	-0.601	0.090
		low	**-0.858**	<0.001*	-1.206	-0.510
	medium	low	**-0.603**	<0.001*	-0.911	-0.294
VR	high	medium	**-0.574**	<0.001*	-0.880	-0.268

	low	**-1.145**	<0.001*	-1.453	-0.837
medium	low	**-0.571**	<0.001*	-0.848	-0.294

Note. * significant at .016 level; PP = Phonological Processing; ASM = Auditory Sequential Memory; VM/PC = Visual Memory/Phonic Skill; BD = Block design; MR = Matrix Reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning.

Pairwise comparisons revealed the following:

- Pupils at high risk of dyslexia had significantly lower scores on Auditory Sequential Memory, Visual Memory/Phonic Skills, verbal reasoning, Phonological Processing, and Digit Span significantly differed between all dyslexia risk groups (all *p*s < .001).
- Children at high risk also had significantly lower scores on Matrix Reasoning than pupils at low risk ($p < .001$), but no difference was found between high and medium risk children ($p = .168$).
- Performance on the Block Design task did not distinguish between children at high and medium risk of dyslexia ($p = .117$). Performance on this task significantly differed between high and low risk ($p < .001$) and between medium and low ($p < .001$).
- The scores on the Bead Threading and RAN tasks could not distinguish between children at medium and low risk of dyslexia ($p = .983$, $p = .470$ respectively). Bead Threading scores also could not distinguish between high and medium risk groups ($p = .018$ with significance at .016 level).

The effects of group in most of the dyslexia screening tests remained statistically significant after controlling for verbal reasoning (Phonological processing: $F(2, 295) = 59.090$; $p < .001$; η^2=.286; Digit span: $F(2, 299) = 25.396$; $p < .001$; η^2=.145; RAN: $F(2, 290) = 7.778$; $p = .001$; η^2=.051; Auditory Sequential Memory: $F(2, 300) = 83.007$; $p < .001$; η^2=.356; Visual Memory/Phonic Skill: $F(2, 300) = 61.854$; $p < .001$; $\eta^2 = .292$). Only the effect of group on the Bead Threading performance ($F(2, 298) = 2.712$; $p = .068$) disappeared after controlling for verbal reasoning.

4.3.5 Relationships between the Dot-to-Dot task measures, dyslexia indicators and reasoning abilities

In order to establish what skills and abilities are associated with the DtD task, correlational analysis was conducted. Spearman correlations were conducted due to non-normal distributions of the scores as tested by investigating skewness and kurtosis. Of those statistically significant correlations, all were weak ($r < .5$). Tables 4.13 and 4.14 present correlations between the DtD measures, dyslexia screening and reasoning measure.

Table 4.13

Spearman correlations between the DtD measures for dominant hand, dyslexia indicators and reasoning skills

DH DtD	Phon. processing[a]	Phonic skills[a]	Visual memory[a]	Bead Thread.[b]	RAN[b]	Digit Span	Aud. seq. memory[a]	Verbal reasoning	Matrix reasoning	Block design
Time	-.044 (N=333)	-.026 (N=105)	**-.243* (N=214)**	-.104 (N=359)	.067 (N=347)	.033 (N=355)	-.071 (N=343)	-.007 (N=353)	-.067 (N=360)	-.118 (N=360)
First sector max error	**-.186* (N=333)**	-.149 (N=105)	**-.179* (N=214)**	-.080 (N=359)	.109 (N=347)	-.094 (N=355)	**-.169* (N=343)**	**-.190* (N=353)**	**-.311* (N=360)**	**-.223* (N=360)**
Total error	**-.127* (N=333)**	**-.265* (N=105)**	**-.196* (N=214)**	**-.153* (N=359)**	**.165* (N=347)**	**-.126* (N=355)**	**-.177* (N=343)**	-.115 (N=353)	**-.269* (N=360)**	**-.228* (N=360)**
SD 2	-.090 (N=333)	**-.235* (N=105)**	**-.253* (N=214)**	-.119 (N=359)	.117 (N=347)	**-.203* (N=355)**	**-.159* (N=343)**	-.067 (N=353)	**-.134* (N=360)**	**-.180* (N=360)**
Time Total	-.122 (N=333)	-.235 (N=105)	**-.277* (N=214)**	**-.151* (N=359)**	**.144* (N=347)**	-.067 (N=355)	**-.164* (N=343)**	-.084 (N=353)	**-.220* (N=360)**	**-.251* (N=360)**
Direction Ratio	**.136* (N=333)**	**.337* (N=105)**	.121 (N=214)	.069 (N=360)	-.079 (N=348)	**.131* (N=356)**	.116 (N=343)	.115 (N=354)	.065 (N=361)	**.146* (N=361)**
FirstDown First sector max. err.	**-.154* (N=333)**	**-.235* (N=105)**	-.126 (N=214)	-.075 (N=359)	.116 (N=347)	-.114 (N=355)	**-.148* (N=343)**	**-.150* (N=353)**	**-.304* (N=360)**	**-.244* (N=360)**
FirstDown Direction ratio	.043 (N=324)	**.332* (N=98)**	.125 (N=212)	.035 (N=350)	-.110 (N=338)	.091 (N=346)	.045 (N=334)	.038 (N=344)	.063 (N=351)	.069 (N=351)
FirstUp First sector max. err.	**-.163* (N=333)**	-.038 (N=105)	**-.174* (N=214)**	-.057 (N=359)	.098 (N=347)	-.052 (N=355)	**-.127* (N=343)**	**-.131* (N=353)**	**-.181* (N=360)**	-.086 (N=360)
FirstUp Direction ratio	.112 (N=221)	.036 (N=73)	.024 (N=141)	.047 (N=240)	.059 (N=232)	.034 (N=236)	.085 (N=229)	.048 (N=235)	.090 (N=239)	**.182* (N=239)**

Note. Number of partcipants in brackets; * significance at the B-H adjusted level [a]derived from Lucid Rapid screening tool;.[b] subtests derived from DEST-2 or DST-J.

Table 4.14

Spearman correlations between the DtD measures for non-dominant hand, dyslexia indicators and reasoning skills

NDH DtD	Phon. processing[a]	Phonic skills[a]	Visual memory[a]	Bead Thread.[b]	RAN[b]	Digit span[b]	Aud. seq. memory[a]	Verbal reasoning	Matrix reasoning	Block design
Time	-.085 (N=265)	-.102 (N=104)	**-.255*** **(N=163)**	-.054 (N=279)	.095 (N=272)	-.044 (N=279)	**-.169*** **(N=275)**	-.082 (N=276)	-.108 (N=280)	-.011 (N=280)
First sector max error	-.106 (N=265)	-.116 (N=104)	-.063 (N=163)	-.082 (N=279)	**.167*** **(N=272)**	**-.145*** **(N=279)**	-.130 (N=275)	**-.209*** **(N=276)**	**-.297*** **(N=280)**	**-.185*** **(N=280)**
Total error	-.096 (N=265)	-.027 (N=104)	-.074 (N=163)	-.134 (N=279)	.095 (N=272)	-.053 (N=279)	-.085 (N=275)	**-.181*** **(N=276)**	**-.250*** **(N=280)**	**-.157*** **(N=280)**
SD 2	-.113 (N=265)	.092 (N=104)	**-.203*** **(N=163)**	-.054 (N=279)	.103 (N=272)	**-.212*** **(N=279)**	-.120 (N=275)	-.053 (N=276)	**-.175*** **(N=280)**	-.126 (N=280)
Time Total	-.100 (N=265)	-.059 (N=104)	**-.206*** **(N=163)**	-.134 (N=279)	.123 (N=272)	-.054 (N=279)	**-.162*** **(N=275)**	**-.148*** **(N=276)**	**-.213*** **(N=280)**	-.114 (N=280)
Direction Ratio	.109 (N=265)	.178 (N=104)	.048 (N=163)	-.035 (N=279)	-.044 (N=272)	.118 (N=279)	.069 (N=275)	.091 (N=276)	.065 (N=280)	.103 (N=280)
FirstDown First sector max. err.	-.070 (N=267)	-.148 (N=105)	-.091 (N=163)	-.046 (N=284)	**.207*** **(N=277)**	-.125 (N=284)	-.130 (N=277)	**-.194*** **(N=281)**	**-.278*** **(N=285)**	**-.167*** **(N=285)**
FirstDown Direction ratio	.065 (N=258)	.093 (N=101)	**.189*** **(N=160)**	.038 (N=272)	-.088 (N=265)	**.156*** **(N=272)**	.100 (N=269)	.075 (N=269)	**.211*** **(N=273)**	.117 (N=273)
FirstUp First sector max. err.	-.118 (N=265)	.000 (N=104)	-.065 (N=163)	-.057 (N=279)	-.089 (N=272)	-.108 (N=279)	-.135 (N=275)	**-.201*** **(N=276)**	**-.238*** **(N=280)**	-.153* (N=280)
FirstUp Direction ratio	0.062 (N=227)	**.292*** **(N=88)**	.028 (N=137)	-.096 (N=239)	-.018 (N=233)	.028 (N=239)	.111 (N=233)	.046 (N=236)	-.011 (N=240)	.064 (N=240)

Note. Number of partcipants in brackets; * significance at the B-H adjusted level [a]derived from Lucid Rapid screening tool;.[b] subtests derived from DEST-2 or DST-J.

The strongest correlations were found between two DtD measures: FSME and FirstDown FSME for dominant hand and matrix reasoning (r_s = -.311; r_s = -.304 respectively) explaining 10% to 9% of the shared variance. In terms of the correlations between the DtD task and dyslexia-sensitive measures, the FirstDown FSME significantly correlated with RAN.

Table 4.15 presents intercorrelations between dyslexia sensitive and reasoning measures with the adjusted significance values. The strongest correlations were found between the phonological processing and auditory sequencing memory (.531) and verbal reasoning (.507).

Table 4.15
Spearman correlations between dyslexia sensitive and reasoning measures

	VM/PS	DS	RAN	BT	PP	BD	MR	VR
ASM	**.473*** (N=342)	**.503*** (N=362)	**-.259*** (N=356)	**.223*** (N=366)	**.531*** (N=344)	**.303*** (N=368)	**.298*** (N=368)	**.452*** (N=361)
VM/PS		**.393*** (N=331)	**-.256*** (N=324)	.109 (N=333)	**.389*** (N=312)	**.364*** (N=335)	**.236*** (N=335)	**.284*** (N=330)
DS			**-.255*** (N=384)	.089 (N=395)	**.438*** (N=358)	**.279*** (N=397)	**.287*** (N=397)	**.264*** (N=392)
RAN				**-.122*** (N=389)	**-.314*** (N=353)	-.079 (N=388)	**-.158*** (N=388)	**-.200*** (N=383)
BT					**.143*** (N=361)	**.157*** (N=402)	**.128*** (N=402)	**.127*** (N=395)
PP						**.339*** (N=362)	**.340*** (N=362)	**.507*** (N=359)
BD							**.389*** (N=407)	**.329*** (N=398)
MR								**.265*** (N=398)

Note. Number of partcipants in brackets; * significance at the B-H adjusted level; PP = Phonological Processing; ASM = Auditory Sequencial Memory VM/PS = Visual Memory/Phonic Skills; BD = Block design; MR = Matrix Reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning.

A cross-correlation of selected DtD measures (DH FirstUp FSME & FirstUp DR as only these could distinguish between low and high risk children) and dyslexia sensitive and reasoning variables is illustrated in Figure 4.3.

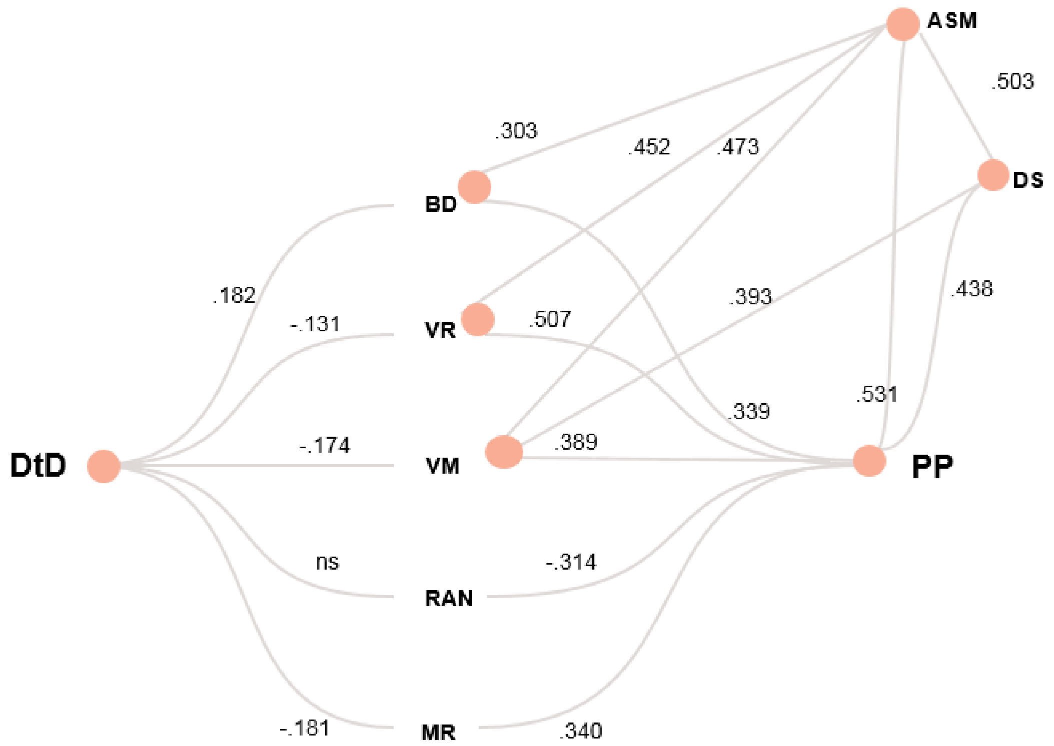

Figure 4.3 Cross-correlations between the DtD measures (only the ones that could distinguish between low and high risk children: FirstUp FSME & FirstUp DR; both for dominant hand), dyslexia sensitive and reasoning measures. DtD = Dot-to-Dot; PP = Phonological Processing; ASM = Auditory Sequential Memory; VM/PS = Visual Memory/Phonic Skills; BD = Block design; MR = Matrix Reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning.

An additional set of correlations was conducted to explore any mediation effect of verbal reasoning (VR). Table 4.16 presents selected partial correlations after controlling for the VR measure.

Table 4.16
Selected partial correlations controlling for Verbal Reasoning (VR)

	NDH FirstDown FSME	Phonological processing	Auditory Sequential Memory	Visual Memory/Phonic Skills	Digit Span
RAN	.151	**-.372***	**-.255***	**-.342***	**-.272***
	(N=113)	(N=134)	(N=135)	(N=135)	(N=135)
NDH FirstDown First sector max. error		.018	.071	.015	-.054
		(N=113)	(N=114)	(N=114)	(N=114)
Phonological processing			**.523***	**.481***	**.444***
			(N=137)	(N=137)	(N=137)
Auditory Sequential Memory				**.485***	**.423***
				(N=140)	(N=139)
Visual Memory/Phonic Skills					**.334***
					(N=139)

Note. Number of participants in brackets; * significant at the level of q value (H-B procedure used). NDH FirstDown FSME= first sector maximum error for pattern with the first dot located below the starting point, non-dominant hand.

The previously found statistically significant correlation between one of the DtD measures (NDH FirstDown First sector max. error) and RAN was no longer significant after controlling for VR (p = .106). The remaining correlations presented in the table were not affected by VR.

4.3.6 Risk of dyslexia between different schools

As shown before (section 4.3.3), significantly more children were being flagged as ‘high’ risk of dyslexia at one school than the others. Therefore, it was decided to look at the performance of children across the schools in more detail.

A number of univariate analyses of variance was run to determine if children attending different schools performed differently on dyslexia-sensitive measures (DS, RAN, BT, PP, ASM, VM/PS), reasoning (BD, MR, VC), and the two DtD measures that appeared to best distinguish between children at low and high risk of dyslexia (FirstUp first sector max. err. and FirstUp direction ratio; both for dominant hand). Exploration of data showed some normality violations but there were no differences in results between the ANOVAs and a non-parametric equivalent

(Kruskal-Wallis H) test. B-H correction was used. Results are provided in Table 4.17.

Table 4.17
Differences in performance on dyslexia sensitive and reasoning tests among schools

	School	*N*	*M*	*SD*	*F(df)*	*p; η²*
Phonological Processing	1	133	-0.252	0.920	**29.144**	<0.001*
	2	88	-0.146	0.677	(2, 359)	η^2=.140
	3	141	0.428	0.713		
Digit Span	1	141	-0.215	1.134	**11.180**	<0.001*;
	2	102	-0.138	0.790	(2, 394)	η^2=.054
	3	154	0.287	0.924		
Random Automatised Naming	1	141	-0.185	1.099	**4.589**	0.011*;
	2	96	-0.008	0.835	(2, 387)	η^2=.023
	3	153	-0.165	0.972		
Bead Threading	1	146	-0.338	0.854	**15.192**	<0.001*;
	2	101	0.077	1.098	(2, 401)	η^2=.070
	3	157	0.265	0.972		
Auditory Sequential Memory	1	145	-0.325	0.870	**28.790**	<0.001*;
	2	96	-0.199	0.933	(2, 379)	η^2=.132
	3	141	0.469	0.994		
Visual Memory/Phonic Skill	1	142	-0.231	0.952	**12.921**	<0.001*;
	2	90	0.106	0.949	(2, 345)	η^2=.070
	3	116	0.366	0.996		
Block Design	1	145	-0.302	0.936	**12.771**	<0.001*;
	2	102	0.021	0.961	(2, 404)	η^2=.059
	3	160	0.260	1.008		
Matrix Reasoning	1	145	-0.145	1.151	**6.095**	0.002*;
	2	102	-0.127	0.865	(2, 404)	η^2=.029
	3	160	0.212	0.893		
Verbal Reasoning	1	143	-0.389	0.957	**22.810**	<0.001*;
	2	99	0.006	0.957	(2, 395)	η^2=.104
	3	156	0.353	0.934		
DH FirstUp First sector max. err.	1	140	0.148	0.993	1.985	.139
	2	99	0.107	1.173	(2, 366)	
	3	130	-0.083	0.840		
DH FirstUp Direction ratio	1	98	-0.024	1.036	.135	.874
	2	70	0.009	1.004	(2, 244)	
	3	79	0.055	0.956		

Note. * significance at the B-H adjusted level.

All of dyslexia screening and reasoning measures showed significant main effects of school, but performance on the two DtD measures did not. Tukey's post hoc tests were conducted to investigate pairwise differences (see Table 4.18).

Table 4.18
Post hoc pairwise comparisons among the three schools

			Mean difference	*p*	95% CI Lower bound	Upper bound
Visual Memory/ Phonic Skill	1	2	-0.125	0.601	-0.620	0.088
		3	**-0.597**	<0.001*	-0.971	-0.289
	2	3	**-0.471**	0.002*	-0.741	0.014
Digit span	1	2	-0.077	0.814	-0.496	0.302
		3	**-0.503**	<0.001*	-1.174	-0.404
	2	3	**-0.426**	0.002*	-1.118	-0.266
Auditory Sequential Memory	1	2	-0.126	0.561	-0.527	0.161
		3	**-0.794**	<0.001*	-1.090	-0.430
	2	3	**-0.668**	0.001*	-0.943	-0.211
Random Automatised Naming	1	2	0.193	0.306	-0.208	0.350
		3	**0.350**	0.007*	0.039	0.576
	2	3	0.157	0.442	-0.061	0.534
Bead Threading	1	2	**-0.416**	0.003*	-0.866	-0.131
		3	**-0.603**	<0.001*	-0.984	-0.276
	2	3	-0.187	0.281	-0.523	0.261
Phonological Processing	1	2	-0.106	.587	-0.462	0.103
		3	**-0.681**	<0.001*	-0.827	-0.282
	2	3	**-0.575**	<0.001*	-0.676	-0.073
Block design	1	2	-0.323	0.028	-0.819	0.002
		3	**-0.562**	<0.001*	-1.259	-0.469
	2	3	-0.234	0.129	-0.893	-0.018
Matrix Reasoning	1	2	-0.018	0.989	-0.400	0.363
		3	**-0.357**	0.005*	-0.892	-0.157
	2	3	-0.339	0.019	-0.912	-0.099
Verbal Reasoning	1	2	**-0.394**	0.005*	-0.787	-0.090
		3	**-0.741**	<0.001*	-0.945	-0.274
	2	3	**-0.347**	0.013*	-0.543	0.201

Note. * significant at the 0.16 level (0.05/3)

Pairwise comparisons showed the following:

- There were significant differences in the performance of children in school 1 in comparison to school 3, and between schools 2 and 3 in phonological processing, visual memory/phonic skills, auditory sequential memory and digit span
- Verbal reasoning could distinguish between all three schools. Children in school 1 (low SES) showed poorer performance than those in school 2 (medium SES) and 3 (high SES); children in school 2 were outperformed by children in school 3.
- Children in school 1 were outperformed by children in school 2 and 3 in the bead threading task.
- Children in school 3 outperformed school 1 children in RAN, block design and matrix reasoning tasks.

4.3.7 Effects of gender

A Chi-square test for association was conducted between gender and dyslexia risk. All expected cell frequencies were greater than five. There were no statistically significant associations between gender and dyslexia risk $\chi^2(2) = 1.377$, $p = .502$. Table 4.19 presents the observed and expected counts of individuals within each of dyslexia risk and gender category.

Table 4.19

Observed and expected counts for dyslexia risk and gender

		gender		
DD risk		Female	male	Total
high	observed	46	40	86
	expected	41.4	44.6	
medium	observed	54	64	118
	expected	56.8	61.2	
low	observed	53	61	114
	expected	54.8	59.2	
Total		153	165	318

4.4 Discussion

The present study aimed to investigate whether the DtD task could reliably differentiate children at different levels of dyslexia risk, estimated using a commercially-available computer software tool (Lucid-Rapid). It also aimed to find out whether performance on the DtD task would be significantly associated with any skills known to be compromised in individuals with dyslexia. Previous anecdotal and pilot studies (see Chapter 3) showed that this task could be possibly used to help identify children at risk of dyslexia. The current study undertook a cross-sectional perspective on addressing these questions in primary-aged children across three socioeconomic backgrounds. Key findings are discussed now in turn.

4.4.1 The Dot-to-Dot Task – key findings

The key findings of this study were that children deemed at high risk of dyslexia, as estimated by Lucid Rapid screening tool, performed significantly worse on the DtD task when they were drawing the FirstUp pattern with their dominant hand supporting the first hypothesis regarding the risk group differences. These children made greater maximum errors in the first sector of this pattern and more often drew the line in the opposite direction to the dot they were supposed to join. From the pilot study, it was already indicated that the first sector might be most informative of the children's performance and abilities. The Direction Ratio measure was added to the analyses as it was noticed that children tended to draw their lines upwards (towards the top panel where they could see the dots and lines) at the beginning of the trials. This measure also showed significant group differences.

These findings may indicate that children at high risk of dyslexia confused the direction of the first line more often than children at low risk. However, this effect disappeared after controlling for verbal reasoning, which suggests at least some of the effect could be explained by children not fully understanding the nature of the task. Further, the problem with confusing the direction was no longer noticeable when the children switched to their non-dominant hands. The non-dominant hand trials were always followed by the dominant hand; therefore, children had enough exposure to the task to understand it better. It has also been shown that the DtD task was weakly related to non-verbal reasoning, which again adds to the argument that the performance on this task is related to reasoning skills.

The Lucid rapid test that was used to identify risk of dyslexia, irrespective of its suitability, involves phonology and memory; therefore it has no obvious link with the DtD task. The DtD measures that could distinguish between children at high and low risk were also not associated with any of the established measures such as phonological processing, lexical access or memory. These findings indicate that this task cannot be conceptualised within the phonological processing deficit theory framework. Relating back to other theoretical explanations of dyslexia, the current findings suggest possible difficulties related to the cerebellar and automaticity deficit explanations of dyslexia. Attentional mechanisms may also be associated with the initiation of the drawing and could indicate attentional delay in DDs possibly related to problems with inhibition or initial difficulty dissociating hand and gaze control. As attentional mechanisms are related to the magnocellular and dorsal stream functioning, a possibility that the DtD being construed under visual deficit is also appealing. Further discussion on the theoretical framework the DtD may be understood within may be more accurate and relevant after considering the level of children's reading (as discussed in Chapter 5) and also after all of the evidence has been presented in the entire thesis – therefore a full reflection on the task and its theoretical explanations is provided in the final chapter of this thesis.

Furthermore, as the DtD task requires manipulation of a pen, arguably a skill which is similar to writing, it was expected that DtD measures signifying how accurately the lines are being drawn would be related to the Bead Threading task requiring fine motor skills. Should this relationship have existed, this would have provided support for the cerebellum deficit theory which proposes that motor control problems are an indicator of cerebellum dysfunction in individuals with dyslexia (Nicolson et al., 2001), as previously discussed in Chapter 2. However, the lack of significant correlations between the DtD measures and motor task provided a contraindication for this expectation. Considering the nature of the tasks, this finding may indicate that the DtD task may require different skills than the Bead Threading task. Perhaps what was different was the level of uncertainty in the DtD task as children would not know where the next dot would appear. Also, it could be argued that children may be more familiar with a bead threading task than with tasks on the computer, particularly with tasks utilizing a tablet. Performance on the bead threading task was, however, significantly poorer in children deemed at high risk compared to low risk children, which is consistent with the cerebellum deficit hypothesis. More recent developments of the theory suggested that a core deficit may be in motor skill acquisition which perhaps could be tested in the future by means of longitudinal DtD testing with a particular focus on the time taken to complete trials with drawing patterns well practised. It could also be argued that the Bead Threading task is purely measuring the motor skills whilst the DtD incorporates many more skills.

As mentioned above, the DtD task and its measures may also reflect the skill of writing. Research on handwriting in dyslexia demonstrated that individuals with dyslexia tend to be slower writers than those without reading problems (Sumner, Connelly, & Barnett, 2013). However, there is no clarity as to whether these differences in the speed of handwriting are due to poorer motor skills or poorer spelling (Berninger, Nielsen, & Abbott, 2008; Rose, 2009). Unlike the tasks used in these studies, the DtD task does not require participants to write actual words, therefore the impact of the ability to spell can be disregarded. The time to complete the DtD task did not differ amongst the risk groups which can be interpreted as evidence for Berninger et al.'s (2008) idea that slow writing in poor readers is related to their poor spelling, not poor motor control. Alternatively, it could be argued that the act of writing requires different abilities than joining the dots using a tablet and individuals with dyslexia should not be expected to show similar deficits. This could be further addressed in future studies.

4.4.2 Dyslexia-Sensitive and Reasoning Skills

Children deemed at high risk of dyslexia performed significantly poorer on all of the tasks associated with dyslexia (Phonological Processing, RAN, Digit Span) than their counterparts deemed at low risk. This is what would be expected on the basis of previous literature on phonological deficit of dyslexia (Snowling, 1981; Ramus, 2003; Snowling, 2000) supporting the first hypothesis. The screening test that was used to estimate the risk of dyslexia also comprised tasks in line with the phonological deficit, therefore, these results do not come as a surprise and can be treated as a confirmation that the children's performance on the established tests was corresponding to what would be expected from previous studies.

Children at high risk of dyslexia were also compromised on verbal reasoning (Similarities task) and non-verbal reasoning (Matrix Reasoning and Block Design) tests in comparison to children at medium and low risk. This indicated that the Lucid Rapid groups children into dyslexia risk categories purely basing on their phonological deficits regardless of their reasoning abilities. This test does not utilise the IQ-reading level discrepancy definition of dyslexia. In fact, the finding showing that children indicated as at high risk of dyslexia had lower reasoning abilities than those at low risk may lead one to a debate whether the screening test is specific enough to indicate dyslexia as it does not filter out those children whose reading problems in the future may be due to their low intelligence. These findings can be related back to the literature on the role of intelligence and the distinction between IQ-reading level and garden variety children, although the discussion is rather speculative at this stage as the current study did not provide an opportunity to use IQ-reading discrepancy operational definition of dyslexia; only the risk of dyslexia was estimated here (Lucid Rapid). The idea that low level intelligence could result in problems with reading has been much debated in the literature (Hoskyn &

Swanson, 2000; Stuebing et al., 2002). Some studies have shown that the main deficits of dyslexia are consistent regardless of the IQ level (Tanaka et al., 2011; Carroll et al. 2016; Siegel, 1989, 1992; Stanovich, 2005), which corresponds to current findings showing that group differences in Phonological Processing, memory and RAN remained significant after controlling for verbal reasoning.

When looking at the features of the high-risk children, their reasoning skills emerged as important factors that need to be considered in greater depth. Both of the DtD scores and dyslexia screening scores were significantly correlated, the latter even more strongly, with the reasoning measures. Conclusions drawn from these results are rather speculative for two main reasons. First, full-scale IQ was not measured in this study, so, it is difficult to comment with confidence on participants' overall intelligence. Although some studies suggest that performance on one task could be indicative of the full IQ scale (Wechsler, 1997), it would be impossible to reject the idea that some children may show better or worse performance depending on the task or skill measured. Second, the scope of the IQ tests could also be debated, as previously indicated by Siegel (1990).

Although the Block Design and Matrix Reasoning tests were designed to test non-verbal reasoning, they could also be associated with other skills, such as working/short-term memory or verbal reasoning (Block Design showed weak but statistically significant correlations with these measures) or with phonological processing (both tasks showed weak significant correlation with PP). The verbal reasoning task, in particular, may not necessarily only reflect reasoning skills, but also vocabulary knowledge. The author noticed that some children, particularly in school 1, struggled with some words (such as 'drought') and had to have their meaning explained before providing an answer. Also, some EAL children, despite having a good command of English, showed some difficulties in understanding of such words. This observation, however, was not statistically verified as a confounding variable; there was no statistically significant difference between native English speakers and non-native good English speakers in verbal reasoning performance.

This is not, however, to say that the high-risk children were of low intelligence. Firstly, the mean scores of the high risk group were -.384 (Matrix Reasoning) and -.457 (Block Design) which indicates that the scores were not lower than 1 SD below the mean score of the entire sample. Also, the distribution of non-verbal reasoning scores was normal (as assessed by skewness and kurtosis) in the high risk group which shows that children at high risk of dyslexia showed a range of reasoning abilities.

As some studies demonstrated different patterns of poor readers' difficulties based on participants' IQ levels (Ferrer et al., 2010; Morris et al., 1998; O'Brien et al., 2012), future research should incorporate the investigation of performance on the DtD task in IQ-reading discrepancy defined groups.

4.4.3 Effects of School (SES) and gender

The rates of high-risk for dyslexia at school 1 were much higher (42%) than any estimates for the general population. Also, children in school 1, which was associated with low SES, performed significantly worse on all of the dyslexia screening and reasoning measures. Performance on the DtD task, however, did not significantly differ between schools. Considerable research demonstrated that children from underprivileged environments show difficulties in a range of cognitive (Farah et al., 2006; Noble et al., 2007; Noble et al., 2005) and reading (Chaney, 2008; Whitehurst & Lonigan, 1998) skills. This, however, needs to be interpreted with caution as socioeconomic status was not directly assessed in the current study. Government statistics for the catchment areas of the schools were used to get the idea of the environment, however, the actual deprivation factors, such as income, employment, mental health or education of children's parents were not available to the researcher.

Gender was not significantly associated with risk of dyslexia which contrasts with some research (Katusic et al., 2001; Miles et al., 1998; Rutter et al., 2004) demonstrating that males are more likely to have dyslexia. The current finding, however, corresponds with Shaywitz's (1996) that did not show the effect of gender. This lack of consistency of previous research derives from different definitions of dyslexia used in these studies.

4.4.4 Limitations

It is important to consider the appropriateness of dyslexia screening tool, Lucid Rapid (Singleton, 2009), used to estimate the risk of dyslexia. First, the skills tested by this tool correspond to the phonological deficit theory (Snowling, 2000) which, as it has been discussed in Chapter 2, may not explain all of the problems that individuals with dyslexia experience. It has been shown previously that not all children who struggle with reading necessarily have problems with phonological representations (Castles & Coltheart, 1996; Ramus & Ahissar, 2012; White et al., 2006). Therefore, judging from the current findings it is not possible to suggest that DtD task could not definitely predict future reading skills as it is possible that this task may measure skills that are important for reading that are not captured by the Lucid Rapid.

The use of Lucid Rapid test was motivated by the fact that it is a standardised test for dyslexia and as it does not require specialist training, it is fairly easy to use. However, it is crucial to recognise that professional dyslexia diagnoses were not obtained in the current study. In the current sample of children, 28.8% of children were flagged as at risk of dyslexia, 36% were indicated as at medium risk and 35.2% as at low risk according to Lucid Rapid. The proportion of high-risk cases in this sample appears considerably higher than most estimates of dyslexia prevalence, which typically range from 4% to 20% (Coles, 1998; Flannery et al., 2000; Maughan & Carroll, 2006; Pastor & Reuben, 2008; Shaywitz, 1996). The reported levels of sensitivity and specificity of the Lucid Rapid test were 82% and 46% respectively (Brookes et al., 2011). It would, therefore, have to be verified whether children indicated as at high risk would actually struggle with reading. This could be remedied through professional assessment, or through a prospective follow up, which will be presented later in the thesis.

In addition, almost 27% of the sample did not complete all of the tasks required to estimate dyslexia risk. In contrast, only nine per cent of children did not complete full set of DtD trials on the dominant hand. In terms of the non-dominant hand, the percentage of incomplete sets was the same as with Lucid Rapid (27%). It is hard to compare these rates of missing data to those in literature as most studies do not report such rates. To the author's knowledge there are no studies that used Lucid Rapid that have discussed this issue. Although the missing data analysis did not reveal any consistent patterns in missing data, such a high proportion of children not willing to complete given tests was worrying and could have impacted on the results as one can assume that if children struggle with certain tasks they would not be willing to complete them. Furthermore, the author's observations indicated that one of the usability issues of the Lucid Rapid tool is that some of the tasks cannot be paused which creates issues when a child loses interest and needs a break. There are implications for the professional practice of the high missing rates and usability issues. If children cannot keep attention during the professional diagnostic tests, they might be incorrectly classified. If that is the case, it is a further justification for an engaging and short task, like the DtD.

The current study also provided an investigation of the relationships between the new measures obtained from the DtD task and the established dyslexia indicators in the cross section of children. Although, this statistical analysis provided interesting results, it can be argued that the patterns of the relationships may be different in good readers in comparison to poor readers. As currently the correlations were conducted in the entire sample, there is a strong suspicion that any patterns that would have been revealed in poor readers would be overshadowed by the remaining of the sample since the prevalence of dyslexia is relatively low. Therefore it is crucial in a further study, once an estimation of children's reading level is available, to revisit the correlational analysis and investigate the relationships separately for the poorly reading and well reading children.

4.5 Conclusion

The current study demonstrate that high risk children appear significantly over-represented in the lowest SES school and that this group of children appear to do significantly worse, on average, across almost all tasks given to them (phonological, memory, reasoning) compared with the low risk counterparts. Of particular importance to the investigation of the new DtD test was the finding that two of its measures could significantly distinguish between children at low and high risk. The task seemed to be mostly related to reasoning measures rather than those tasks that are associated with phonological representations.

The current findings, however, need to be interpreted with caution due to a number of limitations already discussed. This study does not provide sufficient evidence for rejecting the idea that the DtD task could be a useful addition to dyslexia screening assessment. At this point, the risk of dyslexia was assessed using one screening test that focuses primarily on phonological processing which is, in the light of previous findings within the field, only one of the possible manifestations of dyslexia. Particularly encouraging findings were that children's performance on the DtD task did not differ depending on which school they went to or whether they had English as a native tongue which may mean that the DtD task will not be sensitive to problematic variables such as language and SES. The following chapter will further explore the usefulness of the DtD task by implementing a prospective investigation of children's reading abilities after one, two or three years, using regression and other multivariate analyses. This research will allow to identify poor and typical readers and verify whether the children identified as at risk of dyslexia in the present study became poor readers.

Chapter 5

Can children’s performance on the DtD task, dyslexia screening and cognitive tasks predict reading? A prospective investigation.

Abstract

The current study offers a prospective investigation of children’s performance at the baseline measures (as was explored in the previous chapter) in relation to their currently assessed level of reading using Speeded and Nonsense reading tests from DST-J. The study investigated whether performance on the DtD task can feasibly help in indicating children at risk of dyslexia on its own as well as together with other, already well-established measures. Casewise analysis was also utilised in order to explore areas of weaknesses in poor readers. Fifty-two percent of the children tested at the baseline were followed up (N = 240; mean age = 9 years; SD = 1.9, 49% F). The key finding are: (i) DtD measures related to the first sector performance and speed-accuracy trade-off together explained 8% of variance in reading scores; (ii) in addition to phonology, DtD first sector provided a useful prospective prediction of which school children are likely to have reading problems at a later age; (iii) in a sample of pre-readers only phonological processing and DtD total error could significantly predict later reading scores; (iv) a number of DtD measures could distinguish between poor and typical readers. The findings are consistent with the automatisation deficit framework and in general with a developmental delay framework. Furthermore, case wise analyses revealed that only 16% of poor readers display deficits in one area which is in line with multiple deficit model. There is therefore no one single test that could reliably indicate the risk of dyslexia and multiple tests, with DtD being a useful addition, are necessary for accurate identification. Additionally, the impact of children’s socioeconomic status and the operational definition applied to indicating poor readers need also be taken into account. Further research should explore the level of visual processing involved in the DtD task in line with the magnocellular/dorsal stream deficit theory.

5.1 Introduction

The focus of this chapter is on the prospective investigation of various aspects of developmental dyslexia in primary-aged children across three schools located within different socioeconomic backgrounds. The cross-sectional investigation discussed in the previous chapter acted as a baseline to the current investigation, which provided an opportunity to verify the risk estimates. Children tested at baseline in the previous chapter were followed up either after one, two or three years with reading tests, in order to evaluate which of the many possible factors best predicted future reading performance.

The current study aimed to investigate whether the DtD task, established dyslexia screening tests and reasoning tests can distinguish between children identified as poor and typical readers. The study will further examine whether these tests, along with which school the children attended, will be able to predict reading ability (measured with the nonsense passage and speeded reading tasks derived from DST-J) and group membership (poor vs typical readers) after one, two or three years. Further, the current investigation will allow the specificity and sensitivity levels of the established screeners and the DtD measures to be explored.

The previous study demonstrated that some of the DtD measures correlated weakly with reasoning, rapid naming, visual memory and phonic skills. However, as no clear pattern as to the abilities required for good DtD performance was discovered, no reduction in the number of DtD measures could be determined, and therefore all of the measures that the DtD software generated are also used within the current chapter to examine the relationships and the magnitude of the shared variance of the DtD measures and reading measures.

Furthermore, due to the inconsistencies found within the broader literature as to the operational definition of developmental dyslexia, the current research incorporated three such definitions to explore how the pattern of results, the weaknesses poor readers experience, would differ depending on the definition. To operationally define reading difficulty, different cut-off points in reading tests were incorporated. Previous studies used various cut-off points from 1SD up to 2SD below the sample mean, but no study to date investigated within one sample how these cut-off points impact the results. IQ-reading level discrepancy definition was not used as full IQ was not measured; however, the role of reasoning was investigated throughout. On the basis of some definitions used in the literature children whose intelligence was below average were excluded. Such an approach was not adopted here as it could create an artificial, not representative group of readers (Fey, Long, & Cleave, 1994). Such an approach is particularly problematic as upper limit tends not to be set on the IQ scores which in consequence can skew data. Furthermore, research suggests that reading deficits occur across a range of reasoning abilities (Stanovich, 2005; Tanaka et al., 2011) which provides a further argument for using the whole sample, regardless of their reasoning abilities, for the analysis.

The study also aimed to look at a broader picture of developmental dyslexia and it endeavoured to add to the theoretical debate on the multiple manifestations of dyslexia (Pennington, 2006) in children by investigating any potential patterns of weaknesses that poor readers may show. This is important as an investigation if any of the deficits are universal, that is present in all children, could add to our understanding of the causes of reading difficulties. Furthermore, examining group differences by looking at average deficit across a group may conceal individual differences in patterns of the deficit (Carroll et al., 2016). For instance, if only half of the poorly reading group display a deficit in a particular area, it is likely that this area will show a group level deficit despite it not being able to explain reading problems in the other half of children. Therefore, some researchers advocate the use of multiple case study approaches (Ramus, 2003; White et al., 2006).

One way to examine possible causal explanations is to use a prospective study design to assess the deficits that were present in poor readers before they began reading instruction. Cross-section studies, such as the one presented in Chapter 4, are mainly correlational and cannot help in addressing issues of causality. Furthermore, evidence for the most established phonological deficit comes from a range of experimental designs, including longitudinal and intervention studies: however, evidence for other deficits in dyslexia tends to come from group difference studies in which diagnosed dyslexics are compared to typical controls. These studies do not allow assessment of whether a given deficit plays a causal role in a disorder and of what proportion of dyslexic children show the deficit (Carroll et al., 2016).

Looking at a subsample of pre-reading children and exploring which baseline measures could predict reading difficulty is therefore crucial in examining the causes of dyslexia and the possibility of early risk assessment. Additionally, analyzing the differences in performance on baseline measures between reading-level matched children is critical to our understanding of dyslexia, as children indicated as at risk should be given early support and targeted intervention to minimise a negative cycle of achievement (Stanovich, 1986), as discussed in Chapter 2.

5.1.1 Research questions and hypotheses

The current chapter will examine the following research questions and aim to test the following hypotheses:

(1) Will baseline measures (DtD task, dyslexia screening tests and reasoning measures) be correlated with reading ability in children? Based on previous literature, tasks measuring phonological processing, short-term/working memory, random automatised naming (e.g., Snowling, 2000) and reasoning skills (Wechsler, 2013) are expected to correlate with the reading ability. As the DtD tests showed some potential in indicating children at risk of dyslexia in the pilot and previous studies, its measures are hypothesised to correlate with reading too.

(2) How effectively do the baseline measures which significantly correlated with reading predict children's reading abilities? It was hypothesised that the established dyslexia-sensitive, reasoning and DtD measures would predict reading. Further, would different measures be more indicative of poor reading in pre-reading children (nursery and beginning of P1) than in the full sample overall?

(3) How effectively do the measures that can statistically distinguish between poor and typical readers predict which children will become poor readers and which will be typical readers? The sensitivity and specificity of the set of best predictors will be assessed.

(4) How well does the Lucid-Rapid dyslexia screening test predict later reading group membership (poor vs typical)?

(5) Is there evidence for multiple deficits in reading disorder, or is there one common deficit? What proportion of children shows weaknesses in each area? Previous studies have suggested a multifaceted deficit in dyslexia (Pennington, 2006, Carroll et al. 2016), however, no study to date has assessed whether different cut-off points would impact the pattern of weaknesses.

(6) The findings within the previous study (Chapter 4) showed significant differences in all of the dyslexia screening and reasoning tests among the schools children went to. Will the differences among schools remain significant in children who became poor or typical readers as assessed after one, two or three years of formal education? Significant differences were hypothesised.

(7) As no significant associations between gender and dyslexia risk were found in the previous study, a significant association between gender and reading level group is not expected to be found in the current study.

5.2 Methods

5.2.1 Design

Children were followed up with two reading tasks (Speeded Reading and Nonsense-passage Reading tasks) one, two or three years after the baseline tests were conducted (see Chapter 3 for a detailed description of all of the baseline tests). The research used a between-subjects, quasi-experimental design with the reading level group as a grouping (independent) variable with two conditions (poor and typical readers). Classification of the children into the two groups was based on their scores on reading tests. Children were classified as poor readers when their reading scores were below 1SD, 1.5SD or 2 SD below the sample mean. The dependent variables were the participants' performance on a range of tasks outlined in the Materials section. Multiple and logistic regression analyses were conducted to see which of the dyslexia screening tests, DtD and reasoning measures could predict the performance on reading tests.

5.2.2 Participants

Of the 457 children who were tested at baseline (see Chapter 4), 52% (*n* = 240) took part in one of the follow-up assessments (mean age = 9.00 years; *SD* = 1.9, 49% F). Out of this sample, 48% (*n* = 116; 54% F) of children were followed up after one year, 23% (*n* = 56; 41% F) after two years and 28% (*n* = 68; 44% F) after three years. Table 5.1 provides children's ages at the baseline and their age at follow-up. The time difference between the baseline and the follow-up measures was due to time constraints and access to schools.

Table 5.1
Description of mean ages at the baseline and at the follow-up in years (SDs).

		Follow up **either** after[a]		
School year	Baseline	one year	two years	three years
Nursery	4.7 (0.33)			7.2 (0.58)
N	23			17
P1	5.2 (0.38)	6.6 (0.43)	7.2 (0.46)	8.2 (0.43)
N	235	70	29	26
P3	7.8 (0.40)	8.10 (0.28)	9.6 (0.36)	10.1 (0.73)
N	86	23	10	25
P5	9.7 (0.33)	10.8 (0.33)	11.4 (0.23)	
N	88	23	17	
Total N	432	116	56	68

Note. Values in parentheses are standard deviations. [a] Children were followed up only once, either after one, two or three years. The follow-up groups are separate groups of children derived from the original baseline group.

To assess whether these 240 children differed from the original sample of 432, paired samples t-tests were conducted comparing the two groups on the tests administered in phase one (baseline). There were no significant differences on any of the measures (see Appendix B, tables B-5 and B-6).

No significant differences were found on any of the tasks between the original and the followed-up sample. The subsample of the children who were followed up can, therefore, be considered broadly representative of the full sample initially tested.

5.2.3 Materials

Details of all of the measures used in the baseline and in the follow-up studies, together with the test batteries that they were derived from are summarized in Chapter 3.

Reading difficulty was operationally defined as reading performance on Speeded and Nonsense-passage reading tasks (both tasks' scores normalized and then averaged), falling below 1 (def. 1), 1.5 (def. 2) and 2 (def. 3) standard deviations below the sample mean.

5.2.4 Procedure

All data collection took place at the children's schools. Similarly to the previous study, children's parents were informed of the follow-up study and provided with an option to opt their child out of the research. Children were approached in their classroom and informed verbally about the aim and the procedure of the study in age-appropriate terms. Children were assured that they did not have to participate and they could stop at any time without giving a reason. Children were tested individually over one session lasting approximately 10 minutes. Some of the children (71%) were also asked to complete psychophysical tests during this session (see Chapter 6).

5.3 Results

First, the focus is on the investigation of regression analyses in order to investigate which baseline measures uniquely contribute to a reading prediction model. As there were many DtD measures available, correlational analyses were first conducted to aid the selection of appropriate measures that should be included in the multiple regression analysis. Only the variables showing a significant linear relationship with the overall reading score (the outcome variable) were included in the analysis. Similarly, in order to assure that only relevant measures are included into the binary logistic regression, tests of differences were first conducted to establish which measures were able to significantly distinguish between the two groups of readers: poor vs typical and thus to indicate the appropriate measures to be included in the model.

5.3.1 Data treatment

There were no missing data for the follow-up tests; all participants completed the tasks. However, as pointed out earlier, there were some missing data at the baseline and they were missing at random (see section 4.3.1.1 for details). Consistent with procedures outlined in Chapter 4, incomplete DtD trials were disregarded, phonological processing tests derived from Lucid-Rapid and DEST-2/DST-J were combined, and non-native poor English speakers were excluded from the current analyses.

5.3.2 Descriptive statistics

Table 5.2 presents means and standard deviations of the age-residualized scores (in months) for the speeded reading (SR) and nonsense reading (NR) tests.

Table 5.2
Descriptive statistics for reading tests

	N	Minimum	Maximum	Mean	SD
Nonsense reading	240	-2.830	1.396	0.000	0.998
Speeded reading	240	-3.048	2.435	0.000	0.998
Reading total	240	-2.635	1.906	0.000	0.998

5.3.3 Prediction of reading based on baseline measures

The two reading tests' scores (NR and SR) were first residualised for age in months and then combined and averaged to create an "overall" reading score used in the following analyses.

To investigate which of the baseline measures best predicted reading performance, a multiple regression was considered as a suitable statistical test. A core assumption of regression analyses is that the outcome variable needs to show a linear relationship with the predictors. Therefore, correlational analyses were conducted to identify which of the dyslexia screening, reasoning, and DtD measures were significantly correlated with overall reading performance. This allowed the researcher to make an informed choice about the appropriate variables to be included in the regression model (See Appendix B, table B-7 for details: correlates of DtD, dyslexia-sensitive and reasoning measures with an overall score of reading).

The following DtD variables were included in the following regression analysis as they showed significant correlation with reading. DtD measures for *dominant hand*: **First sector max. error, Time, Total error, SD2, FirstDown first sector max. error, FirstUp first sector max. error, and TimeTotal;** DtD measures for *non-dominant hand*: **Time, SD2, Direction ratio, and TimeTotal.**

The listwise deletion method was used to handle missing values, as the pairwise method is not recommended in multiple regression (Field, 2009). First, the multiple regression assumptions were checked. There was one studentized residual greater than ±3 standard deviations. Inspection of the participant's records did not contain any additional information on this individual's performance therefore there was no justification for removal of the score; the score was kept in the analysis.

There was linearity as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was an independence of residuals, as assessed by a Durbin-Watson statistic of 1.695. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. There was no evidence of multicollinearity, as assessed by Variance Inflation Factors (VIF). The assumption of normality was met, as assessed by Q-Q Plot. Data, therefore, met the necessary assumptions for multiple regression.

The multiple stepwise regression generated two statistically significant models. The first model ($F(1, 167) = 8.736$, $p = .004$, adj. $R^2 = .044$) included one variable: TimeTotal for dominant hand. The second model ($F(2, 166) = 8.297$, $p < .001$, adj. $R^2 = .080$) included Direction Ratio for non-dominant hand.

In order to investigate which of the dyslexia sensitive and reasoning measures add to the reading prediction and whether the DtD measures add to the model, another multiple stepwise regression was conducted. The above mentioned DtD measures were included in the model. From the established dyslexia screening and reasoning measures the following were included: **Auditory sequential memory, Verbal memory/phonic skill, digit span, RAN, phonological processing, block design, matrix reasoning and verbal reasoning** as these measures were significantly correlated with reading **(**See Appendix B, table B-7). The **school** was also included as a predictor of results in the previous chapter indicated that school might play a role in reading. Overall, 19 variables were included in the regression analysis. Tabachnick and Fidell (2007) suggest that the minimum sample size for multiple regression should be 104 plus the number of predictors. The current sample (n = 150) for these many predictors was therefore sufficient.

The listwise deletion method was used to handle missing values, as the pairwise method is not recommended in multiple regression (Field, 2009). First, the multiple regression assumptions were checked. There was one studentized residual greater than ±3 standard deviations. Inspection of the participant's records showed that this child was not flagged as at risk of dyslexia at baseline (according to Lucid Rapid), but performed poorly on the follow-up reading tasks. The comments of the researcher administering the test indicated that the child showed signs of distress before taking part in the test and seemed confused during. As this might have affected the child's performance, it was decided to remove the child's results from the further analysis. The sample size after the participant was deselected was 149.

There was linearity as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was an independence of residuals, as assessed by a Durbin-Watson statistic of 1.587. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. There was no evidence of multicollinearity, as assessed by Variance Inflation Factors (VIF). The assumption of normality was met, as assessed by Q-Q Plot. Data, therefore, met the necessary assumptions for multiple regression.

The multiple stepwise regression generated four statistically significant models. The first model ($F(1, 147) = 101.309$, $p < .001$, adj. $R^2 = .408$) included one variable: Phonological Processing. The second model ($F(2, 146) = 55.842$, $p < .001$, adj. $R^2 = .433$) included RAN. The third model ($F(3, 145) = 41.045$, $p < .001$, adj. $R^2 = .459$) included DtD DR for non-dominant hand. The fourth model ($F(4, 144) = 32.732$, $p < .001$, adj. $R^2 = .476$) included the Block Design measure. All variables had statistically significant contributions to the prediction, p < .05. Plotted correlations between reading and each of the significant predictors are in Figure 5.1.

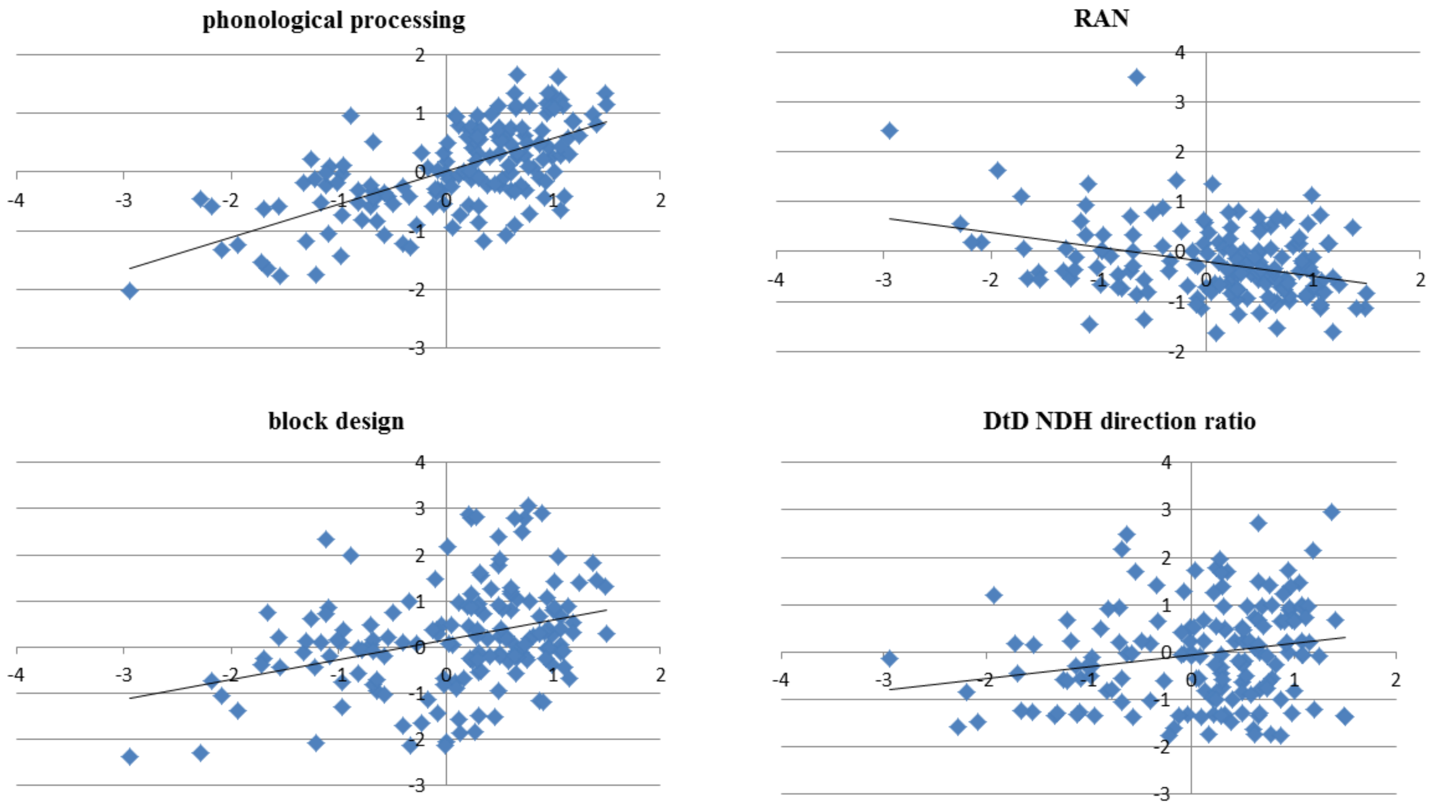

Figure 5.1 Scatter plots presenting correlation between reading scores (indicated on horizontal axis) and reading predictors (vertical axes).

Regression coefficients and standard errors can be found in Table 5.3.

Table 5.3
Summary of hierarchical regression analysis predicting overall reading

Model	IV	B	SE_B	*B*	t	p	95% CI Lower bound	95% CI Upper bound
1	PP	.739	.073	.639	**10.065**	<0.001	.594	.884
2	RAN	-.200	.078	-.166	**-2.559**	.012	-.354	-.046
3	DR NDH	.135	.051	.164	**2.631**	.009	.034	.236
4	BD	.104	.048	.140	**2.162**	.032	.009	.200

Note. B = Unstandardised regression coefficient; SE_B = Standard error of the coefficient; *B* = Standardised beta coefficient; PP = Phonological Processing; RAN = Random automatised naming; DR NDH = Direction ration for non-dominant hadn (DtD); BD = Bead Threading.

A similar result was obtained from a hierarchical multiple regression that included school and verbal reasoning at first step (enter method) and all of the remaining predictors in the second step (stepwise method). After controlling for school and verbal reasoning, which together explained 18% of variance ($F(3,148) = 10.641$, $p < .001$) block design was no longer found to be a significant predictor. Phonological processing ($F(4,148) = 26.306$, $p < .001$), RAN ($F(5,148) = 23.371$, $p < .001$) and DtD direction ratio ($F(6,148) = 21.429$, $p < .001$) still remained significant predictors, all together explaining 48% of variance in reading scores.

To investigate whether Phonological Processing, RAN, and DtD Direction Ratio were independent contributors to reading, a hierarchical, multiple regression was conducted with Phonological Processing inserted in the first step, and the remaining predictors in the second step. After controlling for Phonological Processing, which explained 41% of variance ($F(1,150) = 104.680$, $p < .001$), RAN still significantly contributed to the model by additionally explaining 2.6% of the variance ($F(2,150) = 57.953$, $p < .001$). The DtD direction ratio for dominant hand added an additional 2.5% ($F(3,150) = 42.430$, $p < .001$). Together with block design ($F(4,150) = 33.776$, $p < .001$), all four predictors together explained 48% of the variance.

The question of the importance of memory in predicting reading was further explored. A multiple regression was conducted, again with reading as an outcome variable and with both memory measures (Digit Span and Auditory Sequential Memory) as predictors. The stepwise method was used. The first model included Digit Span and proved to be significant ($F(1,214) = 43.606$, $p < .001$) explaining 17% of variance. The second model included ASM ($F(2,214) = 30.999$, $p < .001$) and explained additional 5.6% of variance.

After controlling for phonological processing, which explained 37% of variance ($F(1,200) = 118.926$, $p < .001$), only Digit Span remained a significant contributor adding 1.6% of the variance ($F(2,200) = 63.280$, $p < .001$).

5.3.3.1 Investigation of reading predictors in pre-reading sample

The predictive value of tests conducted when children were at pre-reading age on their reading level at follow up after one, two or three years was important in order to be able to comment on the possible causes of dyslexia.

Correlation analyses (see Appendix B, table B-8) revealed which of the variables significantly correlated with reading. This was used as the indicator to which variable should be included in multiple regression.

The following variables were included in the regression: DtD measures for *dominant hand*: **First Sector Max. Error, Total Error, SD2, and TimeTotal**. From the established dyslexia screening and reasoning measures the following were included: **Auditory sequential memory, Verbal memory/phonic skill, digit span, RAN, phonological processing, block design and verbal reasoning**. The **school** was also included as a predictor. Overall, 11 variables were included. The current sample ($n = 81$) for these many predictors was therefore insufficient (Tabachnick & Fidell, 2007). However, the analysis was still conducted, and results interpreted with caution.

The listwise deletion method was used to handle missing values as the pairwise method is not recommended in multiple regression (Field, 2009). The multiple regression assumptions were checked and satisfied. There were no studentized residual greater than ±3 standard deviation.

The multiple stepwise regression generated two statistically significant models. The first model ($F(1, 79) = 34.048$, $p < .001$, adj. $R^2 = .301$) included only one variable, phonological processing. The second model ($F(2, 78) = 21.185$, $p < .001$, adj. $R^2 = .352$) included DtD total error for dominant hand. Regression coefficients and standard errors can be found in Table 5.4

Table 5.4
Summary of hierarchical regression analysis predicting overall reading (pre-reading sample)

Model	IV	B	SE_B	*B*	t	P	95% CI Lower bound	95% CI Upper bound
1	PP	.593	.102	.549	**5.835**	<0.001	0.391	0.795
2	Total err. DH	-.194	.079	-.226	**-2.473**	0.016	-0.373	0.767

Note. B= Unstandardised regression coefficient; SE_B=Standard error of the coefficient; *B*= Standardised beta coefficient; PP = Phonological Processing; Total err. DH = Total error for dominant hand (DtD).

5.3.4 Reading performance and the use of different cut-off points

Further analysis aimed to explore differences between poor and typical readers. Due to inconsistencies in literature in regard to the cut-off points used for indicating poor readers, the use of three cut-off points was explored.

Children who performed one standard deviation (*SD)* below the mean score (on the combined Speeded and Nonsense passage reading) were considered to be poor readers ($n = 44$; 18.4% of the followed-up group). Fifty-nine percent of these children were in School 1, 20.5% in School 2, and 20.5% in School 3.

Children who performed one and a half of *SD* below the mean score were considered as very poor readers (*n* = 20; 8.4% of the sample). Seventy per cent of these children were in School 1, 25% in School 2 and 5% in School 3.

Children who performed two *SD*s below the mean score were considered as severely poor readers (*n* = 7; 2.9% of the sample). Over seventy (71.4) percent of these children were in School 1, 14.3% in School 2 and 14.3% in School 3. Children who did not meet these criteria were assigned to the typically reading group (*n* = 195; *n* = 219; *n* = 232; for each school respectively). Table 5.5 presents basic information on the poor and typically reading group.

Table 5.5
Age and school by reading group

			Age (in years)			School *N (%)*		
Cut-off level	reader	*N*	*M (SD)*	Min.	Max.	1	2	3
-1 SD	poor	44	5.6 (1.6)	4	10	26 (59.1)	9 (20.5)	9 (20.5)
	typical	195	6.8 (1.8)	4	11	55 (28.2)	59 (30.3)	81 (41.5)
-1.5 SD	Very poor	20	5.95 (1.8)	4	10	14 (70)	5 (25)	1 (5)
	typical	219	6.1 (1.8)	4	11	67 (30.6)	63 (28.8)	89 (40.6)
-2 SD	Severely poor	7	7 (1.4)	5	9	5 (71.4)	1 (14.3)	1 (14.3)
	typical	232	6.1 (1.8)	4	11	76 (32.8)	67 (28.9)	89 (38.4)

Due to the small number of participants allocated to the groups of severely poor and very poor readers, the following comparative analyses will use the -1 *SD* criterion to distinguish poor readers. The exploration of deficits, presented in the section 5.3.8 will, however, distinguish between different levels of severity in order to inform the debate on how operational definitions inconsistencies may affect the patterns of reading difficulty manifestations.

5.3.5 Poor vs typical readers: investigating the differences

The following set of analyses aimed to compare performance on dyslexia sensitive, DtD and reasoning tests that were administered one, two or three years before the individuals were grouped into 'poor reader' and 'typical reader' groups based on the combined scores on nonsense passage and speeded reading tests. The purpose of conducting these analyses of differences was also to indicate which variables may distinguish between the two groups and could be further included into a logistic regression in order to assess their sensitivity and specificity (as will be presented in the next subsection).

Data obtained from the two groups did not meet the assumptions for parametric tests (as assessed by kurtosis and skewness); therefore multiple Mann-Whitney U tests were run. Distributions of the scores for dyslexia and control group were not similar, as assessed by visual inspection. Tables 5.6 and 5.7 present the group comparisons together with descriptive statistics for DtD and dyslexia screening/cognitive measures, respectively. As multiple comparisons were conducted, to control for Type I error the Benjamini-Hochberg (BH) Procedure was used (Benjamini & Hochberg, 1995) to establish threshold value for each *p*-value.

Table 5.6

Differences between poor and typical readers on the main DtD measures for dominant and non-dominant hand

DtD	reader	N	Mean rank	Sum of ranks	U	z	*p (q)*
DH First sector max. error	poor typical	36 171	136.08 97.25	4899 16629	1923	**-3.536**	<0.001* (<0.014)
DH Time	poor typical	36 171	120.03 100.63	4321 17207	2501	-1.766	0.077
DH Total error	poor typical	36 171	129.22 98.69	4652 16876	2170	**-2.780**	0.005* (0.022)
DH SD2	poor typical	36 171	123.07 99.99	4431 17098	2392	-2.106	0.036
DH Direction ratio	poor typical	36 171	96.85 105.51	3487 18042	2821	-1.509	0.131
DH TimeTotal	poor typical	36 171	128.11 98.92	4612 16916	2210	**-2.657**	0.008* (0.024)
DH FirstDown FSME	poor typical	36 171	132.33 98.04	4764 16764	2058	**-3.123**	0.002* (<0.021)
DH FirstDown Direction ratio	poor typical	28 143	103.76 100.40	3736 16566	2871	-.315	0.753
DH FirstUp FSME	poor typical	28 143	132.78 97.94	4780 16748	2042	**-3.172**	0.002* (<0.021)
DH FirstUp Direction ratio	poor typical	24 114	61.92 71.10	1486 8105	1186	-1.022	0.307
NDH First sector max. err.	poor typical	28 143	97.89 83.67	2741 11965	1669	-1.390	0.165
NDH Time	poor typical	28 143	98.46 83.56	2757 11949	1653	-1.457	0.145
NDH Total error	poor typical	28 143	93.14 84.60	2608 12098	1802	-.835	0.404
NDH SD2	poor typical	28 143	99.14 83.43	2776 11930	1634	-1.536	0.125
NDH Direction ratio	poor typical	28 143	67.13 89.70	1880 12827	1474	**-2.206**	0.026* (0.026)
NDH TimeTotal	poor typical	28 143	95.68 84.10	2679 12027	1731	-1.131	0.258
NDH FirstDown FSME	poor typical	28 146	97.75 85.53	2737 12488	1757	-1.175	0.240
NDH FirstDown Direction ratio	poor typical	28 139	83.20 84.16	2330 11699	1924	-.096	0.923
NDH FirstUp FSME	poor typical	28 143	102.21 82.83	2862 11844	1548	-1.895;	0.058
NDH FirstUp Direction ratio	poor typical	27 117	68.74 73.37	1856 8584	1478	-.520	0.603

Note. * significance at the B-H adjusted level *critical q values in brackets;* SD2 = points over 2 standard deviations; DH = dominant hand; NDH= non-dominant hand.

Table 5.7
Differences between poor and typical readers on the dyslexia sensitive and reasoning tests

DtD	reader	*N*	Mean rank	Sum of ranks	*U*	*z*	*p (q)*
PP	poor	30	46.25	1388	923	**-5.769**	<0.001*
	typical	180	115.38	20768			(<0.014)
DS	poor	38	69.01	2623	1882	**-4.685**	<0.001*
	typical	191	124.15	23713			(<0.014)
RAN	poor	39	152.42	5945	2129	**-4.087**	<0.001*
	typical	187	105.38	19707			(<0.014)
BT	poor	39	105.77	4125	3345	**-1.002**	<0.001*
	typical	191	117.49	22440			(<0.014)
ASM	poor	39	69.62	2715	1935	**-4.486**	<0.001*
	typical	183	120.43	22038			(<0.014)
VM/PS	poor	37	70.57	2611	1908	**-3.747**	<0.001*
	typical	170	111.28	18917			(<0.014)
BD	poor	39	86.33	3367	2587	**-5.769**	0.002*
	typical	192	122.03	23429			(<0.021)
MR	poor	39	84.44	3293	2513	**-3.235**	0.001*
	typical	192	122.41	23503			(0.016)
VR	poor	37	66.86	2474	1771	**-4.772**	<0.001*
	typical	190	123.18	23404			(<0.014)

Note. *significance at the B-H adjusted level *critical q values in brackets;* PP = Phonological Processing; ASM = Auditory Sequencial Memory VM/PS = Visual Memory/Phonic Skills; BD = Block design; MR = Matrix Reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning.

The scrutiny of group differences in performance on the dyslexia screening and reasoning tasks showed that poor readers performed significantly worse on all of dyslexia sensitive tests than the good readers. In terms of the DtD task, children who were indicated as poor readers were outperformed by their typically-reading counterparts when drawing both the FirstDown and FirstUp patterns with their dominant hand; they made greater errors in the first sector. In addition, they made greater total error over the entire pattern, and when both speed and accuracy (TimeTotal) were taken into consideration. Furthermore, direction ratio for non-dominant hand also reached significance level.

5.3.6 Prediction of reading group membership based on selected predictors: assessing sensitivity and specificity

To establish which of the DtD measures and how well they can predict reading group membership, a binominal logistic regression was conducted. The two groups explored were poor readers (scoring below 1 SD of the mean score on combined reading tests) and typical readers (the remaining children). In order to identify the potential predictors, analyses of group differences were conducted first as described above. The following predictors (IVs) were included in the model FSME, FirstDown FSME, FirstUp FSME, Total Error, TimeTotal and for non-dominant hand the Direction Ratio. This pattern largely replicates the group differences found in previous research and confirms the validity of selecting these tasks to predict literacy difficulties. The stepwise (forward: wald) method was used.

The logistic regression two-factor model was statistically significant ($\chi^2(2) = 15.276$, $p < .001$) and explained 14.6% (Nagelkerke R^2) of the variance in reading and correctly classified 85.8% of cases. Sensitivity was 14.3%, specificity was 100%. The positive predictive value was 100% and negative predictive value was 87.2%. Of the six predictor variables only two were statistically significant: FSME for dominant hand and direction ratio for non-dominant hand (DR NDH). Details are provided in Table 5.8

Table 5.8

Logistic regression predicting likelihood of group membership (poor and typical readers) based on the DtD measures

IV	B	SE_B	Wald	df	p	95% CI for EXP (B)		
						Odds ratio[a]	Lower bound	Upper bound
FSME DH	0.643	.215	8.943	1	0.003	1.903	1.248	2.900
DR NDH	-0.632	.250	6.407	1	0.011	0.531	0.326	0.867

Note. N = 168 (28 DD and 141 NDD); B = Unstandardised regression coefficient; SE_B=Standard error of the coefficient; N = 162; FSME DH = First Sector Maximum Error for dominant-hand; DR NDH = Direction Ratio for non-dominant hand; [a]The *odds ratio* informs of the change in the odds for each increase in one unit of the independent variable.

To establish how well the baseline measures can predict reading group membership, and whether the DtD measures can add to the model another binominal logistic regression was conducted. The following predictors (IVs) were included in the model: dyslexia sensitive measures (PP, RAN, BT, ASM, DS), the reasoning measures (BD, VR, MR); and the DtD measures for dominant hand: FSME, FirstDown FSME, FirstUp FSME, Total Error, TimeTotal and for non-dominant hand the Direction Ratio. This pattern largely replicates the group differences found in previous research and confirms the validity of selecting these tasks to predict literacy difficulties. The stepwise (forward: wald) method was used.

The logistic regression two-factor model was statistically significant ($\chi^2(2)$ =39.218, $p < .001$) and explained 43% (Nagelkerke R^2) of the variance in reading and correctly classified 91% of cases. Sensitivity was 98.5%, specificity was 36.8%. The positive predictive value was 77.8% and negative predictive value was 91.8%. Of the predictor variables only two were statistically significant: phonological processing (PP) and direction ratio for non-dominant hand (DR NDH) (as shown in Table 5.9).

Table 5.9
Logistic regression predicting likelihood of group membership (poor and typical readers)based on baseline measures

						95% CI for EXP (B)		
IV	B	SE_B	Wald	df	p	Odds ratio[a]	Lower bound	Upper bound
PP	-2.140	.468	20.890	1	<0.001	0.118	0.047	0.295
DR NDH	-.905	.371	5.962	1	0.015	0.404	0.196	0.836

Note. N = 155 (19 DD and 136 NDD); B = Unstandardised regression coefficient; SE_B=Standard error of the coefficient; N = 162; PP = Phonological Processing; DR NDH = Direction Ratio for non-dominant hand; [a]The *odds ratio* informs of the change in the odds for each increase in one unit of the independent variable.

An increase in one unit on PP and DR decreases the odds of being classified as a poor reader by .118 and .404, respectively.

A casewise list revealed six children who were misclassified by this model. All of them were predicted to be typical readers by the model but were identified by the two reading tests as poor readers. All of them scored slightly below 1 SD below the mean on the reading measure (-1.17, -1.02, -1.08, -1.12, -1.22 and -1.25) which signifies that if another criterion was used (-1.5SD for instance), these children would not be considered as poor readers but as typical readers, in line with what the model predicted.

Receiver Operator Characteristic (ROC) analyses were also conducted to test for sensitivity and specificity of dyslexia predictors. The area under the curve measures discrimination, the ability of the test to correctly classify those with and without reading problem. The graphical presentation of the results for each test is presented in Figure 5.2.

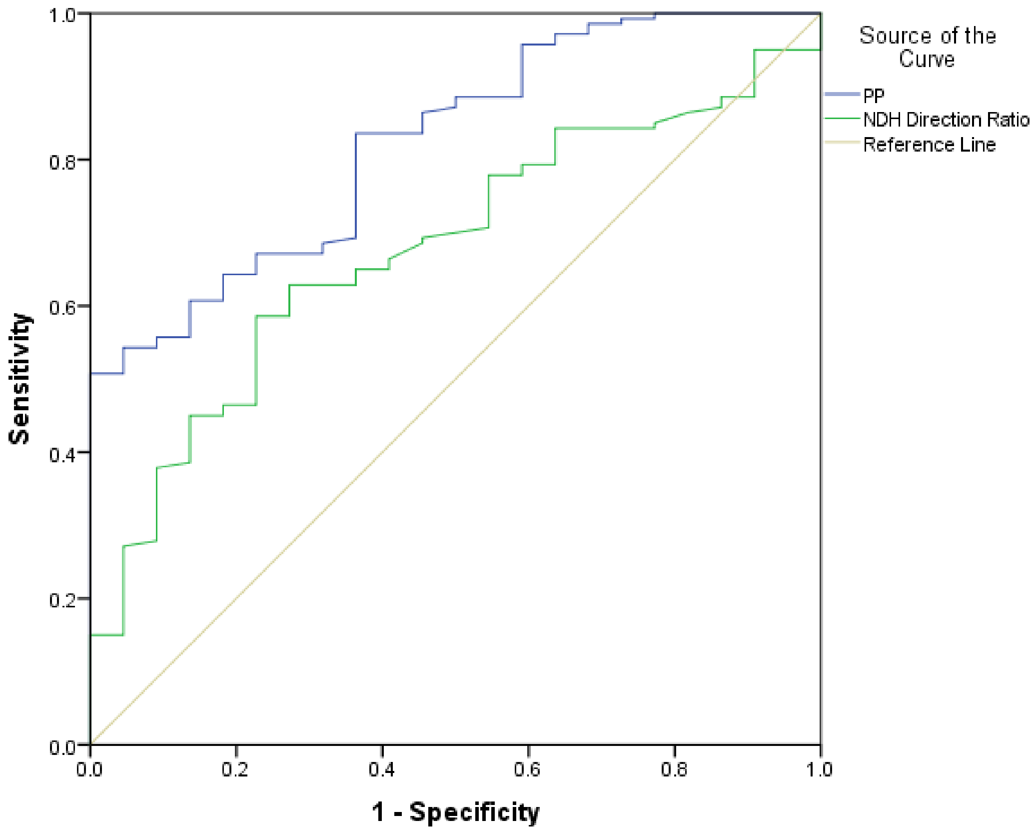

Figure 5.2. Receiver Operator Characteristic (ROC) curves for phonological processing (PP) and direction ratio for non-dominant hand (DR NDH); the further the line from the reference line the better the diagnostic test.

The closer the curve follows the left-hand, top border of the ROC space the more accurate the test. The figure shows that phonological processing is a more accurate test than the DtD direction ratio measure. Areas under the curve for each test are presented in Table 5.10.

Table 5.10
Receiver Operator Characteristic for Phonological Processing and DtD direction ratio (NDH)

					95% CI	
Measure	N	AUC[a]	SE	*p*	Lower Bound	Upper Bound
PP	74	0.823	0.042	**<0.001**	0.742	0.905
DR NDH	41	0.677	0.053	**0.008**	0.573	0.781

Note. Areas under the curve for DtD DR (non-dominant hand), PP tasks. *p<.05; **p<.001. [a] AUC-area under curve, if greater than .9 the test is considered as excellent; >.8 good; >.7 fair; >.6 poor.

Phonological processing's area under the curve was .82 which signifies good accuracy. The DtD direction ratio's accuracy was poor (.68).

5.3.7 Revisiting relationships between the DtD and baseline measures – reading level group comparison

As previously discussed (Chapter 4, p. 158) an investigation of the relationships between the new measures obtained from the DtD task and the established dyslexia indicators in the cross section of children provided in the previous chapter might have been problematic due to the use of the entire sample. Now, since it is possible to indicate poor and typical readers with greater confidence, it is useful to revisit the correlational analysis and investigate the relationships separately for the poor and typical readers in order to understand better why the key DtD measures (those that significantly added to the prediction model) indicated to be important in the context of already known and established dyslexia indicators. Table 5.11 presents the correlation coefficients for the two key DtD measures (NDH Direction Ratio and DH TimeTotal) with the remaining baseline measures.

Table 5.11

Spearman's correlation coefficients conducted separately for groups of typical and poor readers

	Readers			
	typical		poor	
	NDH DR	DH TimeTotal	NDH DR	DH TimeTotal
ASM	0.061 (*n*=141)	-0.106 (*n*=165)	-0.249 (*n*=26)	-0.149 (*n*=33)
DS	0.08 (*n*=143)	-0.007 (*n*=171)	-0.367 (*n*=26)	0.134 (*n*=32)
RAN	0.101 (*n*=141)	**0.229*** (*n*=167)	0.295 (*n*=26)	-0.119 (*n*=33)
PP	0.074 (*n*=140)	-0.089 (*n*=163)	-0.257 (*n*=22)	-0.014 (*n*=28)
VM/PS	0.103 (*n*=136)	**-0.257*** (*n*=156)	-0.305 (*n*=26)	-0.234 (*n*=33)
BT	-0.072 (*n*=143)	-0.156 (*n*=171)	-0.141 (*n*=26)	-0.102 (*n*=33)
BD	0.118 (*n*=143)	**-0.244*** (*n*=171)	-0.182 (*n*=26)	-0.113 (*n*=33)
MR	0.033 (*n*=143)	**-0.206*** (*n*=171)	-0.160 (*n*=26)	**-0.452***[a] (*n*=33)
VR	0.03 (*n*=142)	-0.095 (*n*=169)	-0.324 (*n*=24)	-0.298 (*n*=31)

Note. *significance at the B-H adjusted level; [a] p = 0.008 (the p value not adjusted due to small number of participants. NDH DR = non-dominant hand direction ratio; DH TimeTotal = dominant hand measure accounting for time and accuracy trade-off; PP = Phonological Processing; ASM = Auditory Sequencial Memory VM/PS = Visual Memory/Phonic Skills; BD = Block design; MR = Matrix Reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning

The results reveal that the TimeTotal measure for dominant hand is statistically significantly correlated with non-verbal reasoning measures, the RAN task and the Visual Memory/Phonic Skills task; the correlations were of weak strength sharing only 4% to 6% of variance. This was only the case in the group of typical readers. The poor readers' investigation showed only one significant correlation: between the TimeTotal measure and Matrix Reasoning Measure, sharing 20% of variance. Fisher's R to Z transformation conversion revealed that the significant correlations between TimeTotal and MR for the typical readers (r = -.206) and for the poor readers (r = -.452) were not statistically different (Z = -1.4; p = .161). Arguably the best DtD predictor, the Direction Ratio measure that uniquely added to model variance explanation, is not significantly correlated with any of the baseline measures.

One of the concerns of the above analysis is a small number of participants in the poor reading group which could perhaps explain lack of significant correlations found between measures that were related in the typical group. This assumption was further investigated using the post-hoc power analysis for the correlation analyses (using G*Power 3.1.9.2; Faul et al., 2007). Measuring for medium effect (r = .5) with α set at 0.05 (following the norm; no adjustment due to small sample size) the analysis indicated 1-β to be .89. This indicated that the study was powered enough to capture medium effect.

5.3.8 School differences

A one-way independent-samples ANOVA revealed a significant difference in overall reading score (residualised for age) between schools (F (2, 236) = 16.234, $p < .001$, partial eta squared = .121, medium effect size). Tukey post-hoc pairwise comparisons revealed that children from school 1 (low SES) were significantly outperformed by children from school 3 (high SES), who also performed significantly better than those from school 2 (medium SES) (see Table 5.12).

Table 5.12
Differences between schools on reading tests (SR & NR combined)

School		Mean difference	p	95% CI Lower bound	95% CI Upper bound
1	2	-0.189	0.588	-.541	.163
	3	**-0.744***	<0.001	-1.071	-.416
2	3	**-0.554***	<0.001	-.898	-.211

5.3.9 Investigating areas of weaknesses in poor readers

Further investigation was built around the question of what deficits do poor readers display and whether these readers show multiple deficits or if there is one common deficit. Table 5.13 presents the proportion of participants showing weaknesses in the areas measured at the baseline. As there is a lack of consistency in literature as to the cut-off point to be used to indicate poor readers, three different cut-off points were used here to illustrate how the pattern of weaknesses changes when a different operational definition is used. Weaknesses are defined here as scores 1SD below the sample mean.

Table 5.13

Percentage of children showing weaknesses on each task

	reader (-1SD) %		reader (-1.5SD) %		reader (-2SD) %	
Test	poor *n*=44	typical *n*=195	poor *n*=20	typical *n*=219	poor *n*=7	typical *n*=232
PP	44.15	5.56	56.25	7.65	40.00	9.76
ASM	30.77	8.20	27.78	10.28	42.86	11.16
VM/PS	32.43	11.18	41.18	12.63	42.86	12.17
RAN	30.77	5.35	47.06	6.70	33.34	9.09
DS	18.42	8.90	25.00	9.39	20.00	10.27
BD	23.08	10.42	31.25	11.16	60.00	11.50
MR	38.46	12.11	56.25	15.81	80.00	17.27
VR	43.24	12.11	53.34	14.62	60.00	16.22
DR NDH	32.14	17.48	38.46	18.35	50.00	18.79
BT	15.38	16.75	29.41	16.50	16.67	16.52

Note. The weaknesses are indicated if the performance is below 1Sd of the mean for the sample. PP = Phonological Processing; ASM = Auditory Sequential Memory; VM/PS = Visual Memory/Phonic Skill; BD = Block design; MR = Matrix Reasoning; VR = verbal reasoning; DS = Digit Span; RAN = Random Automatised Naming; BT = Bead Threading; BD = block design; MR = matrix reasoning; VR = verbal reasoning. DR = direction ratio; NDH = non-dominant hand.

It was also important to explore how many deficits children who identified as poor readers showed. Tables 5.14 and 5.15 present the proportion of children, identified using the -1SD and -1.5SD criteria respectively, who showed from zero to six deficits. The details of the combination of deficits are also provided in the table, revealing a number of different combinations with only a couple of combinations found in more than one child.

Table 5.14

Weaknesses in poor readers (-1 SD criterion used)

Number of deficits	*n* (%) of poor readers	Combination of deficits (*n*)	Mean reading score
0	8 (18%)	Missing baseline scores (3)	-1.57
1	7 (16%)	DtD (3), RAN (1), M (1), PP (1)	-1.19
2	8 (18%)	M & DtD (1); M & NR (1); PP & RAN (1); DtD & NR (1); PP & DtD (1); BT & DtD (1); RAN & DtD (1); NR & VR (1)	-1.61
3	12 (27%)	PP & M &VR (3); PP & BT & RAN (2); M & VR & RAN (1); PP & VR & NR (1); NR & VR & RAN (1); PP & VR & RAN (1); DtD & NR & VR (1); NR & BT & RAN (1); M & BT & RAN (1)	-1.34
4	5 (11%)	PP & M & VR & NR (1);PP & M & RAN & NR (1); PP & M & BT & RAN (1); PP & NR & DtD & VR (1); NR & BT & DtD & VR (1)	-1.71
5	3 (7%)	PP & M & NR & VR & RAN (1); PP & M & NR & VR & RAN (1); PP & M & NR & BT & VR (1)	-1.60
6	1 (2%)	DtD & PP & M & RAN & NR & VR	-2.94

Note. Poor readers assigned to the group using -1SD criterion. M = memory component (deficits on either the ASM or DS); NR = non-verbal reasoning (BD or MR),VR = verbal reasoning; PP = phonological processing; RAN = rapid automatised naming; DtD = dot-to-dot; BT = bead threading;

Table 5.15

Weaknesses in poor readers (-1.5 SD criterion used)

Number of deficits	*n* (%) of poor readers	Combination of deficits (*n*)	Mean reading score
0	4 (20%)	Missing baseline scores (2)	-1.94
1	0		
2	5 (25%)	M & DtD (1); PP & RAN (1); DtD & NR (1); BT & DtD (1); NR & VR (1)	-1.99
3	5 (25%)	PP & BT & RAN (2); PP & VR & NR (1); PP & VR & RAN (1); NR & BT & RAN (1); M & BT & RAN (1)	-1.73
4	4 (20%)	PP & M & VR & RAN (1);PP & M & RAN & NR (1); PP & NR & DtD & VR (1); NR & BT & DtD & VR (1)	-1.75
5	1 (5%)	PP & M & NR & VR & DtD	-1.21
6	1 (5%)	DtD & PP & M & RAN & NR & VR	-2.94

Note. Poor readers assigned to the group using -1.5 SD criterion. M = memory component (deficits on eaither the ASM or DS); NR = non-verbal reasoning (BD or MR),VR = verbal reasoning; PP = phonological processing; RAN = rapid automatised naming; DtD = dot-to-dot; BT = bead threading;

Out of the seven severely poor readers (scoring below 2SD), three did no complete the full set of tests, one did not display deficits in any of the baseline measures, one showed only verbal and non-verbal reasoning deficits, one showed deficits in PP, verbal and non-verbal reasoning, Bead Threading and DtD, and one child showed deficits acress all measures apart from the Bead threading task.

Figure 5.3 shows the overall percentage of the main deficits in dyslexia and how many precent of children have a mixture of the deficits (indicated as shaded, overlapping areas). The way this figure needs to be interpreted is following: if we were test the children on only the phonological tasks, we would be able to indicate 44% of the poor readers (regardless of their other deficits); this number does not represent the pure/single phonological processing deficit (these can be found in the table 5.16). The overlapping areas indicate the percentage of children who had both of the deficits; for instance, 15.8% of the poor readers displayed both the Phonological Processing and RAN problems.

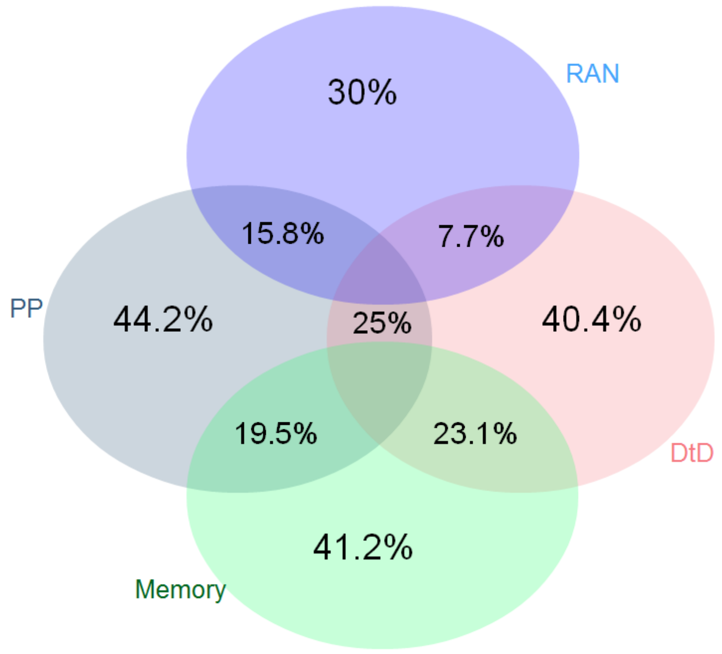

Figure 5.3 Venn diagram presenting areas of weaknesses shown by the poor readers (those who scored below 1SD of the mean on the reading, nonsense and speeded, tests). Deficits were operationalised as falling below 1SD of the sample mean.

5.3.10 Reading performance and dyslexia risk

At the baseline, children's risk of dyslexia was assessed by the Lucid Rapid screening tool. Out of the poor readers, if the -1SD criterion was used; only 53% of children were identified by Lucid Rapid as being at high risk; that was the sensitivity level of the test. The positive predictive value was 32%. Twenty-one percent (the specificity of the test) of the typical readers were flagged as at high risk; the negative predictive value was 89%. If the 1.5 SD or 2 SD criteria were used to assign children into the reading level groups, 66.6% of poor readers would be correctly flagged as at risk (positive predictive value: 20% and 8.7%, respectively), whilst 22.7% (with 1.5SD criterion; negative predictive value: 94.3%) and 24.7% (with 2SD criterion; negative predictive value: 98.6%) of typical readers would be incorrectly flagged as at high risk. Table 5.16 below presents the number of poor and typical readers who were assigned to risk groups at the baseline testing.

Table 5.16
Number of poor and typical children and which dyslexia risk group they were assigned at baseline

			Dyslexia risk			
Cut-off level	reader	*N*	high	moderate	low	Not assessed
-1 SD	poor	44	16	10	4	14
	typical	195	34	59	68	34
-1.5 SD	poor	20	10	4	1	5
	typical	219	40	65	71	43
-2 SD	poor	7	4	1	1	1
	typical	232	46	68	71	47

Note. Dyslexia risk assessed by Lucid Rapid.

5.3.11 Effects of gender

A chi-square test for association was conducted between gender and reading group (poor vs typical readers). All expected cell frequencies were greater than five. There was no statistically significant association between gender and reading group, $\chi^2(1) = .046$, $p = .868$. Table 5.17 presents details.

Table 5.17
Contingency table of gender and reading group

		gender		
reader		female	male	Total
poor	count	22	22	116
	expected count	21.4	21.4	
typical	count	94	101	195
	expected count	94.6	100.4	
Total		153	165	318

5.4 Discussion

The current study investigated which and how efficiently baseline measures, including measures from the novel DtD test, as well as the DtD test on its own, could predict reading assessed prospectively in an unselected sample of primary school children. Whether reading level in the entire sample can be predicted by the same tests as was found in the pre-reading sample was an important question aiding the causality discussion. Furthermore, the patterns of weaknesses were explored in children at different levels of reading difficulty as determined by differently operationally defined reading problems. The current study built on and addressed some of the limitations of the study presented in Chapter 4 which only looked at the cross-section of children. Key findings will be discussed followed by a section aiming to explore potential explanations of the DtD task.

5.4.1 Group differences and reading predictors

The DtD test's two measures: TimeTotal for dominant hand and Direction Ratio for non-dominant together explained 8% of varience in reading scores. Looking at all of the available measures, the strongest significant predictors of overall reading performance across the whole sample were Phonological Processing, RAN, DtD Direction ratio for non-dominant hand, and Block Design – a measure of non-verbal reasoning. All these together could explain 46% of variance in reading scores. Children who were indicated as poor readers were also outperformed by their typically-reading counterparts on a range of the DtD measures, Time, SD2, Direction ratio, and TimeTotal, the established dyslexia-sensitive tests: Phonological Processing, Verbal Memory/Phonic Skill, RAN, as well as the verbal and non-verbal reasoning measures. These results provide support for the study's hypotheses that were raled to reading groups differences and predictive abilities of the used measures. In line with the previous study presented in Chapter 4 and with previous literature, the current investigation found significant differences in reading scores between children across different schools. Children from school 1, which is associated with low socioeconomic status, were outperformed by their counterparts from school 3 (high SES) on reading. This finding confirms the previously found effect of socioeconomic status on children's risk of dyslexia (as per previous chapter). However, the school variable was not a statistically significant predictor of reading level in the regression model. Some of the findings were expected based on the previous literature and were consistent with the results presented in the previous chapter. This will now be discussed in detail.

The Dot-to-Dot task

The DtD Direction Ratio for non-dominant hand was a significant predictor of overall reading scores in the full sample of children contributing additional three per cent on top of the contributions of phonological processing and RAN. When included on its own, the DtD measures: Direction Ratio for NDH and TimeTotal for DH together could explain 8% of variance in reading scores. In terms of the pre-reading children, the Total Error for dominant hand proved a significant contributor to the model and accounted for a further five per cent, on top of the phonological processing, of the variance in reading performance. This particular measure is related to the accuracy of the performance as it calculates how far the drawn line is from the perfect line over the entire pattern. These findings add to the discussion on the causality of dyslexia as the deficits found in children who were not yet exposed to reading instruction cannot be a consequence of poor schooling or lack of practice. Furthermore, the model with two variables, Phonological Processing and DtD Total Error, could explain 35% or variance in reading which indicates that reading is such a complex task that requires many other skills that were not measured in the current study. It also directs one to the idea of reading disorder being caused by multiple deficits.

Although only some measures were found to be significant predictors, children defined as poor readers on the basis of their reading performance showed significant group disadvantage in almost all areas tested. Analyses of differences revealed that a number of DtD measures related to the accuracy of the drawn lines (e.g., Total Error), combined speed and accuracy (TimeTotal) and measures reflecting initiation of the trials (Direction Ratio, first sector maximum error) could distinguish between the two reading level groups with the poor readers showing worse performance. This finding contrasts somewhat with the cross-sectional investigation provided in the previous chapter.

Children who were deemed at high risk of dyslexia were outperformed by those at low risk on DtD measures related to the first sector error only. This could be explained by the limited scope of the risk assessment used at the baseline. The Lucid Rapid screening test consists three tasks that measure the core aspects of phonological representations: phonological processing, auditory-sequencial and visual memory. Although these are all important for reading development, they are not sufficient to explain all reading development. The current results provide evidence for this notion by showing that the weaknesses found in the DtD task performance may reflect poor skills that are not related to phonological processing (as the correlations found between them were very weak) but which are impacting reading. Further discussion on the DtD and theoretical framework it can be interpreted in is provided in section 5.4.3. Before delving into this discussion, it is important to provide a discussion for all of the remaining findings related to contrasting theoretical explanations (e.g., PAD) and an informative exploration of the casewise weaknesses.

Phonological processing deficit

Phonological Processing measure on its own explained almost 41% of the reading variance. This corresponds to previous research which showed a significant link between phonological processing and real- and pseudo-word reading (Bosse et al., 2007). As discussed in Chapter 2, it has been widely agreed that phonological deficit is a proximal cause of dyslexia (Ramus et al. 2003; Snowling, 2000; Vellutino et al., 2004). The current findings confirm a significant role of phonological processing in reading showing it to be the strongest predictor of reading level assessed prospectively. Phonological processing is consistently being shown to be the best predictor of subsequent reading performance due to, as argued in the literature, it being typically the key symptom/problem in dyslexia (Snowling, 2001). Reading skills, in particular the non-word reading, are also believed to require the same kind of skills as the phonological processing. Future studies could incorporate other tests of reading, such as comprehension tests to explore whether phonological processing would still be the main predictor. What needs to be emphasised here, however, is that only one child (2%) out of the poor readers group had pure phonological deficit; the remaining children who displayed phonological processing deficit (44% of poor readers) were also compromised on different measures. This shows that, although useful, the phonological deficit hypothesis cannot fully explain reading difficulties in children and cannot be seen as a sole cause. Therefore, other theoretical explanations, such as automaticity or visual deficits hypotheses, must be considered in order to understand and indicate the risk of dyslexia better.

Along with the phonological processing deficit hypothesis, RAN was also currently found to be contributing uniquely to reading. The RAN task contributed additional two percent to the variance in reading, on top of the phonological processing. After controlling for phonological processing, this task still remained a statistically significant predictor of reading which further shows it to be independent of the phonological processing. Rapid naming showed only moderate correlation with phonological processing. This provides some evidence for double processing deficit. The double deficit hypothesis (Savage & Frederickson, 2005; Wolf & Bowers, 1999; Wolf et al., 2002) proposes that the phonological deficit and processes required for rapid naming represent separate sources of the reading problem. However, it needs to be recognised that the unique contribution of RAN does not seem to be very high. This will be further discussed in the section focusing on the case analysis of weaknesses (section 5.4.2).

In line with the phonological processing deficit, apart from the phonological processing problems, poorly reading children were expected to also be compromised on memory and rapid naming tasks. This was found to be the case, as shown in the analysis of group differences. Interestingly, none of the memory measures made it through to the significant model explaining reading performance. That is not to say that memory is not an important skill needed for good reading: poor readers were compromised on both of the memory tests used, the Auditory Sequential Memory and the Digit Span task, when compared to typical readers. These memory measures also moderately correlated with reading and Phonological Processing, however were not found to contribute to the prediction model. It is possible that memory measures require phonological processing as they depend on subvocal rehearsal (Nelson & Warrington, 1980) and that they do not, therefore, contribute uniquely to the model. This possibility was tested in the current study and the findings showed that both Digit Span and Auditory Sequential Memory could predict reading performance by explaining 17% and 5% of reading variance, respectively. However, when Phonological Processing was controlled for, only the Digit Span remained a significant contributor but adding only 1.6% to the explained variance. The Auditory Sequential Memory has therefore not been shown to be a significant contributor to reading after controlling for phonological processing. These findings add to the understanding of phonological processing deficit as they provide evidence to support that the phonological processing and memory may not be affecting reading independently.

In the subsample comprising only pre-reading children, phonological processing remained a significant predictor explaining 30% of the variance in overall reading performance. However, RAN and Block Design did not contribute significantly to the model. Again, this demonstrates that poorer phonological processing is apparent before children learn to read, lending further weight to the idea that phonological processing is one of the causes, rather than consequences, of poor reading. This finding also demonstrates that poor RAN and Block Design performance cannot be seen as causal.

5.4.2 Exploring the weaknesses in poor readers

In the light of many debates related to the definitions and causes of dyslexia, it was crucial in the current study to investigate the areas of weaknesses in children who were indicated as poor readers. The weaknesses were recognised when a child scored at least 1 SD below the sample mean on a given task. Investigation of the patterns of weaknesses in children, who were identified as poor readers according to different operational definitions, by using different cut-off points, contributes to the field as it provides an opportunity to investigate the impact of definition on the findings. It seems that the more stringent the operational definition was, the more children showed deficits in memory, reasoning and DtD measures (see Table 5.15 for details). This suggests that the most severely poor readers had more problems around these areas while children who were categorised as poor readers due to their reading scores being between 1 and 1.5 SD below the sample mean showed relatively fewer problems in those areas. Interestingly, the prevelance of phonological deficit was the highest (56%) in children scoring between 1.5 and 2 SD below the mean. These findings are particularly interesting as they clearly illustrate how important is operationalising of definitions in research in order to get consistent results.

The number and pattern of deficits in poor readers also varied depending on the definition used. When the -1SD criterion was used to assign children into the poor readers group, only one child out of 44 poor readers showed a single deficit in Phonological Processing, and only one child showed a single deficit in RAN. Three children showed a single deficit in the DtD task. Most of the poor readers had three co-occurring deficits. A child with the lowest reading score (-2.94) showed weaknesses in six areas which were: DtD, Phonological Processing, memory, RAN, verbal and non-verbal reasoning. The only task on which her performance was close to the mean of the entire sample, was the Bead Threading task. This further provides evidence for the multiple deficits in dyslexia and also validates the use of multiple case analysis to complement the regression and group comparison analyses.

It also needs to be emphasised that the analysis of single cases treated reasoning skills as possible areas of weaknesses to see if they consistently appear in poor readers. This is a novel approach that adds to our understanding of the role of reasoning skills in reading. There were 40% of poor readers who showed a deficit on either of the verbal or non-verbal reasoning skills along with other deficits. There was only one child who displayed deficits in reasoning skills but not in any other skills currently tested. This indicates that weaknesses in reasoning skills may be seen as possible reasons for poor reading, however in a very small percentage of children, but more likely they simply co-occur with other deficits.

The heterogeneity of the manifestations of dyslexia found previously, and in the current study, lead to considerations of alternative views of dyslexia arising from multiple and independent deficits, such as a multifactorial view of dyslexia (Pennington, 2006).

The results from the current study correspond to some extent to the previous research. Studies by Pennington et al. (2012) and Carroll et al. (2016) contrasted different theoretical explanations for reading difficulties at an individual level. Pennington et al. (2012) found that one-third of their sample of dyslexic children display multiple deficits. In the current study, it was found that 81% of poor readers showed multiple deficits. Pennington et al. (2012) showed that 26% of their sample displayed a single deficit which contrasts with 16% found in the current study. These differences in findings between the current and Pennington et al's studies could be due to different tests and area measures. In the exploration of the current sample's weaknesses, the reasoning abilities were also included as potential areas of weaknesses. Also, the current study included a novel measure, the DtD task that has no known equivalent in the literature as far as the author is aware. Despite these methodological differences, it seems apparent that both of these studies indicate that the majority of children have more than one deficit and minority have only one deficit. The current results, therefore, provide evidence for multiple deficit model.

5.4.3 Making sense of the DtD task

In the remaining sections of the discussion, the author will address the following points. First, what is the putative nature of the DtD task measures that were found to be unique contributors to the model explaining variance in reading? What difficulties these measures could reflect and the potential causal link between these measures will be discussed. In this section, speculations as to why the DtD task seems to be helping in predicting reading will be provided trying to link with the alternative to phonological processing deficit theories in the literature, which will lead to further research questions. From the correlations between the DtD measures and the established dyslexia screening tests shown in Chapter 4, that were revisited in the current chapter, one cannot conclude univocally what does the DtD measure, but current study shows that its components play a unique role in reading. Possible explanations for the DtD measures will be now discussed.

Initially, at the pilot study stage, when the author considered the nature, cognitive and motor requirements of the task, it was suggested that the task requires visual attention, perhaps divided attention between the two panels on the screen and the graphics tablet requiring participant to dissociate the eye and hand gaze in line with automaticity and visual defictis. Also, it was expected that the task measures motor skills in line with the cerebellar theory (Nicolson et al., 1995).

As the DtD task is novel, it is difficult to pin point precisely what it measures. However, there have been some tasks reported in the literature that are somewhat similar to the DtD task (Fawcett & Nicolson, 1994; Stoodley et al., 2006) and could aid the understanding of the DtD task. Such tasks are speeded motor tasks created in line with the cerebellar deficit hypothesis first proposed by Nicolson et al. (1995). The cerebellum, as previously discussed in Chapter 2, is vital for smooth coordination of rapid movements. Children and adolescents with dyslexia were slower than their age- and IQ-matched peers on the Annett peg-moving task (Fawcett & Nicolson, 1994). In this task, children were required to move pegs, which were previously placed in the top row of a board by the experimenters, with the dominant hand as quickly as possible, jumping over the empty row into the third row of holes, while holding the board steady with the non-dominant hand. Similarly to the DtD task, this task required a novel, speeded hand movement. The peg-moving task showed group differences in time taken to complete the series of movements. There were no significant differences between the poor and typical readers in the time they took to complete the DtD task; however there were differences in the measure taking into account the speed-accuracy trade-offs (TimeTotal for dominant hand) which indicates that poor children were compromised when drawing the entire pattern and the time they took was considered. The TimeTotal measure also was a significant predictor of reading scores (explaining 4.4% of variance) on its own. Stoodley et al.'s (2006) study, using a rapid pointing task, showed that the pointing scores combining speed and accuracy contributed significantly to the variance in literacy skills. Although the tasks differed on some key aspects, unlike the DtD task the peg-moving task did not require one to dissociate between eye and the hand gaze, the similarity of those tasks and the findings obtained may point one to the assumption that the DtD task can be construed under the cerebellar deficit theory.

Drawing on the last point, the current investigation did not reveal significant relationships between any of the DtD measures and the Bead Threading task associated with fine motor skills and thus the cerebellar functioning. It is unlikely that the DtD task represents a purely "motor" task, then. Another explanation may be that the Bead Threading task may not be a reliable dyslexia indicator. Performance on the Bead Threading task was not correlated with reading scores which resonates with Barth et al.'s (2010) findings also indicating no association between the Bead Threading performance and academic performance. Similarly, Carroll et al.'s (2016) study did not find motor skills to be predictive of reading level group membership but did find significant group differences (exactly the same pattern of results was found here). Poor readers in the present study were also compromised on the Bead Threading task comparing to typical readers. Also, in the current study there was not a single poor reader whose only deficit was in the Bead Threading task. There were children who showed this deficit along with another deficit, such as DtD, RAN and memory, however. It is possible that the Bead Threading task may not be the best proxy of cerebellar functioning or that individuals with dyslexia may have deficits in a range of cerebellum – related functions and this task may not reflect that. Studies using a range of different motor tasks, such as toe tapping, arm shaking and postural stability (Fawcett & Nicolson, 1999), eye-blink conditioning (Nicolson, Daum, Schugens, Fawcett & Schulz, 200) and time estimation (Nicolson et al, 1995) showed deficits in children with dyslexia. The current investigation would, therefore, benefit from adding more measures of cerebellum – dependent abilities.

The DtD measures compromised in poor readers could reflect a deficit in motor skill learning which would also be in line with the cerebellum deficit theory. Cerebellar impairment may also affect automatisation of skills; the greater its impairment the greater the range of deficits displayed by the poor readers (Nicolson & Fawcett, 1999). Sela and Karni (2012) showed evidence for language-independent deficits in dyslexia that are related to recruitment of motor systems to perform a task requiring learning a new movement sequence. The authors distinguished between a so-called 'on-line' learning that can be observed within a session, and an 'off-line' learning that reflects between-session gains. The latter gains require time and sleep to be expressd, reflecting procedural memory consolidation processes (e.g., Karni et al., 1998), and could not be investigated in the current study as children completed the DtD task only once. It could be argued, however, that the significantly greater total errors made by children identified as poor readers were due to their poor on-line motor skill learning. The task consisted of six trials per each hand so the children would be expected to show improvement with each trial that would lead to better overall score as the total score represents the mean of all six trials. The significantly better score of typical readers may be a reflection of these volitional skills learning processes as being more effective than in children with dyslexia. This only relates to the motor skills acquisition that was arguably measured by the Total Error and Time measures.

The meaning of different results shown on scores obtained while using dominant vs non-dominant hand could be interpreted in the context of the already mentioned 'on-line' learning, but only to some extent. The Total Error and Time measures did not differ between groups when the non-dominant hand was used (performance using this hand was always measured after the dominant hand was used). This may indicate that the task could have been too difficult as it required the use of a hand that was less often practiced hence there might have been more noise, more variability within each of the groups, and the comparisons did not reveal any differences. The 'on-line' learning of these completely new motor skills would require a lot more practice. Beyond the motor skills, however, an interesting cognitive mechanisms may be drawn upon when it comes to the Direction Ratio measure. The lack of group differences in this measure in trials where the dominant hand was used may be fairly easily explained by the fact that all children needed some time to adjust to the rules of a new task and both groups of readers struggled equally. However, when they switched to the non-dominant hand the group differences were found. Children who were indicated as typical readers did not confuse the direction of the first line as much as those identified as poor readers. As the patterns of the dots were repeated (in random order) it is possible that implicit learning of the sequences by the time children saw six patterns took place. This learning was not as effective in poor readers though.

It can be assumed that different DtD measures reflect different skills as they are not strongly correlated with each other. One of the most interesting measures in the DtD task that seemed to be important from the onset of the pilot study were the measures related to the first sector. Similarly to the Touch Sequence Task (TST), developed by Sosnik, Hauptmann, Karni, and Flash (2004) and Sosnik, Shemesh, and Abeles (2007), in which participants were asked to perform rapid and accurate trajectories with their hand, the DtD task required a number of pre-motor processes that perhaps are reflected in the first sector measures. These pre-motor processes could include visual perception, decision making, initiation of a movement and recruitment of motor systems engaging complex feed-forward processes and sensorimotor loops (Sosnik et al., 2004). The first sector measures may also reflect processes such as hand-eye coordination which would be partially supported by its significant correlation with the block design task also requiring such a coordination (Wechsler, 1993, 2004, 2013). What is more, Sela and Karni (2012) suggested that the same parameters may correspond to different sub-systems at different stages of a task practice. This notion was also supported by studies showing different neural representations depending on the level of experience (Bock & Schneider, 2001; Hikosaka, et al. 1999; Karni et al., 1998; Korman, Raz, Flash, & Karni, 2003). Researchers indicated chunking and co-articulation processes that may change movement routine with practice (Engel, Flanders, & Soechting, 1997; Hikosaka, et al. 1999; Sosnik et al., 2004).

Another aspect that could have affected children's performance on the DtD task was their visual attention. This was not tested empirically in the current study. However, further exploration of this would be an important future research direction. In line with a multifactorial view of dyslexia, difficulties of individuals with dyslexia in processing multi-element strings have been shown in the literature (Bednarek et al., 2004; Hawelka & Wimmer, 2005; Pammer et al., 2004; Valdois et al., 2003). Such difficulties might reflect the allocation of attention deficits which could perhaps explain difficulties in the first sector of the DtD task.

Another potential theoretical framework in the context of which the DtD can be interpreted is one of the biological explanations of dyslexia, as discussed in chapter 2, focusing around the visual aspects. The magnocellular-dorsal (MD) deficit hypothesis suggests that cognitive mechanisms controlled by the MD pathway may precede the orthographic-to-phonological mapping that is crucial for successful reading. The MD pathway also is believed to provide a mechanism for the early selection of features in space (e.g., Vidyasagar, 1998) therefore it is possible that it may be related to the DtD's first sector error measures. This hypothesis will be further tested in the following chapter.

5.5 Limitations and directions for further research

Children were categorised as poor readers on the basis of only two readings tests measuring the speed accuracy of non-word and real words reading. This identification, although practised by many researchers (e.g., Carroll et al., 2016; Gori et al., 2016) is not as accurate as a professional diagnosis would be. Also, the reading tests were administered either one, two or three years after the baseline measure and the scores were combined. Data analysis did not allow distinguishing between the long and short term predictors: some studies suggest that some predictors may be more or less stable over time (Rose, 2009). Although the baseline sample size was suitable, not all children took part in all follow-up session, and some children did not complete some of the tasks leading to a fairly substantial loss of participants. As the sample was unselected, the number of children identified as poor readers was not sufficient for some analyses to achieve adequate power. These results then need to be considered with caution.

Further studies should explore the above mentioned explanations for the DtD task in order to find out what is the nature of this task's measures and whether the contribution of these measures to the model predicting reading is due to motor skill acquisition, attentional aspects or low- and high-level visual processing. The importance of the latter processes is addressed in the following chapter.

In term of causality, often researchers conduct a comparison of performance between poor readers and younger reading-level-matched children which can reveal any discrepancies found between the groups that cannot be attributed to their differing reading experience (Bryant & Goswami, 1986; Goswami & Bryant, 1989). The current study did not incorporate such a design due to a small number of children indicated as poor readers who could be matched for reading level. Future studies should, however, include such an analysis.

5.6 Conclusion

The study presented in the current chapter seems to provide some evidence for the DtD task helping to identify reading problems in the long term but little evidence for the DtD being a reliable stand-alone screener. An encouraging finding was that there were three children who displayed single deficit that was in the DtD task. This indicates that there may be a subgroup of poor readers who do not show any of the phonological or reasoning problems but can be identified by means of the DtD task. At this point, it is clear that the DtD measures are associated with some abilities that are important for reading, as one of the DtD measures added to the prediction model; however, the results did not reveal what those skills are. The implications of the current study are that focusing solely on phonological and language related difficulties may not be enough to screen reliably for dyslexia in young children. These are practical implications suggesting a need of a broad range of tests required in order to capture all of the at risk children. The next chapter will explore visual aspects of poor and typical readers and it will aim to investigate if the DtD measure is related to them.

Chapter 6.

Are DtD measures related to low- and high-level visual processing?

Abstract

The current study investigated the novel DtD measure in the context of magnocellular-dorsal deficit theory. As presented in the previous chapter, the DtD measures related to first sector error and speed-accuracy trade-off could significantly add to the model predicting reading. Thus far, no significant correlates were found between these measures and established dyslexia indicators. It is therefore hypothesised that the performance on these measures may be related to visual processing, often indicated as compromised in children with dyslexia. Overall, 171 children (mean age = 8.3 years; SD = 1.8; 45% F) took part in the study. Children's sensitivity threshold to low level (preferentially activating magnocellular and parvocellular cells) and high level (dorsal and ventral) visual stimuli was measured; their baseline and reading performance described in previous chapters was also available. The key findings are: (i) DtD measures for dominant hand that previously showed to be able to distinguish between poor and typical readers significantly correlated with sensitivity threshold to stimuli preferentially activating the magnocellular pathway; (ii) Direction Ratio for non-dominant hand, arguably the best DtD indicator of poor reading, did not correlate with any of the psychophysical tests; and (iii) Coherent Form and Motion tasks, both related to high-level vision processing, could distinguish between poor and typical readers. These findings provide little support for the assumption that the DtD can be interpreted as being in line with MD deficits hypothesis.

6.1 Introduction

The previous chapter showed that some of the DtD measures (e.g., Direction Ratio for NDH, TimeTotal for DH) might help predict reading performance in primary school and pre-school age children. These DtD measures did not correlate significantly with any of the established predictors of dyslexia. Therefore, it is not entirely clear why they seem to play a role in reading. Initially, it was hypothesised that the DtD task may be associated with motor skills. However, in the light of the findings from Chapters 4 and 5, this has not been upheld. This chapter aimed to test the extent to which performance on perceptual tasks believed to be mediated primarily by magnocellular/dorsal processing streams, may contribute to the observed relationship between DtD and reading performance.

The current study aligns to the magnocellular-dorsal (MD) deficit theory (Stein, 2001), discussed in Chapter 2. The theory stems from an observation that there are two visual pathways dominated by two types of neurons: magnocellular and parvocellular that appear to process different attributes of the visual world (Merigan & Maunsell, 1990). M cells appear to subserve sensitivity to low spatial frequencies and rapid time frequencies stimuli at contrast threshold. Dyslexia has been associated with deficits in behaviours related to these magnocellular processes (e.g., Cornelissen et al., 1995; Lovegrove, Bowling, Badcock, Blackwood, 1980).

Evidence supporting the MD deficit theory of dyslexia also comes from research on the perception of coherent motion (CM) which relies on high-level vision processes associated with the dorsal stream (e.g., Boets et al. 2011; Cornelissen et al. 1995; Stein, 2001, 2014; Talcott et al. 2000). Consistent with the MD deficit theory of dyslexia, individuals with diagnosed dyslexia and pre-readers at familial risk of dyslexia are outperformed on CM tasks by their typically-reading counterparts (Boets et al. 2011; Eden et al. 1996; Kevan and Pammer 2008), while performing similarly to the control group on tasks, such as those involving coherent form (Merigan & Maunsell 1993). Coherent (or global) form tasks are believed to be mediated primarily by the parvocellular-ventral pathway (Kevan & Pammer 2009; Gori et al., 2014). Also, research has found that individuals with dyslexia while being sensitive to stimuli preferentially activating the magnocellular function, they are equally good at tasks with stimuli associated with the parvocellular function in comparison to typical readers.

Recently, Gori et al. (2016) showed evidence for a causal role of the MD functioning in dyslexia using causal experimental designs. The researchers found that children with dyslexia were compromised on the motion perception task in comparison to both age-match and reading-level control groups. The deficit in motion perception was also present in pre-reading children at risk of dyslexia. Finally, Gori and colleagues also provided DD children with an intervention in the form of an active video game (AVG) that, as they argued, taps into MD pathway due to its emphasis on rapidly moving objects and perceptual, motor and peripheral processing. They found that reading skills improved after the AVG training in children with dyslexia.

The relationship between the DtD task measures and the MD functioning is proposed in the current study as, presumably, both may involve similar abilities. Cognitive mechanisms controlled by the MD pathway are believed to precede the orthographic-to-phonological mapping. Reading depends on precise visual analysis of the stimulus before any complex integration of orthographic and phonological information may take place (Pammer, Hansen, Holliday, & Cornelissen, 2006; Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005; Pammer, Lavis, Hansen, & Cornelissen, 2004). The magnocellular-dorsal pathway provides a mechanism for the early selection of features in space (e.g., Vidyasagar, 1998) therefore its contribution may also be required while completing the DtD task, especially when planning for the first movement which is reflected in the first sector measures. According to Vidyasagar (1998), the MD pathway identifies and selects relevant regions in space to be then passed onto the ventral pathway. As Stein (2001) and more recently Gori et al. (2016) reiterated, a deficit in the MD pathway function could have a cascade effect on all of the successive cognitive processes.

6.1.1 Research aims and hypotheses

The study will examine the following research questions and hypotheses:

(1) Will performance on vision tasks be correlated with the DtD, reading measures and reasoning measures?

(2) Will performance on vision tests be associated with MD sensitivity significantly differ between poor readers and typical readers? It is hypothesised that there will be group differences in the magnocellular and dorsal sensitivity tasks and that there will be no difference in control tasks associated with the parvocellular and ventral pathways. This pattern of results has been previously shown (Cornelissen, 1998; Stein & Walsh, 1997).

6.2 Methods

6.2.1 Design

The research used a correlational design to examine whether performance on the visual tasks (magnocellular: contrast sensitivity to high spatial and low temporal stimuli; parvocellular: contrast sensitivity to low spatial and high temporal stimuli; dorsal: coherent dot motion task; ventral: coherent form task) outlined in the Materials section was related to the DtD task and reading tasks. In addition, a between-subjects, quasi-experimental design was implemented, with the level of reading as a grouping (independent) variable with two conditions (poor readers vs typical readers). The dependent variables were the participants' performance on four visual tasks.

6.2.2 Participants

Overall, 171 children (mean age = 8.3 years; SD = 1.8; 45% F) with normal or corrected-to-normal vision participated in the study. The participants were from two different schools, each located within different catchment areas characterised by different socioeconomic status: school 1: low SES (n = 94), school 3: high SES (n = 77). School 2 was not included due to lack of time and available facilities to conduct the tests. For details on the schools' profiles and ethical considerations see Chapter 3.

6.2.3 Materials

The summary of the measures together with the test batteries that they were derived from is presented in Chapter 3. The visual tests are provided in Table 6.1 below; the descriptions of the tasks are provided in the following sections.

Table 6.1

Visual tests used in the study

Skill	Task/measure
Magnocellular sensitivity	Contrast sensitivity: low special and high temporal frequency (M)
Parvocellular sensitivity	Contrast sensitivity: high special and low temporal frequency (P)
Dorsal stream sensitivity	Coherent motion task (CM)
Ventral stream sensitivity	Coherent form task (CF)

6.2.3.1 Apparatus

All stimuli were designed using Psykinematix version 2.0 software (KyberVision Japan LLC) and a MacBook Air (1.6 GHz dual-core Intel Core i5 with 3MB shared L3 cache). Children were exposed to stimuli on three different monitors: MacBook Air 13.3-inch; LED-backlit glossy widescreen display with native resolution of 1440 x 900, 60Hz), CRT Dell (17-inch) and CRT Mitsubishi (17-inch). The use of different monitors was motivated by research showing that the CRT monitors are more suitable for vision research (Ghodrati, Morris, & Price, 2015). As the CRT monitors are not manufactured anymore, it was difficult to find one in a good working condition. Both Dell and Mitsubishi monitors were first used but they broke down after few days of data collection. Therefore, finally the majority of tests were conducted on the MacBook monitor.

A one-way multivariate analysis of variance was run to determine the effect of the type of monitor on visual tests performance. Measures of vision sensitivity thresholds associated with four areas were assessed: magnocellular, parvocellular, dorsal and ventral. Descriptive statistics are presented in Table 6.2. The differences between the monitors on the dependent variables was not statistically significant, $F(8, 166) = .658$, $p = .728$; Pillai's Trace = .061; partial $\eta2 = .031$. Due to the lack of evidence for different performance depending on the type of monitor used, the results obtained from trials using all three monitors were combined for the analyses in the following sections.

Table 6.2
Descriptive statistics for visua l tests scores obtained using three monitors

	Monitor (N)					
task	MacBook (57)		CRT Dell (15)		CRT Mitsubishi (16)	
	Mean	SD	Mean	SD	Mean	SD
M	-0.031	0.609	0.080	1.707	-0.297	0.193
P	0.005	0.486	0.049	0.831	-0.144	0.385
CM	-0.033	1.017	-0.128	0.993	0.158	0.920
CF	.122	1.006	-.248	.986	-.217	.986

Note. M = magnocellular; P = parvocellular; CM = coherent motion task; CF = coherent form.

Stimuli were presented at a viewing distance of 60cm; the participants were seated at the correct distance and asked to not move during the trials. The field of view was set as 26.99 x 17.06 degree. All data collection took place in a room with the lights switched off, with only natural light coming through the windows with shades. As the study took place in the schools, complete control over the light levels was not possible. Participants viewed the screen binocularly. The screen was always sheltered with a screen shade to protect it from the direct light exposure (an example shown in Figure 6.1).

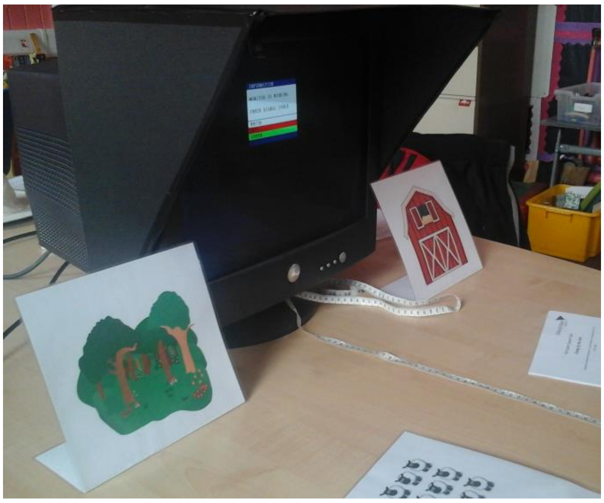

Figure 6.1 Shaded monitor with pictures of the forest and barn to the sides (for the coherent dot motion task)

6.2.3.2 Visual tasks

The calculated threshold defined the minimum level of coherence or contrast (depending on a task) required to produce conscious awareness of a stimulus. For all tasks, a staircase method was used to determine a threshold. The staircase was set up as 3-up 1-down which means that after three correct responses the rate of contrast (in the contrast sensitivity test) or the rate of coherence (in CM and CF) was decreased and after one incorrect response the rate was increased. After the first three correct responses, the rate decreased by 50% (from 100% down to 50% in case of the CF task). Every consequent rate decrease was set up at 12.5%. Each incorrect response is called a reversal and the reversal rate was set up at 25%. Once the sixth reversal was reached, the task stopped and the threshold was calculated by averaging the sensitivity rate from all of the reversals (arithmetic threshold estimation based on troughs). The tests were piloted with 30 children to decide on the optimal number of reversals (the bigger the number of reversals the longer the task takes time). Children tended to get disengaged or bored if the task had more than six reversals.

To address potential difficulties with left/right side confusion, children had a choice to indicate answers verbally by naming the objects that were placed to the left and to the right of the screen (barn and forest) or point with their finger; the researcher keyed in the responses using a keyboard. For all of the tasks, a practice session preceded the main test trials.

Low-level processing: magnocellular and parvocellular at the level of retina

Contrast sensitivity

Two tasks measuring low-level visual sensitivity were used. Low spatial frequency (0.25 c deg^{1}) sinusoidal gratings, counterphase-modulated at high temporal frequencies (15Hz), to preferentially stimulate *magnocellular* (M) pathway and high spatial frequency (2 c deg^{1}) sinusoidal gratings of low temporal frequencies (5Hz) to stimulate *parvocellular* (P) pathway, were used. Grating stimuli were presented for 1 second in the middle of the screen on a grey background. The gratings were either vertical or horizontal, and participants were instructed to indicate the orientation on each trial.

Children were told that they would see some zebras running away in the mist and that their job was to spot them and indicate (either by hand gesture or by a verbal response) the position of the zebras' stripes: up or sideways. Similar instructions were previously used in research (Kevan & Pammer, 2009) and they seemed to be an adequate explanation of the task appealing to children. Screenshots for both tasks are presented in Figure 6.2.

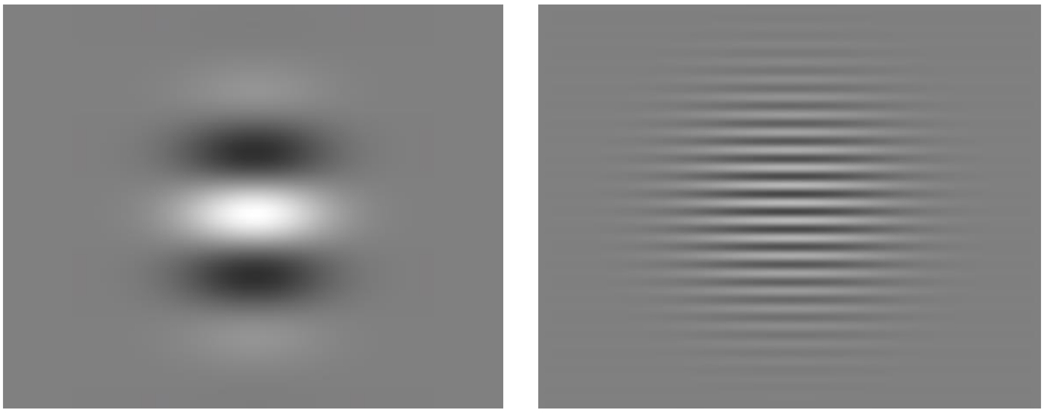

Figure 6.2 Stimulus designed to preferentially activate the magnocellular system (left) and the parvocellular system (right)

Single cell physiology studies with monkeys (Merigan & Maunsell, 1993; Merigan, Katz, & Maunsell, 1991) and humans (Wolf & Arden, 1996) with magnocellular or parvocellular cells lesions support the idea that their function can be measured by means of contrast sensitivity tasks.

High-level processing: dorsal and ventral stream at extrastriate level

Coherent motion (CM)

A random dot kinematogram (RDK) consisting of a patch of 100 white dots (0.1°) randomly distributed within a 23° ×23° region on a black background was used. A variable proportion of the dots moved coherently (signal dots), at a velocity of 4.4 deg/s, either to the left or to the right amongst the remaining randomly moving dots (noise dots) along with Kevan and Pammer’s (2009) study. Stimuli were presented as 18-frame sequences, with each frame lasting 16.7 ms. To ensure that participants did not track the path of a single signal dot, both the random dots and the dots carrying the coherent signal had a limited lifetime of 50ms (3 frames).

Children were told that the white dots were sheep seen from a distance that were running away to the forest (right) or to the barn (left) and they had to decide which way the most of them were going. A schematic representation of the stimuli (in the middle) and the pictures of the barn and forest are shown in Figure 6.3.

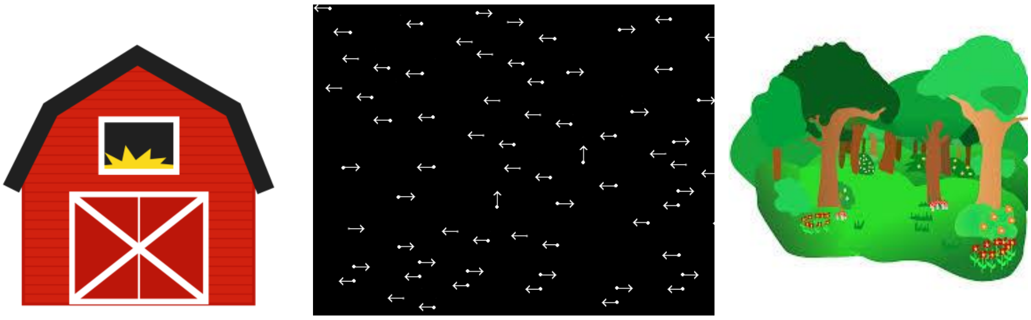

Figure 6.3 Random dot kinematogram stimuli used in the Coherent Motion (CM) detection task. Arrows are added for presentation purposes.

The initial coherence was set up at 95% and then it was manipulated using a staircase method explained above. The threshold level reflects the lowest percentage of coherently moving dots required to detect motion direction.

The task is believed to rely upon processing within the dorsal stream, specifically in the middle temporal visual area-MT (Newsome & Paré, 1988). While motion perception is just a single function of the dorsal stream pathway, it is the most accepted proxy of dorsal functioning (Boets et al., 2011; Kevan & Pammer, 2009; Olulade et al., 2013; Sperling, Lu, Manis, & Seidenberg, 2006; Stein, Talcott, & Walsh, 2000).

Coherent form (CF)

A static array of 900 oriented white line segments presented within a 23°×23° patch was used. The target stimulus was a 23° x 11.5° region defined by line segments that were oriented tangential to concentric circles. On each trial the target circles were presented randomly to the left or to the right of the centre of the display for 1800ms (see Figure 6.4). The size of the line segments used in the form task was 0.25° x 0.05°. Noise stimuli were line segments that were oriented randomly. Children were told that the white lines are pencils randomly thrown on a table where some magical creatures came to put them in a circular shape but managed to do so only on one side of the table. Participants were asked to indicate which side of the screen contained the circular pattern by showing the side with a finger or indicating verbally.

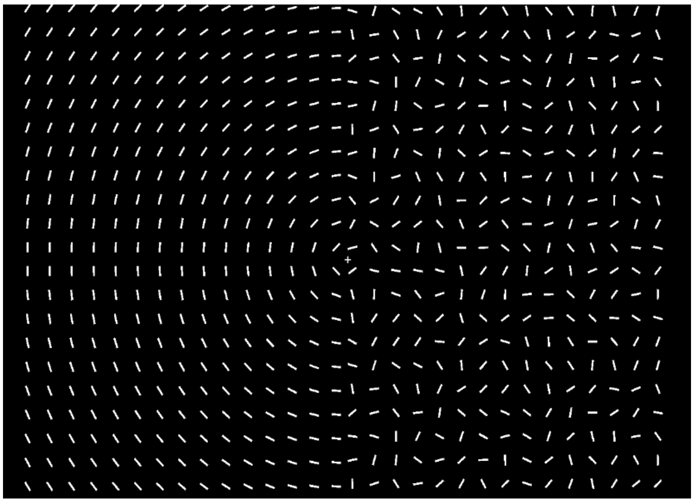

Figure 6.4 Coherent form task. A perfectly coherent half-circle is seen to the right, the left side is incoherent.

This task is a test of global form processing and acts as a control task for the CM task as it is believed to be associated specifically to the ventral stream functioning (Braddick, O'Brien, Wattam-Bell, Atkinson, & Turner, 2000).

6.2.4 Procedure

Children were tested on the vision tests during a follow-up testing session involving reading tests (see Chapter 5) The order of tasks was randomized. The whole session lasted approximately 30 minutes. Children had a practice session for each test before proceeding to the test trials. Children were assured that they could stop or take a break whenever they wished. The time to complete the tasks was not recorded.

6.3 Results

6.3.1 Data treatment

Some children did not complete the full set of tests. It was, therefore, important to investigate whether there were any patterns to the missing values. Little's MCAR test, as a part of the missing values analysis, was conducted to investigate if the missing values found in the data set were missing completely at random (MCAR). The test was non-significant (χ^2 (28) = 27.297, p = .502) which indicated that the missing data were missing at random. It was decided that the best method of managing missing data was to use pairwise deletion method because it allows using as many cases as possible for each analysis. The B-H procedure was used to control for Type 1 error.

Other considerations that were described in Chapter 4 - that the incomplete DtD trials were disregarded; that the phonological processing tests derived from LucidRapid; and DEST-2/DST-J were combined and the poor English speakers deselected - still apply in the current chapter. The vision tests scores were residualised for age.

6.3.2 Descriptive statistics

Descriptive statistics for each of the tasks are provided in Table 6.3. The table shows raw scores to get the idea of the threshold levels. However, the following analysis uses residualised scores to account for age. The mean for residualised scores was always 0 and the standard deviation was close to 1.

Table 6.3
Descriptive statisticsfor the vision tests thresholds

task	N	Minimum	Maximum	Mean	SD
M	135	0.390	44.240	3.068	6.034
P	118	<0.001	9.111	0.986	1.908
CM	118	22.230	81.250	65.049	16.374
CF	118	20.750	76.350	45.181	12.165

Note. M = magnocellular; P = parvocellular; CM = coherent motion task; CF = coherent form;

6.3.3 Relationships between the vision tests, selected Dot-to-Dot task, dyslexia sensitive and reasoning measures

To establish which skills and abilities the DTD task measures are associated with, an investigation of its relationships with the vision tests was conducted. Correlational analyses were conducted to investigate the relationships between the four vision tests and dyslexia-sensitive and reading tests.

The correlation analysis included only those DtD measures that could distinguish between poor and typical readers and those which added to reading prediction model as determined in Chapter 5. The following measures were included: Dominant hand:

First sector max. error, Total error, Time total, FirstDown First sector max. error, FirstUp First sector max. error. Non-dominant hand: Direction ratio.

Table 6.4 presents correlation between the above DtD measures, the vision tests and reading scores.

Table 6.4
Spearman's correlations between selected DtD measures, vision and reading tests

	Coherent motion	Coherent form	Magno-cellular	Parvo-cellular	Reading
DH First sector max.err.	-.030 (N = 118)	.111 (N = 120)	**.339*** (N = 114)	.180 (N =114)	**-.281*** (N = 207)
DH total error	.076 (N = 118)	.024 (N = 120)	**.305*** (N = 114)	.161 (N = 114)	**-.272*** (N = 207)
DH FirstDown First sector max.err.	-.073 (N = 118)	.038 (N = 120)	**.324*** (N = 114)	.209 (N = 114)	**-.234*** (N = 207)
DH FirstUp First sector max.err.	.022 (N = 118)	.130 (N = 120)	**.299*** (N = 114)	.103 (N = 114)	**-.258*** (N = 207)
DH TimeTotal	.056 (N = 118)	.084 (N = 120)	**.372*** (N = 114)	**.233*** (N = 114)	**-.289*** (N = 207)
NDH Direction ratio	.029 (N = 98)	-.176 (N = 100)	.036 (N = 95)	-.061 (N = 94)	**.202*** (N = 171)
Coherent motion	-	.118 (N = 107)	-.028 (N = 107)	.078 (N = 106)	-.162 (N = 123)
Coherent form	.118 (N = 107)	-	**.258*** (N = 107)	.206 (N = 103)	**-.351*** (N = 128)
Magnocellular	-.028 (N = 107)	**.258*** (N = 107)	-	**.469*** (N = 116)	**-.397*** (N = 123)
Parvocellular	.078 (N = 106)	.206 (N = 103)	**.469*** (N = 116)	-	**-.293*** (N = 124)

Note. * significant at the *q* adjusted level.

Significant correlations were found between all of the selected dominant-hand measures and sensitivity to the magnocellular-activating stimuli. All of these correlations were of weak strength and of positive direction sharing from 9% to 14% of variance. Also, the TimeTotal measure significantly correlated with the parvocellular test sharing 5% of variance. The non-dominant hand Direction Ratio measure, that had previously been shown to significantly contribute to the model predicting reading, did not correlate with any of the vision tests.

The vision tests also significantly correlated with each other. The M and P tasks were positively correlated sharing 22% of variance. The coherent form task also correlated with the magnocellular task sharing 7% of variance.

To explore the possibility that the tasks used in the current study were related to children's reasoning was further explored. Table 6.5 presents correlations between the verbal and nonverbal reasoning skills and the vision tasks.

Table 6.5
Spearman's correlations between vision and reading tests

	Matrix reasoning	Block design	Verbal reasoning
Coherent motion	.009 (N = 125)	.100 (N = 125)	.001 (N = 124)
Coherent form	**-.248*** (N = 133)	**-.203*** (N = 133)	**-.239*** (N = 132)
Magnocellular	-.123 (N = 126)	-.127 (N = 126)	**-.270*** (N = 125)
Parvocellular	-.047 (N = 128)	-.099 (N = 128)	-.057 (N = 127)

Note. * significant at the *q* adjusted level.

The coherent form task showed a significant, weak and negative correlation with both verbal and non-verbal reasoning skills indicating that the highest threshold of the form coherence is needed for children to recognise a shape the lower the reasoning skills. Verbal reasoning also correlated with the magnocellular task. It was therefore further investigated whether verbal reasoning could be a mediator between the magnocellular and DtD tasks. A partial correlation between the magnocellular task and most of the DtD measures controlling for verbal reasoning showed that the above presented significant correlations were no longer significant [DH First sector max. error: $r_s = .236$; $p = .023$, $q < .019$; DH Total error: $r_s = .159$; $p = .130$; DH FirstDown First sector max. error: $r_s = .204$; p = .051; DH FirstUp First sector max. error: $r_s = .201$; $p = .055$; DH TimeTotal: $r_s = .210$; $p = .045$, $q < .020$].

As previously discussed in chapter 4 and 5 (pp. 158 and 182, respectively), it may be problematic to investigate correlation in the cross-section of children, therefore a subsequent analyses were conducted in order to explore the correlations between the key DtD measures and the visual tests separately for poor and typical readers. The results are presented in Table 6.6.

Table 6.6
Spearman's correlation coefficients conducted separately for groups of typical and poor readers

	CF	CM	M	P

typical	DH TimeTotal	-0.003	0.054	**.331***	**.324***
		(n = 97)	(n = 94)	(n = 90)	(n = 91)
	NDH DR	-0.141	0.048	0.013	-0.070
		(n = 83)	(n = 78)	(n = 74)	(n = 75)
poor	DH TimeTotal	0.157	-0.107	**.585*** [a]	0.018
		(n = 17)	(n = 20)	(n = 20)	(n = 18)
	NDH DR	-0.121	0.065	0.243	0.229
		(n = 13)	(n = 16)	(n = 17)	(n = 15)

Note. *significance at the B-H adjusted level; [a] p = 0.007 (the p value not adjusted due to small number of participants)NDH DR = non-dominant hand direction ratio; DH TimeTotal = dominant hand measure accounting for time and accuracy trade-off; CF = Coherent Form; CM = Coherent Motion; P = parvocellular; M = magnocellular.

The results reveal that the TimeTotal measure for dominant hand is statistically significantly correlated with both low-level visual contrast sensitivity; the correlations were of weak strength sharing only 10% to 11% of variance. This was only the case in the group of typical readers. The poor readers' investigation showed only one significant correlation: between the TimeTotal measure and sensitivity to stimuli preferentially activating the magnocellular pathway, sharing 34% of variance. Fisher's R to Z transformation conversion revealed that the significant correlations between TimeTotal and M for the typical readers (r = .331) and for the poor readers (r = .585) were not statistically different (Z = -1.23; p = .110). The Direction Ratio measure that uniquely added to model variance explanation was not significantly correlated with any of the visual measures.

One of the concerns of the above analysis is a small number of participants in the poor reading group which could perhaps explain lack of significant correlations found between measures that were related in the typical group. This assumption was further investigated using the post-hoc power analysis for the correlation analyses (using G*Power 3.1.9.2; Faul et al., 2007). Measuring for moderate strength (r = .32) α set at 0.05 (following the norm; no adjustment due to small sample size) the analysis indicated 1-β to be .59. This indicated that the analysis was not powered enough to capture even a medium effect.

6.3.4 Visual sensitivity in poor readers and typical readers

The following set of analyses aimed to compare performance on the vision tests between two groups: poor readers and typical readers based on the combined scores on Nonsense passage and Speeded reading tests. Poor readers were identified if they scored below 1 SD of the mean on the reading tests. The remaining children were classified as typical readers. Table 6.7 presents means and standard deviation on the four visual measures for poor and typical readers.

Table 6.7
Means and standard deviations for poor and typical readers on vision tests (residualised scores)

	poor readers			typical readers		
task	*n*	mean	SD	*n*	mean	SD
M	24	0.229	1.190	99	-0.048	0.961
P	21	0.059	0.654	103	0.008	1.073
CM	23	0.279	0.533	100	-0.103	0.991
CF	19	0.509	1.106	109	-0.121	0.952

Note. M = magnocellular; P = parvocellular; CM = coherent motion task; CF = coherent form

An independent samples t-test was conducted to compare the performance between the two groups on Coherent Form and Coherent Motion tasks (skewness and kurtosis for both were within the acceptable range). Due to the nonparametric distribution of the two remaining tests (M and P), the Mann-Whitney U test was conducted. As multiple comparisons were conducted, to control for Type I error, the Benjamini-Hochberg (BH) Procedure was used (Benjamini & Hochberg, 1995) to establish threshold value for each *p*-value.

The independent samples t-test showed that children identified as poor readers performed significantly poorer (M = 0.51, SD = 1.11) than the typical readers (M = -0.12, SD = 0.95) on the coherent form task ($t(126) = -2.602$, $p = .010$; significant with the BH adjusted q value $< .01$; Cohen’s $d = .611$, medium effect size). Poor readers also performed significantly poorer (M = 0.28, SD = 0.28) than the typical readers (M = -0.10, SD = 0.99) on the coherent dot motion task ($t(62.199) = -2.562$, $p = .013$; $q < .025$; Cohen’s $d = .480$; small effect size).

Multiple Mann-Whitney U tests revealed no significant differences between the two reading groups on the M task (U = 1502.00, p = .045; q < .038) or on the P task (U = 1189.00, p = .474).

6.4 Discussion

The aim of this study was to explore the idea that the DtD task measures showed to be important in reading were related to visual aspects in line with magnocellular-dorsal (MD) deficit theory of dyslexia. Four psychophysical tasks associated with magnocellular, parvocellular, dorsal and ventral stream functioning were used. The current investigation was of importance as it was expected that it would reveal the visual skills that are related to the novel DtD test. Also, due to the debatable nature of previous findings on the magnocellular pathway and dorsal stream deficits in developmental dyslexia, the present study contributed to this debate by measuring the sensitivity in a relatively big sample of children. This is particularly the case as most of the previous research used very small samples of children (most recently Gori et al., 2015 with just seven participants in each group) or selected samples with children at familial risk of dyslexia.

The current investigation demonstrated that many of the DtD measures predominantly correlated with the magnocellular processing, which in turn, significantly correlated with reading. This, however, seemed to be mediated by verbal reasoning as the relationships between the DtD measures and magnocellular sensitivity were no longer statistically significant after controlling for verbal reasoning. It could be perhaps explained by a lack of understanding of the task which seemed very new for children. However, the order of the magnocellular and parvocellular tasks (which are very similar) was counterbalanced therefore it seems unlikely that children could not follow the instructions of only one of the tasks, and not the other.

It was also hypothesised that children who were identified as poor readers on the basis of two reading tests, taking into consideration both accuracy and speed of reading, would be less sensitive to flickering gratings of low spatial and high temporal frequency (associated with magnocellular sensitivity) and to the coherent movement of dots (dorsal-stream sensitivity), compared to typical readers. Poor readers were expected to perform similarly to typical readers on the control tasks; that is, on contrast sensitivity to gratings of high spatial and low temporal frequency (parvocellular) and on the coherent form task (ventral stream). These hypotheses were not fully supported. Poor readers were shown to be less sensitive to the coherent motion stimuli showing higher thresholds needed for these children to be able to perceive the direction of movement of the dots. This group difference showed small effect size, however.

This finding corresponds to previous research to some extent (Gori et al., 2015) as it seems to support the idea that dorsal stream functioning may be selectively compromised in children with reading disability. However, there were no significant group differences found between contrast sensitivity thresholds associated with the magnocellular pathway. This indicates that poor readers show a deficit in high-level visual processing, but not in low-level processing at the retina level. This agrees to some of the previous research, as the field in the last ten years has shifted focus from the pure magnocellular deficit theory first proposed by Stein (2001) and has now further looked into the dorsal dysfunctions in individuals with dyslexia.

These findings must be considered carefully, however, as the task used in the current study that was associated with the magnocellular function differed in some respects from those used in some previous studies. Some studies which have shown significant differences between groups used 2-alternative forced choice paradigm (2-AFC) (e.g., Cornelissen et al., 1995), where one batch containing moving dots was shown after another and participants had to determine which one was faster or slower. This type of task has been criticised for relying on short term memory or temporal judgements (Peli & Garcia-Perez, 1997). The tasks in the current study uses forced-choice task where the choice needs to be made whilst stimulus is displayed, or right after. Such a paradigm does not require working or short-term memory therefore it is more likely to indicate pure problems with cells' sensitivity regardless of the cognitive load. Since the current study found no significant difference between poor and typical readers using forced choice task, this may add to criticisms put forward by Peli and Garcia-Perez (1997) suggesting that previous evidence showing such differences was confounded by memory, which is known to be compromised in children with dyslexia.

Another contrasting to previous literature finding is that the magnocellular and dorsal tests scores did not correlate with each other. Previous studies have shown that the dorsal stream receives the majority of the input from the magnocellular cells (Enroth-Kugel & Robson, 1966; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982), therefore it would have been expected that performance on the tasks associated with the magnocellular and dorsal stream function would be related. The pattern of results may be explained in two ways. In line with Stein's (2001) magnocellular deficit theory, the deficit may be located somewhere along the visual pathway, therefore, it is possible that only high-level visual processing may be affected in some individuals leaving the low-level processing intact. Under this assumption, correlation between low and high level visual processing would not be found. This particularly seems to be the case in the current research as poor readers showed deficits only in the dorsal stream, but not in the magnocellular-related, functioning,. A fairly recent review (Schulte-Körne & Bruder, 2010) found an inconsistent evidence for contrast sensitivity tasks but more supportive evidence for a role of coherent motion processing. In addition, several studies showed that approximately one-third of individuals with dyslexia display motion processing deficits (Conlon et al., 2012; Conlon et al., 2009; Ramus et al., 2003; Wright & Conlon, 2009). Another possible explanation is that the tasks used in the current study were not precise enough to activate the assumed pathways, which will be further discussed in the limitations section.

In the current study, it was also expected that the two reading groups would not differ in their performance on the ventral stream-activating task which would show the dissociation between the functions of dorsal and ventral visual streams. The current findings did not provide evidence to support this idea. In contrary, poor readers needed a higher proportion of coherently organised lines to be able to spot a circular shape than typical readers. The effect size of this significant difference was medium. The Coherent Form task also correlated with reading. Although it is not in line with the MD deficit theory, the findings can be understood in the context of the previous research. It has been quite established that the ventral stream takes part in visual processing of fine details, such as letters (Dehaene & Cohen, 2011). Therefore, it has been shown that activation of this part of the brain is related to reading. This provides evidence against a deficit in dyslexia that is specific to dorsal stream functioning but points to the idea that generally high-level vision processes may be deficient in poor readers.

6.4.1 Limitations and directions for further research

There were a number of limitations in the current study which could have affected the results and that need to be considered before drawing final conclusions. First, data collection took place within the schools' classrooms where the light levels could not be controlled. Although the author made sure that there was no direct sun light on the screen by shading the monitor and covering window blinds, there remains a possibility that the level of light could have affected the visibility of the screen. This is of particular importance in terms of the contrast sensitivity task. Another limitation of the study was that there was no explicit control over the children's head movements. Children were asked to not move their heads during the tests and they were seated in the best viewing position (visual angle and the distance from the screen were calculated); however, some would still move slightly during the task. The author assured the children could have a break and recommence the task at any time in order to avoid fatigue. Again, with the contrast sensitivity tasks the children's movement could have affected their perception. This is especially the case when a laptop (with LED monitor) was used. These two limitations could explain why the results from both of the contrast tasks did not show an expected pattern.

It is also possible that the tasks were not preferentially activating the MD or PV streams as intended. Some researchers suggest that the best way to activate the magnocellular and parvocellular cells using psychophysics would be by the pulsed- and steady-pedestal paradigms (Pokorny & Smith, 1997)[9]. Also, previous research

[9] The author attempted to use the pulsed- and steady-pedestal paradigm following Pokorny and Smith's (1997) work. However, during the piloting of the task, it turned out that the tasks were too difficult for children. Therefore the simpler contrast sensitivity tasks were used instead.

has used sophisticated equipment (Humphrey FD machine) and a frequency doubling illusion to measure the low-level vision processing (Kevan & Pammer, 2009). Other researchers argue that psychophysical stimuli are not good enough to measure the different cells' responsiveness (Skottun, 2000). It could be further argued that the findings indicate that low-level visual sensitivity, as tested using commercially-available hardware, is unlikely to provide an effective way of screening for potential dyslexia in pre-reading children.

Another aspect of the current study that was different than in previous studies was that the poor and typical readers were not matched for IQ level and age. Full IQ, in particular, was not possible to control for due to lack of time to administer the full-scale test. However, when controlling for verbal reasoning, the correlation between the magnocellular functioning and the DtD measures disappeared. This may indicate that children who struggled with the vision tasks did so not because of the poor visual processing but because they did not fully understand the task, as has been argued, too, in the earlier chapters.

6.5 Conclusion

The findings of the current study do provide evidence that the DtD task is related to visual skills that are believed to be specific to the low-level visual processing in the magnocellular pathway. Sensitivity to the magnocellular-activating stimuli did not, however, differ between the poor and typical readers. Therefore, the current investigation did not help in identifying visual skills related to the DtD task that would also play a role in reading. The results do, however, provide evidence for high-level visual processing deficits related to both dorsal and ventral visual streams processing in children with reading problems. This further adds to the discussion on the nature of dyslexia and it can be recognised that dyslexia is most likely related to a number of deficits rather than a single one such as the phonological processing deficit.

One of the crucial limitations of the studies involving children presented so far is that there was no professional dyslexia diagnosis provided. Therefore, the study presented in the proceeding chapter will investigate this issue with an adult sample which includes individuals with and without a DD diagnosis.

Chapter 7.

Investigation of performance on the DtD task, dyslexia screening and reasoning tasks in adults with and without developmental dyslexia

Abstract

The current study investigated adults' performance on the novel DtD test. Participants with formal dyslexia diagnosis (*N* = 37; mean age = 27.76 y.o.; SD = 10.92 years) comprised the DD group and those who self-reported no reading problems were in control group (*N* = 37; mean age = 24.76 y.o.; SD = 6.29 years); groups were matched for age, gender and occupation. The key findings were: (i) the DtD TimeTotal measure for non-dominant hand related to speed and accuracy trade-off could distinguish between individuals with and without dyslexia and it could also correctly categorise almost 64% of them; (ii) none of the established dyslexia screening or reasoning measured were significantly associated to the TimeTotal measure; (iii) the best indicators of dyslexia, correctly categorising 90% of participants, were phonological processing and word construction tests. These findings indicate that the DtD task is more likely to be underpinned by the automaticity, rather than phonological deficit theory. The results show that phonological processing is most predictive of reading problems. However, casewise analyses revealed that only 24% of readers with dyslexia display deficits in one area which is in line with multiple deficit model. One of the limitations of the current study was the use of highly functioning sample of individuals with dyslexia, therefore, further studies should aim to obtain more representative sample in order to confirm the current findings.

7.1 Introduction

Reading and writing difficulties in children with dyslexia tend to persist into adulthood (Bruck, 1992; Swanson & Hsieh, 2009). Previous research has demonstrated a range of possible deficits manifested in adults with dyslexia (Swanson & Hsieh, 2009), and based on the findings in the previous chapters, it is clear that language-based phonological problems are only one of many possible problems. Adults for whom English is not the first language or those who do not exhibit phonological deficits may not be accurately screened for dyslexia using already existing screening tests, and a test which is associated to aspects outwith language problems is desirable. The previous chapters have shown that the DtD task has shown some potential in predicting reading performance in young children. The overarching aim of the current chapter is therefore to investigate the potential usefulness of the DtD task in screening for an adult sample.

An advantage of using an adult sample was that a subsection of them had a formal dyslexia diagnosis, which was not available in child samples. This is important in addressing the question whether individuals with dyslexia are compromised on the DtD test and if yes, which measures are indicative of their poor performance. While a similar question was posed in Chapters 5 and 6, it was not possible to fully address it due to lack of professional diagnosis in child populations participating in these studies.

7.1.1 Research aims and hypotheses

The present study aimed to investigate the performance of the novel DtD task in a sample of adults and to explore its correlates with standardised cognitive and dyslexia screening tests. Due to the novelty of the DtD task, the current research examined various measures which the software generates to indicate those correlated with the standardised tests. This also allowed to comment on the convergent and discriminant validity of the measures. Due to a possibility that participants with dyslexia who took part in the study were affected by this disorder differently and had learned various coping strategies, it was an imperative to test the types of weaknesses they experience.

The following research questions were formulated:

(1) Will the performance on dyslexia screening, the DtD and reasoning measures differ between adult participants with and without developmental dyslexia? It was hypothesised that performance on dyslexia screening tests (Phonemic Segmentation, RAN, Bead Threading, Memory, Word Recognition, and Word Construction), the DtD task measures and reasoning tests (Similarities, Matrix Reasoning, Block Design, non-verbal and verbal reasoning) will significantly differ between dyslexia and age-, gender- and occupation-matched control group.

(2) Will the performance on various dyslexia screening tests be related to reasoning tests and the DtD task in adults?

(3) How well the DtD task can classify individual into those with and without dyslexia? Which of the dyslexia screening and DtD measures will be the best predictors of dyslexia in adults?

(4) Is there evidence for multiple deficits in dyslexia, or is there one common deficit? What proportion of adults shows weaknesses in each area?

7.2 Methods

7.2.1 Design

The research utilised a between-subjects, quasi-experimental design, with dyslexia diagnosis as a grouping (independent) variable containing two conditions (dyslexia and control). The dependent variables were the participants' performance on a range of tasks outlined in the Materials section. Logistic regression analysis was conducted to see which factors predicted the membership of each group. Correlational analyses were also conducted to determine if the variables tapping into different skills were related. The study was conducted in two phases: the participants were tested on the DtD task and then they were invited to return and complete a number of cognitive and dyslexia screening tests in phase two.

7.2.2 Participants

Overall, 111 individuals (age ranged from 17 - 66 years of age, mean age = 27.36 years; SD = 10.39; 72% females) with normal or corrected-to-normal vision participated in the study. All participants gave informed written consent to take part once procedures had been explained. Participants were recruited using email advertisements via an email distribution list at Edinburgh Napier University which specified the inclusion criteria: participants with diagnosed developmental dyslexia (to form the dyslexia group), and individuals who self-reported as not having any reading difficulties (control group). Participants who thought they might have dyslexia were also invited to maintain the nature of unselected sample for the correlational analyses. Snowball sampling was implemented.

Thirty-seven participants had a diagnosis of developmental dyslexia (68% F). Participants within this group were aged between 17 - 62 years (mean = 27.76 years; SD = 10.92 years). There were two bilingual participants in this group. Out of the 62 participants who self-reported as experiencing no reading problems, 37 (70% F) were selected for the comparison group. They were age, gender and occupation matched with the dyslexia group. Participants within this group were aged between 17-46 years (mean = 24.76 years; SD = 6.29). There were two bilingual and four participants who spoke English as a second language in this group. Table 7.1 presents details of the variables the two groups were matched on. The table shows that the two groups did not significantly differ in terms of their age, gender and occupation.

Table 7.1

Dyslexia and control groups' characteristics and group comparison statistics

		Dyslexia group (N=37)	Control group (N=37)	Group difference
Mean age		27.97	24.76	$t(72) = -1.552$,
95% CI		[24.45, 31.49]	[22.73, 26,79]	$p = .126$
SD		10.92	6.29	
Gender	females	25	26	$\chi^2(1) = 0.63$,
	males	5	6	$p = .802$
Occupation	students	32	31	$\chi^2(1) = 0.11$,
	employees	5	6	$p = .744$

Although it is possible that some participants were both students and had jobs, they were asked to identify their main/primary occupation; for instance, if they were full-time students and also worked part time they would indicate that being a student was their main occupation.

The participants who volunteered to take part in the study and had no dyslexia diagnosis but thought that they might have had dyslexia created a ‘not sure’ group (*n* = 11; 64% 7F). The individuals in this group were aged between 23 and 60 years (mean age = 38.18 years; SD = 13.69). One participant, who was initially included into this group, was flagged as ‘at risk’ of dyslexia by the LADS dyslexia screening tool and decided to seek a professional assessment. This participant received a diagnosis provided by an educational psychologist within the university and therefore was included in the dyslexia group. The remaining participants from the ‘not sure’ group were not included in the final analysis.

The possibility of attention deficit disorder or developmental coordination disorder in the participants, which are known to comorbid with developmental dyslexia, was not assessed; however, no participant reported a diagnosis of either of these.

7.2.3 Materials

The summary of all of the measures together with the test batteries that they were derived from is presented in Table 7.2 below. Short descriptions of the tasks are provided in the following sections. The dyslexia screening tests were tested for internal reliability. Cronbach’s alpha was .753, which is acceptable.

Table 7.2
A summary of all the tests used in the study, what skills they measure and what test set they were derived from

Skill	Task/measure	Test Set
Phase one		
DtD	First Sector Max Error (FSME); Total Error (TE), Time (T), SD2, Direction Ratio (DR), TimeTotal (TT)	Dot-to-Dot
Phase two		
Lexical decoding (phonological processing & lexical access)	Word recognition (WR)	LADS/ LADS Plus
Lexical encoding (phonological processing)	Word construction (WC)	LADS/ LADS Plus
Working memory	Backward digit span (BDS)	LADS/ LADS Plus
Non-verbal reasoning	Non-verbal reasoning N-VR)	LADS/ LADS Plus
Verbal reasoning	Verbal reasoning (V)	LADS Plus
Phonological Processing	Phonemic segmentation & spoonerisms (PS&S)	DAST
Processing speed and lexical access	Rapid automated naming (RAN)	DAST
Motor skills	Bead threading (BT)	
Perceptual reasoning and visuo-motor skills	Block design (BD)	WAIS-III
Perceptual reasoning	Matrix reasoning (MR)	WAIS-III
Verbal comprehension	Similarities (S)	WAIS-III
Working Memory	Digit span (DS)	WAIS-III

7.2.3.1 The Dot-to-Dot task

The computer and tablet-based DtD task was used. A more detailed explanation of the task in provided in Chapter 3 section 3.4.1. The measures generated by the software were following: *Time* in seconds, *First Sector Maximum Error (FSME)* between the first two dots of each pattern, *Total Error (TE)*, and *TimeTotal* a measure of speed and accuracy trade-off and *SD2* measure indicated the count of the points (pixels) over 2 standard deviations relative to the perfect fit line. Lower scores on all these measures are indicative of better performance. *Direction Ratio* (DR) measured the direction accuracy of the first line being drawn by the participants. The value of 1 indicated that all patterns had a correct direction and 0 indicated all wrong direction. The calculation distinguishing between the two types of patterns was a feature added in the middle of the data collection (without affecting the results) therefore these values are not available for the participants who took part in the study at the beginning (n = 44).

7.2.3.2 Lucid LADS and DAST

The tests described below were derived from The *Lads Dyslexia Screening* The tests described below were derived from The Lads Dyslexia Screening software v. 5.X (Lucid Research, 2004) and Lads Plus Dyslexia Screening v. 6.05-N (Lucid Research, 2014). Both Word Recognition and Word Construction tasks employed a CAST (Computerised Adaptive Sequential Testing) technique in which blocks of items of known difficulty are adapted sequentially (Drasgow & Olson-Buchanan, 1999). The CAST utilises fractionation algorithm that assigns individuals to dyslexia risk category depending on their performance on each module. The scores for WR, WC and WM tasks may range from 1 to 9 where the higher the score achieved, the higher the probability of dyslexia. Scores above 7 can be interpreted as a strong indication of dyslexia (high risk), scores between 6 and 4 as a weak indication (borderline) and scores below 3 as no indication (low risk). Reasoning tasks (N-VR and VR) were scored from 1 to 5, where the higher the score, the better the performance. The reasoning tests were included in order to improve an accuracy of dyslexia detection in bright and well-compensated individuals with dyslexia. The non-verbal reasoning test is always administered first allowing adjusting the time limit in the WR and WC tasks; a very bright person will have time limit decreased. Hence, LADS and LADS Plus were built on a model of dyslexia screening that encompasses key dyslexia indicators (phonological processing and working memory) and performance that are below expectations based on estimated intelligence. A study by Singleton et al. (2009) showed that this test demonstrates sensitivity and specificity rates of 90.6 % and 90 %, respectively.

Word Recognition (WR). A test of lexical decoding involving speeded discrimination between real word and non-words, taken from Lucid-LADS. On each trial, five words appear on the screen in random positions. Only one word was real (e.g. *toad*) and the other four were pseudowords (e.g. *tode*, *troad*, *todday*, *toap*). The participants needed to click on the real word as quickly as they could. A new item appeared after 30 seconds if no response was given. However, individuals who scored high (within 10% of the population) on reasoning ability, administered before this test, were allowed to spend a maximum of eight seconds on each item. The test began with four practice items accompanied with auditory instructions. Figure 7.1 presents an example screen from this task. The cognitive processes required for this task are rapid retrieval from real word mental lexicon and rapid and efficient phonological decoding to eliminate distractors.

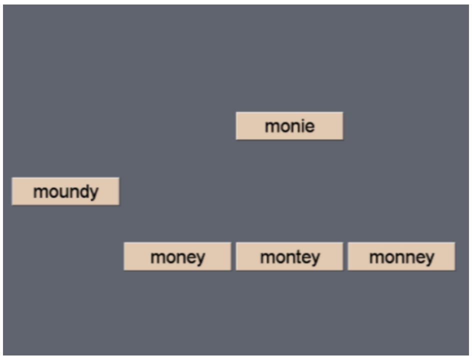

Figure 7.1 Example screen from the LADS word recognition test

Word Construction (WC). Word construction is a test involving speeded lexical encoding of non-words from syllables. The computer spoke a three-syllable non-word and the participant needed to select from nine different syllables the ones that made up this non-word in the right order and press an arrow at the bottom to proceed to the next item (see Figure 7.2). Response needed to be given within 30 s (or six seconds for individuals with high reasoning ability). The test begans with two practice items accompanied with spoken instructions. The cognitive processes required in this task are following: good phonological awareness (ability to segment the spoken word into syllables), good auditory short-term working memory (simultaneous processing of syllables on the screen and retaining the heard non-word in the phonological loop), an efficient phonologic encoding (grapheme-phoneme correspondence).

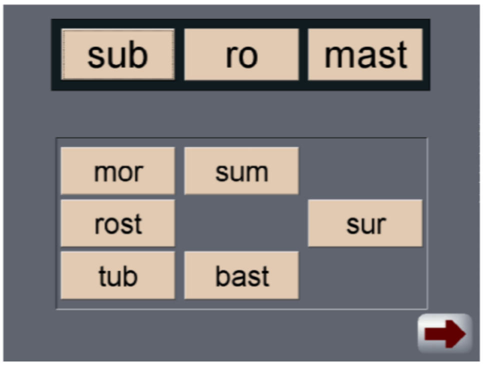

Figure 7.2 Example screen from the LADS word construction test

Backward digit span (BDS). Backward digit span is a measure of working memory. A sequence of digits was spoken, and the participant needed to enter these in reverse order using the keyboard. Two practice items (with verbal instructions) were followed by the test starting with two digits in sequence, up to nine digits. Each level contained two items. The program terminated after two incorrect items within the same level. The time limit was also given.

Non-verbal Reasoning (N-VR). This test involves matrix puzzles requiring logical reasoning. Individuals needed to choose which of the six squares at the bottom of the screen complete the pattern (see Figure 7.3).

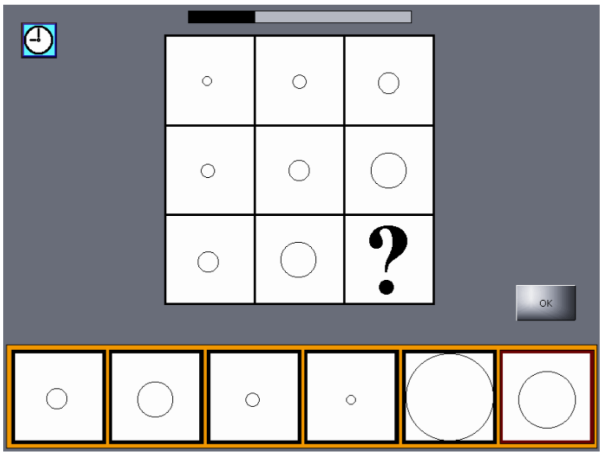

Figure 7.3 Example screen from the LADS Non-verbal Reasoning test

Verbal Reasoning (VR). This test was a new addition to the new version of LADS: LADS Plus). In this task two pictures were presented on the screen and the participants need to choose one of six words that provides the best conceptual link between the two pictures (see Figure 7.4).

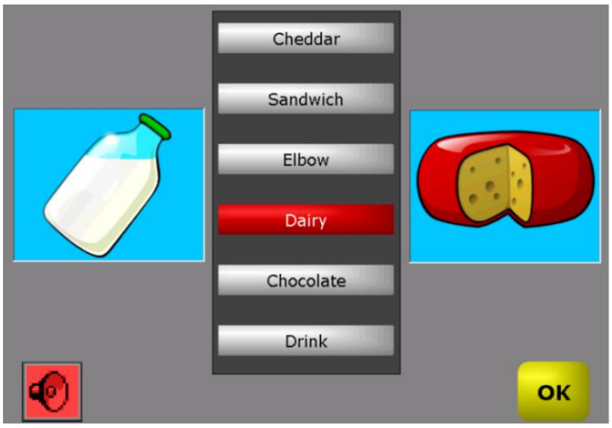

Figure 7.4. Example screen from the LADS Verbal Reasoning test

The following tests were derived from the Dyslexia Adults Screening Test (DAST).

Rapid Automatised Naming (RAN). In this task, participants were required to name 40 outline drawings as fast as they could (see Chapter 3). Practice with half of the pictures was given prior to the timed task. The scores in seconds were converted into age standardised scores.

Phonemic segmentation & spoonerisms (PS&S). A measure of phonological processing. This test consisted of two parts that measured phonemic segmentation abilities. In the first part, participants had to manipulate single, real words (for instance ‘say “doormat” without the “mat”’). Twelve items were administered preceded by three practice items. The second part was a Spoonerism task where participants were asked to exchange the beginning sounds of two words. The words were well-known names (e.g., ‘Michael Jackson’ would become ‘Jichael Mackson’). Following one example and one practice item, three test items were administered. Both speed and accuracy (no points if the participants took longer than 50 seconds to come up with the answer) were recorded. The maximum score for the full test was 15.

Bead Threading (BT). The test measures fine motor skills, hand-eye co-ordination and manipulative skills. This task was included in the DEST-2 and in DST-J (both designed for children) but does not appear in the adults’ version of dyslexia screening (DAST). However, it was decided to include this test for consistency across the thesis’ research investigations.

The scoring of these tests utilises an at-risk quotient (ARQ). For each of the subtests, participants’ raw scores are first converted to visual codes using scoring keys based on age. For instance, a triple minus (- - -) indicates that performance falls at least 3 standard deviations below the mean for that particular subtest. In the current study the codes were converted into numerical scores and treated as data at scale level of measurement with 1 corresponding to code (- - -), 2 corresponding to (- -), 3 to (-), 4 to (0) and 5 to (+). Reliability and validity have been demonstrated in dyslexic adult and student samples (Nicolson & Fawcett, 1997).

7.2.3.3 Intelligence tests: WAIS-III

The Wechsler Adult Intelligence Scale (WAIS-III) was designed for people at the age of 16 years and over (Wechsler, 1997). The average reliability coefficients for all measures range from .82 to .93 in typical and reading disorder samples (Wechsler, 1997).

Block Design (BD.) Participants were asked to re-create a design using red-and-white blocks (from a constructed model or a Stimulus Book) within a specified time. There were 14 items in total worth four points each. If any of the last six items was completed quickly, a time bonus was awarded. The test discontinued after three consecutive scores of zero. The maximum possible raw score is 68. The task was designed to measure the ability to analyse and synthesise abstract visual stimuli. It involves nonverbal concept formation, visual perception and organisation, simultaneous processing, visual-motor skills, learning, and the ability to separate figure and ground in visual stimuli.

Matrix Reasoning (MR). In this task, participants looked at an incomplete matrix and selected the missing part from five response options. This test had 26 items (preceded by three practice items) designed to measure visual information processing and abstract reasoning (continuous and discrete pattern completion, classification, analogical reasoning and serial reasoning). The test is seen as a measure of fluid intelligence and general intellectual ability.

Digit Span (DS). This test comprises two parts: Digit Span Forward (repeating numbers in the same order; 16 items) and Digit Span Backward (repeating in the reverse order than presented by the examiner; 14 items). Each part consisted of two trials with the same number of digits. The test was discontinued after two scores of zero within one item. This test was designed to measure auditory short-term memory, sequencing skills, attention and concentration. Specifically, the skills required for the first part of the test were rote learning and memory, attention, encoding and auditory processing, the second part involved working memory, transformation of information, mental manipulation and visuospatial imaging.

Similarities (S). In this task two words representing common objects or concepts were presented (verbally) and a participant needed to explain in what way they are similar (e.g., 'In what way are ICE and STEAM alike?'). There were 19 items. The test was discontinued after 4 consecutive scores of zero. The task was designed to measure verbal reasoning and concept formation. It also requires good auditory comprehension, memory, ability to distinguish between non-essential and essential features, and verbal expression.

The raw scores obtained in these tests were converted into age normed scores. The scaled scores range from 1-19, where 1 indicates scores below 3 standard deviations, 4 in below 2 standard deviations, 10 indicates the mean, and 19 indicates scores beyond 3 standard deviations.

7.2.4 Procedure

Participants were tested individually in person in Edinburgh Napier University's Psychology laboratories. The instructions to every task were given verbally with time allocated to ask questions if needed. Following completion, participants were thanked and excused.

All participants were tested on the DtD test during the first phase of testing. Fifty-two per cent of the participants came back within a year to complete the second phase during which they completed a number of dyslexia screening and reasoning tests. The detailed information regarding participants' occupation, level of English, when they were diagnosed and family history of dyslexia was only collected on the second session, therefore, the information is incomplete.

7.3 Results

The results section is divided into two main subsections reflecting the study design. The first section is focused on the analyses of differences in the DtD task, dyslexia-sensitive and reasoning tasks between two groups: participants with developmental dyslexia and those who self-reported having no reading problems. In the second subsection, the analyses of relationships between the DtD, dyslexia screening tests and reasoning skills are provided. The analysis subsections are preceded with a data treatment section.

7.3.1 Data treatment

7.3.1.1 Standardising and combining scores

The two standardised tests used in the study (WAIS-III and DAST) required the raw scores to be converted into age and population (students vs general population; only in DAST) standardised scores. The age categories recommended by the two scales corresponded to each other only to some extent (see Table 7.3).

Table 7.3
Age categories provided by DAST (Dyslexia Adults Screening Test) and WAIS-III (Wechsler's Intelligence Scale)

DAST	WAIS-III
Students 16:6-21	16-17
Students 22-24	18-19
Population 16:6-24	20-24
Population 25-34	25-29
Population 35-44	30-34
Population 45-54	35-44
Population > 55	45-54
	55-64
	65-69

A preliminary analysis was conducted in order to investigate a need to standardise the DtD scores in adults. The aim was to investigate if there were any differences in DtD performance between participants in different age and population groups proposed by the WAIS-III and DAST. First, the sample was grouped according to WAIS-III criteria, and then the sample was grouped according to the DAST criteria. Next, two analyses (one-way MANOVAs) were conducted to test for the differences. There were no significant differences in the measures between the age and population categorised groups (following DAST guidelines), F(161.000, 31.468) =

1.597, p = .061, Wilk's Λ = <.001 and between age categorised groups (following WAIS-III guidelines), F (161.000, 31.468) = 1.402, p = .133, Wilk's Λ = <.001. These results indicate that performance on DtD did not differ between age groups. For this reason, raw scores for all of the DtD measures were used in the following analyses.

Before conducting the analyses of differences and relationships, it has been considered whether some of the measures should be combined due to common skills they are deemed to test. A principal component analysis (PCA) and factor analysis were considered. However, due to small sample size (*n* ranging from 36 to 57) and data violating the assumption of normality, these analyses were deemed inappropriate. In order to make a decision, a preliminary correlational analysis was therefore conducted to investigate the strength of any relationships, and whether the tasks reflected the same skills (see Table 7.4).

Table 7.4
Spearman's correlations between dyslexia screening and reasoning tests

	Block Design	Matrix Reasoning	Digit Span	Phonemic Segment.& Spoonerisms	Similarities
Non-Verbal Reasoning	**.431***	**.396***	**.352***	**.401***	.085
	(N = 56)	(N = 56)	(N = 56)	(N = 56)	(N = 56)
Verbal Reasoning	-.219	.372	.198	.055	.190
	(N = 33)	(N = 33)	(N = 33)	(N = 33)	(N = 33)
Word Recognition	-.035	-.180	**-.606***	**-.348***	-.285
	(N = 56)	(N = 56)	(N = 56)	(N = 56)	(N = 56)
Word Construction	-.124	-.109	**-.376***	**-.412***	-.123
	(N = 56)	(N = 56)	(N = 56)	(N = 56)	(N = 56)
Backward Digit Span	**-.305***	-.278	**-.366***	**-.400***	**-.341***
	(N = 56)	(N = 56)	(N = 56)	(N = 56)	(N = 56)

Note. * significance at the B-H adjusted level

Phonemic Segmentation & Spoonerisms task (DAST) and Word Recognition and Word Construction (LADS) tasks were all measures of phonological processing; however, they were only moderately correlated with 12% to 16% of the shared variance. Backward Digit Span (LADS) and Digit Span, that involved both backward and forward digit span (WAIS-III), were both measures of working memory. They were also moderately correlated with 13% of the shared variance. The Non-Verbal

Reasoning task (LADS) moderately correlated with other reasoning tasks: Block Design and Matrix Reasoning (WAIS-III) with 16% to 19% of the shared variance. Verbal Reasoning task (LADS) did not significantly correlate with Similarities task (WAIS-III) which deemed to test the same cognitive skills. This preliminary analysis showed that the tasks derived from different test sets, some from paper-based tests (DAST, WAIS-III) and some from the computer based tests (LADS) were not strongly correlated. Therefore, the tasks were not combined for the remaining of the inferential analysis.

As multiple comparisons were conducted, to control for Type I error Benjamini-Hochberg (BH) Procedure was used (Benjamini & Hochberg, 1995) to establish a threshold value for each *p*-value.

Descriptive statistics will be presented along with inferential analyses.

7.3.2 Differences in performance on the DtD, dyslexia screening and reasoning tests between individuals with and without developmental dyslexia.

The following set of analyses compared performance on the DtD task, dyslexia-sensitive, the and intelligence tests between individuals with developmental dyslexia and a control group. The data obtained from the two groups were not parametric, as assessed by consulting skewness and kurtosis. Multiple Mann-Whitney U[10] tests were run, as they were deemed more appropriate. Distributions of the scores for dyslexia and control group were not similar, as assessed by visual inspection.

In terms of the DtD measures, no significant differences were found on the speed and accuracy measures (for details see table B-9 in Appendix B). However, there was one significant difference on the measure that combined Time and Total Error

[10] Some of the variables met parametric test assumptions, however the results between t-test and Mann-Whitney U test did not differ, therefore, for clarity of results' presentation, this table presents only Mann-Whitney U tests results.

for non-dominant hand (TimeTotal). Dyslexic group performed significantly[11], poorer (M = .184, SD = .621) than the control group (M = -.184, SD = .397): $t(61.25) = -3.033$, $p = .004$, Cohen's d=.707 (medium effect size). This is illustrated in Figure 7.5. This shows that normal readers were less vulnerable than dyslexic readers to speed and accuracy trade-off when they were using their non-dominant hand.

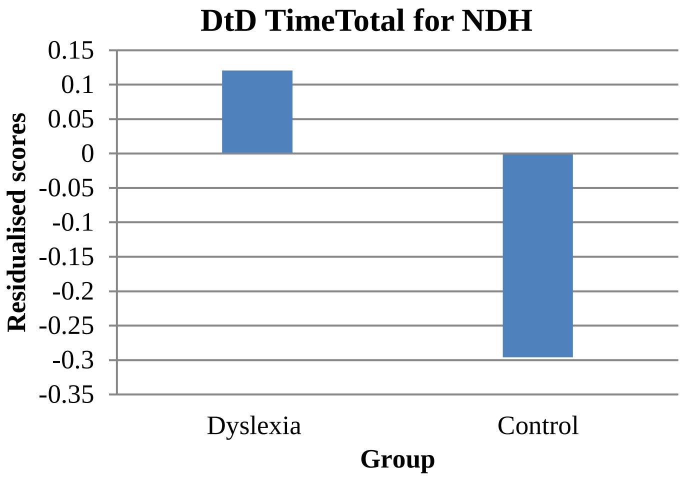

Figure 7.5 Differences between dyslexia and control group on DtD TimeTotal for non-dominant hand measure.

The scrutiny of the group differences in dyslexia screening tests showed that dyslexic readers performed significantly poorer on the Word Recognition (U=389.5; $p < .001$; $\eta^2 = .331$), Word Construction (U=389.5; $p < .001$; $\eta^2 = .331$), Working Memory (U=361; $p < .001$; $\eta^2 = .288$), Digit Span (U=83.5; $p < .001$; $\eta^2 = .264$) and Phonemic Segmentation (U=54; $p < .001$; $\eta^2 = .443$) tasks. The effect sizes show that 26% to 44% of the variability in the mean ranks is accounted by the independent variables. The detailed results are provided in table B-10 in Appendix B.

7.3.3 Prediction of group membership based on the standardised screening tests and the DtD measures.

Discriminant analysis was considered in this context to predict a group membership based on the available standardised as well as novel measures. However, due to the violation of some of its assumptions (normal distribution, equal variances), this

[11] Data for this group comparison were parametric and met the t-test assumptions. T-test analysis proved to be more sensitive than Mann-Whitney U test (that showed p=.008), therefore these result were reported here.

analysis could not be conducted. Logistic regression was, therefore, an appropriate alternative.

A binomial logistic regression was performed to ascertain the effects of DtD measures (TimeTotal for non-dominant hand) on the likelihood that participants have developmental dyslexia. Only this DtD measure was included in the regression as it was the only measure that distinguished between dyslexic and control groups as presented in the previous section. The forward stepwise (Wald) method was used. The linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell (1962) procedure. The model which was statistically significant, $\chi^2(1) = 8.392$, $p = .004$, and explained 14.3% (Nagelkerke R^2) of the variance in dyslexia and correctly classified 63.5% of cases. Sensitivity was 62.2%, specificity was 64.9%, positive predictive value was 63.9% and negative predictive value was 63.2%.

A binomial logistic regression was performed to ascertain the effects of phonological processing (PS&S, WR, WC), rapid naming (RAN), and working/short-term memory (BDS, DS), on the likelihood that participants have developmental dyslexia. Only one of the DtD measures (TimeTotal for non-dominant hand) was included in the regression as it was the only measure that distinguished between dyslexic and control groups as presented in the previous section. The forward stepwise (Wald) method was used. The linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell (1962) procedure. The logistic regression included two significant factors (Phonemic Segmentation & Spoonerisms and Word Construction) in the model which was statistically significant, $\chi^2(2) = 37.848$, $p < .001$. Table 7.5 presents the contribution of both of the predictors in the model.

Table 7.5
Logistic regression predicting likelihood of dyslexia and control group membership

	B	SE	Wald	*df*	*p*	Odds Ratio	95% CI for Odds Ratio Lower	Upper
PS&S	-2.927	1.045	7.854	1	.005	.054	.007	.415
WC	1.255	.602	4.342	1	.037	3.507	1.077	11.417

Note. WC = Word Construction, PS&S = Phonemic Segmentation & Spoonerisms (PS&S) tasks. *p < .05; N=40

The model explained 88% (Nagelkerke R^2) of the variance in dyslexia and correctly classified 95% of cases. Sensitivity was 87.5%, specificity was 100%, positive predictive value was 92.3% and negative predictive value was 100%. The model with the two predictors remained significant ($\chi^2(2) = 33.095$, $p < .001$) after controlling for verbal reasoning.

Power analysis for a logistic regression was conducted using the guidelines established in Lipsey and Wilson, (2001) and G*Power 3.1.9.2 (Faul et al., 2013) to determine the achieved power given the sample size ($n = 40$) using an alpha of 0.05, a medium effect size (odd ratio = 3.47) and two-tailed test. Based on the aforementioned assumptions, the achieved power was .75. Therefore, the results for this model were not adequately powered.

7.3.4 Relationships between performance on the Dot-to-Dot, dyslexia sensitive and reasoning tests

In order to establish what skills and abilities are associated with the DtD task, correlational analysis was conducted. Spearman correlations were conducted due to non-normal distributions of the scores as tested by investigating skewness and kurtosis. Tables B-11 and B-12 (Appendix B) present correlations between the DtD measures, dyslexia screening and reasoning measures. None of the correlations turned out to be statistically significant (all ps > .05).

Post-hoc power analysis for the correlations (using G*Power 3.1.9.2; Faul et al., 2007) measuring for moderate strength (0.4, following Cohen's conventions), with α set at 0.05 (following the norm) indicated 1-β to be 0.89. It was, therefore, concluded that the study was adequately powered for the correlational analyses.

7.3.5 Investigating areas of weaknesses in individuals with dyslexia

The question around which deficits are shown by participants who had formal dyslexia diagnosis and those who did not is addressed in this section. 17 participants with diagnosed dyslexia completed all of the additional measures derived from Lucid Lads, DAST and WAIS-III. Table 7.7 presents the proportion of these participants showing weaknesses in the areas measured by these tests and the DtD task. Weaknesses are defined here as scores 1SD below the sample mean (for DtD), below the score of seven on reasoning tests (equivalent to -1SD below the sample mean), below the score of 2 on Lucid Lads, and the scores below of - , - - , or - - - on DAST. The majority of participants showed deficits in two areas.

Table 7.6
Combination of deficits found in individuals with dyslexia

Number of deficits	*n* (%) of poor readers	Combination of deficits (*n*)
1	4 (24)	PP (1), RAN (1); M (2);
2	9 (53)	M & RAN (3); M & PP (4); PP & NVR (2);
3	3 (17)	DtD & M & RAN (1); PP & M & RAN (1); VR & PP & M (1)
5	1 (9)	DtD & NVR & VR & PP & M (1)

Note. M = memory component (deficits on eaither the ASM or DS); NR = non-verbal reasoning (BD or MR),VR = verbal reasoning; PP = phonological processing; RAN = rapid automatised naming; DtD = dot-to-dot.

7.3.6 Dyslexia risk

Dyslexia risk as assessed by LADS was not of key importance, however, the sensitivity and specificity of this screening tool were interesting to explore. Table 7.12 presents the number and percentage of adult participants who had a formal dyslexia diagnosis, those who self-reported no reading difficulties and those who were not sure if they had dyslexia and their risk estimate according to LADS.

Table 7.7
Number of readers with and without dyslexia and which risk group they were assigned to by LADS

		Dyslexia risk N (%)			
dyslexia	*N*	high	borderline	low	not assessed
Yes	37	4 (21)	9 (47)	6 (32)	18
No	63	4 (11)	6 (17)	26 (72)	27
Not sure	11	1 (20)	1 (20)	3 (60)	6
Total	111	9	16	35	111

Note. Dyslexia risk assessed by Lucid LADS; percentages are calculated out of the number of participants who were tested

The sensitivity of the LADS test, that is the percentage of adults with dyslexia who were indicated as at high or borderline risk, in the current study was 68%. The specificity level was 72%.

7.4 Discussion

Previous studies have suggested that, together with a well-established phonological deficit present in developmental dyslexia, visual, motor and attentional problems often occur. Despite the controversy around theories aiming to explain the causes of dyslexia, it has been recognised that efficient screening for dyslexia is imperative. This is the case in both workplace and educational context (see Chapter 1 for a full discussion). A screening tool that would not rely on language and phonological coding would be particularly useful for estimating dyslexia risk in non-native English speakers. In order to inform academic debate regarding the co-occurrence of the DtD task-related deficits with skills known to be compromised in dyslexia, the present study aimed to investigate performance on the DtD task in a sample of adults and its correlates with standardised cognitive and dyslexia predicting tasks. This study further aimed to investigate whether any of the DtD measures had the potential to identify individuals with and without dyslexia, in line with the earlier findings in the child population.

Performance on the DtD task, along with all the screening and reasoning tests, was compared between groups of individuals professionally diagnosed with developmental dyslexia, and age, gender and occupation matched control groups.

Only one of the DtD measures could significantly distinguish between the two groups. This measure was the TimeTotal for non-dominant hand which indicates that individuals with dyslexia showed a speed-accuracy trade-off when they joined the dots with their non-dominant hand. A prediction model contacting this measure could also correctly categorise almost 64% of readers into DD or non-DD. This particular measure turned out to be predictive in the child sample used in the previous chapter, however was not strong enough to add to the model comprising other measures. The finding also contrasts with the pilot study (see Chapter 3) with adults which showed that the first sector maximum error was significantly greater in dyslexia group than in the control group. The pilot study, however, did not use a measure accounting for both time and error as this measure was added for the purpose of current investigation.

The current finding could be linked to studies using speeded motor tasks in line with the cerebellar deficit hypothesis first proposed by Nicolson et al. (1995). The cerebellum is essential for smooth coordination of rapid movements which explains why some dyslexic children and adults have slower, more uncoordinated performance on motor tasks. For example, on the Annett peg-moving task, adults with dyslexia were slower than their age- and IQ-matched peers (Stoodley & Stein, 2006). Stoodley, Fawcett, Nicolson, and Stein (2006) found that dyslexic adults were outperformed by controls on a combined speed-accuracy measure during rapid pointing, which is similar to the current result. Stoodley et al.'s (2006) study, however, showed that the pointing scores contributed significantly to the variance in literacy skills. This could not be tested directly in the present study as literacy skills were not measured.

The significance of the non-dominant hand measure could be interpreted in the context of procedural learning (Nicolson & Fawcett, 2007). There is an assumption that adult participants had enough practice over the years of education to work on their writing skills, which are assumed to approximate the DtD task or any other skills that DtD requires. It can be proposed that some individuals who could have been compromised on the said skills as children, along with the previous studies' findings, could have improved through experience which is reflected by the lack of group differences in performance in trials where the dominant hand was used. As the non-dominant hand does not tend to be practised as much, the performance deficits in this hand remain in adulthood.

Previous research also indicated that adults with dyslexia are slower on a speeded pointing task compared to controls (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Velay, Daffaure, Giraud, & Habib, 2002). The current findings do not entirely correspond to this. The level of the participants' intelligence could play a role in this, Bonifacci and Snowling (2008) suggested. They showed that only low-IQ poor readers were slower on processing-speed measures. Individuals with dyslexia who took part in the present study did not differ in their reasoning skills from the control group which may explain why differences in speed were not found, as would have been expected based on past research findings. The current results, therefore, provide evidence for lack of slow motor processing amongst adults with dyslexia.

Further group comparisons demonstrated that individuals with dyslexia performed significantly poorer on most of the dyslexia predictors (Word Construction, Memory and Phonemic Segmentation and Spoonerisms), apart from the RAN task, than the control group. These findings correspond to some extent to the previous literature. Hatcher et al. (2002), who also used a sample of university students, found that students with diagnosed dyslexia were also outperformed by the control group on short-term memory and working memory tests, on spoonerisms, a measure of phonological skill, the test that was also included in the phonological test in the current study, and on processing speed. The lack of significant differences between the two groups in the RAN test in the current study, however, contrasts with previous findings (Hatcher et al., 2002; Norton & Wolf, 2012; Savage & Frederickson, 2006). This could be perhaps explained by the tasks used in previous and the present study. Previous research used more than one RAN measures (Hatcher et al., 2002) or included the rapid naming of digits or letters which arguably may be more demanding than a single task with pictures (Norton & Wolf, 2012; Savage & Frederickson, 2006).

Cirino et al. (2005) presented evidence that the dyslexia predictors may differ depending on the type of definition and criteria used in order to classify individuals into reading disabled/dyslexic and normal readers. Specifically, they found that phonological awareness or visual naming speed deficits were not particularly good at predicting reading disability defined as timed coding or comprehension deficit. The importance of definition and its impact on results was also evident in the previous study involving child sample. In the current study, all of the DD participants reported being professionally diagnosed with dyslexia. This does not mean that the participants' cognitive and learning profiles were similar. The current study had no access to the diagnosis reports; however, it can be assumed that the diagnosis was given on the basis of the discrepancy definition, which is a common practice (for discussion see Chapter 2). This would indicate that the participants' reading level was significantly lower than a level expected of their intelligence. Also, it is not certain what difficulties did the participants experience as a result of their dyslexia. This is important in the context of the thesis' over-arching debate in regards to the nature of dyslexia and its manifestations and individuals with dyslexia could be indicated as such on the basis of their various weaknesses.

The discriminant function analysis performed by Hatcher and colleagues (2002) showed that it is possible to correctly classify individuals into DD or non-DD readers on the basis of their performance on nonsense passage reading, writing speed and verbal short-term memory. Unfortunately, the current study did not include measures of reading which could be seen as a limitation. However, the tasks that were included in the prediction model in the current study (Phonemic Segmentation and Spoonerisms and Word Construction) were sufficient to correctly classify 95% of the individuals. The Lucid LADS indicated only 21% of the DD individuals as at high risk, 47% at borderline risk and 32% as at low risk. This indicates that the Lucid LADS was not an accurate screening tool for the current sample. In line with previous chapters' findings, it can be speculated that good reading relies on more than just the phonological processing and intelligence. The LADS test used in the current study measured only phonological processing and memory levels, also controlling for reasoning measures, which may not entirely explain reading difficulty thus giving inaccurate risk assessment.

As the task under the current research investigation was novel, it was important to identify correlates of this task with other standardised measures in order to be able to comment on the convergent and discriminant validity of the test. The DtD measures did not correlate with any of dyslexia sensitive and reasoning measures. This contrasts with the child sample's results demonstrating weak but statistically significant correlations with phonological processing, RAN, memory and reasoning measures. This discrepancy of findings between the adult and child samples can be explained by a small sample of adult participants and insufficient power. This is especially important, as the expected correlations would be of weak strength which, by default, would require a big sample to be able to detect. The multivariate correction to control Type I error was applied along with guidelines (Benjamin & Hochberg, 1995) however can be seen as quite stringent for such a small sample. The small sample could also explain that the prediction models did not include any of the DtD measures. This also stands in contrast to Stoodley et al.'s (2006) analysis which revealed that the visually guided pointing scores (accuracy and time combined) were the best at predicting the literacy level. Carello, LeVasseur, and Schmidt (2002) found that their sequential finger tapping task associated with cerebellum functioning was related to phonological decoding (Nicolson et al., 1999).

7.4.1 Limitations and directions for further research

One of the key limitations of the present study was that a non-probability sampling and snowballing were implemented to recruit the participants. The sample cannot be seen as representative of the population. The majority of participants were students and Edinburgh Napier University staff. One can assume that these individuals were academically able or may have developed coping strategies that let them succeed in an academic context. This can be supported by the Lucid LADS test's results. Of all the participants with diagnosed dyslexia who completed the test (n = 19), only four were indicated as at high risk of dyslexia, nine were borderline and six were at low risk. A high percentage of the participants with developmental dyslexia were diagnosed in their adults/student life which may indicate that despite not getting any support throughout the primary and secondary education they still managed to enter higher education. It may be expected then that was a select group with better than average coping strategies and possibly no co-morbid difficulties (Callens et al., 2012). Furthermore, sample bias may be present within this study as participants volunteered to take part in the research in their own time, and the study was advertised as involving dyslexia. It is, therefore, probable that the participants had a particular interest in psychology research and dyslexia before taking part. Future research should include more representative sample and should also include more measures verifying their dyslexia manifestations.

7.5 Conclusion

The current study seems to suggest that the DtD task may not be a useful addition to already existing dyslexia screening tests for adult students and highly achieving populations. This study provides little evidence for the potential utility of the DtD task in helping to identify dyslexia in adults. From the correlational analyses, it seems clear that the DtD is not related to the key predictors of dyslexia that are established within the literature, such as phonological processing, memory or rapid naming. This task was also not associated with a fine motor skills task, the bead threading task. In contrast to the findings derived from a similar investigation of the child sample, the DtD task turned out to be unrelated to reasoning abilities. Participants with diagnosed dyslexia performed poorer when both the accuracy and speed of their performance was considered than their non-dyslexic counterparts. In terms of the prediction model however, phonological processing tests were sufficient to correctly identify 95% of the participants. Future studies should be more specific with their sampling techniques and seek to obtain representative samples. Also, they should include reliable measures of motor, visually guided motion skills and perhaps attentional tasks in order to understand the DtD task and the set of skills it requires.

Chapter 8.
General discussion

8.1 Introduction

The present research was concerned with the investigation of whether non-linguistic, sensorimotor deficits underlie developmental dyslexia, and if so, whether they can be used for screening in the child and adult populations. The practical value of the thesis was in the examination of whether a novel DtD task could be used on its own or as an addition to existing screening tools and to establish whether any measures from this test could reliably predict future reading performance in primary-aged children and in adults. The research also aimed to contribute to the theoretical debate on the possible core deficits in and causes of dyslexia: the nature of dyslexia was, therefore, a prominent theme throughout the thesis.

The DtD task was developed in response to a number of serendipitous observations of children with dyslexia who showed clumsiness and poor eye-motor coordination whilst taking part in drawing and walking games. The DtD task was assumed to pose difficulties in performance of individuals with dyslexia as it presumably requires to dissociate the eye and pen gaze; thus to divide attention. The pilot study preceding the current doctoral investigation with two groups of adults - those with diagnosed dyslexia and a control group - also led to the assumption that the DtD task may be a useful addition to existing screening tests. As the task did not involve any language or phonological knowledge, its potential was particularly valued as, if successful, it could help in a screening of pre-reading children and of individuals, both children and adults, for whom English was an additional language.

After reviewing the literature in the field of dyslexia, a great number of inconsistencies around the definition and possible causal explanations was found. Although the consensus is that phonological difficulties represent the primary, or proximal, cause of dyslexia (Snowling, 2000), reading difficulties are also associated with a range of sensory and motor problems. Individuals with dyslexia are often compromised on tasks requiring motor control (Fawcett et al., 1996), visual motion perception (e.g., Kevan & Pammer, 2009), and/or visual-spatial attention (e.g., Lallier et al., 2013). Pennington (2006, 2009) also proposed an idea that multiple deficits may be present in individuals with dyslexia. The review of the literature led to initial speculations of possible dyslexia theoretical frameworks within which the DtD task could be placed and understood. It was assumed that the DtD task required motor and visual processing skills – skills that would reflect the deficits in dyslexia explained by the cerebellar and automaticity deficit (Fawcett et al., 1996) and magnocellular-dorsal stream deficit (Stein, 2001) theories of dyslexia.

Building on this premise, the research presented in this thesis was designed to determine empirically if these assumptions would stand. The key aim was to investigate if the novel task could help to indicate risk of dyslexia in children and adults. Therefore, the first study looked at a cross-section of children to see if their performance on the DtD task would be related to performance on the established screening tests in line with the phonological deficit theory, that is in phonological processing, memory and rapid naming measures. The relationships between motor and reasoning skills and the DtD task were also investigated at that point, as was the efficacy of performance on the DtD task in being able to distinguish between children at different levels of dyslexia risk. To be able to comment on the predictive potential of the DtD task, the second part of the study (presented in chapter 5) offered a prospective investigation of which of many DtD and dyslexia-sensitive measures could accurately predict reading level and reading group membership. A detailed investigation of weaknesses found in poor readers and the impact of different operational definitions on the results was provided. The impact of the gender and of the school which children went to, as a proxy for their socioeconomic status, on dyslexia risk was also investigated. Furthermore, an examination of visual perception in a subgroup of children to identify whether the performance on the DtD task was related to their sensitivity to stimuli preferentially activating low or high-level visual processing pathways was provided. The final study used a similar design to address the questions of the DtD task's associations with established screening tests for dyslexia and its predictive potential in the adult sample. The results of each study were discussed in detail in the relevant chapters. The discussion presented here addresses the key questions that cut across the body of research as a whole. Additionally, a table summarising all of the hypotheses and findings is provided in Appendic C (Table C1, p. 320)

8.2 Can the DtD task identify children indicated as poor readers and adults with dyslexia?

The key findings in this study indicated that children deemed at high risk of dyslexia, as estimated by Lucid Rapid, performed significantly poorer than their "low risk" counterparts on the DtD task when drawing the FirstUp pattern with their dominant hand. These children also made a greater Maximum Error in the First Sector of this pattern and more often drew the line in the opposite direction to the dot that they were supposed to join, as identified by the Direction Ratio measure (see section 4.3.4 for detailed results). Further, analyses of differences between poor and typical readers, as assessed prospectively, revealed that a number of DtD measures that are related to the accuracy of the drawn lines (Total Error) - the combination of the speed-accuracy measures (TimeTotal) and the measures reflecting the initiation of the trials (Direction Ratio, First Sector Maximum Error) - could distinguish between the groups with the poor readers showing poorer performance (see section 5.3.5). This finding contrasts slightly with the cross-sectional investigation, however, which could be explained by the limited scope of the risk assessment with the use of Lucid Rapid screening test. This test's components reflect two core aspects of phonological representations: phonological processing and working/short-term memory. These results showed that the DtD measures on which poor readers were compromised might reflect poor skills that are not related to Phonological Processing but which are impacting reading.

This was further supported by the findings demonstrating that the DtD TimeTotal and Direction Ratio (DR) for NDH together could explain 8% of variance in reading scores and that the latter measure was a significant predictor of reading across the whole sample, in addition to both Phonological Processing and RAN. This was still the case even after controlling for reasoning abilities. The prediction model including Phonological Processing, RAN and DtD DR and Block Design correctly classified 91% of children into the poorly and typically reading groups. In the pre-reading subsample of children also the DtD Total Error measure contributed to their reading measured at the follow-up. While exploring the areas of weaknesses of poor readers, three children out of 36 showed a deficit only on the DtD task (on at least one of the above measures) but no other deficits. This could indicate that there may be a sub-type of poor readers who do not have language or memory-related deficits.

Taken together, these findings suggest that the DtD measures related to the first sector of the drawn patterns, and the accuracy of the drawn lines across the whole patterns, could be a valuable addition to existing screening tests for dyslexia, such as Phonological Processing and RAN. Based on the current findings, it seems that this would be the case only in a child sample. The investigation of the adult sample showed that the DtD measures could not significantly contribute to the group membership prediction model beyond the established measures. However, individuals with dyslexia were outperformed by the control group on the DtD measure combining both speed and accuracy (TimeTotal); this measure could correctly categorise individuals into DD or non-DD groups 14% more accurately than a chance level. Particular caution, however, needs to be taken whilst interpreting adults' results due to a poor power of the statistical analyses. Overall, the current findings suggest that the DtD task could be useful in helping to predict reading problems in children. Further studies with greater number of participants need to be conducted to decide on the potential use of the DtD task in adults.

8.3 The DtD task: theoretical frameworks

Having established that the DtD measures can explain some variance in reading scores, add unique contributions to the predictive models in child samples as well as distinguish between poor and typical readers, it is now important to understand the theoretical underpinnings of this task. An attempt to gain some understanding of the task was made by means of correlational analyses presented throughout the chapters. This investigation, however, turned out to be rather fruitless. The DtD Direction

Ratio, the measure that turned out to be a significant predictor in the prospective study of reading in children, did not correlate with any of the baseline measures or with vision tests, however, it did correlate with reading. The TimeTotal, another indicative measure for both child and adult samples, was related to non-verbal reasoning measured by Matrix Reasoning and to magnocellular processing in both typical and poor readers. In the sample consisting only typical readers, significant correlations were found between the TimeTotal measure and RAN, Visual Memory/Phonic Skills, Block Design and parvocellular sensitivity; these correlations disappeared when the analysis was conducted using only the, relatively small, sample of poor readers. Other DtD measures which were able to distinguish between poor and typical readers also correlated with sensitivity to stimuli preferentially activating the magnocellular visual pathway. All of the correlations found were weak and could not unequivocally explain why the skills needed for good performance on the DtD task also seem to be important for reading. In particular, the lack of significant correlations between the performance on the DtD and Bead Threading tasks stood against one of the main assumptions that the DtD task is associated with motor skills which would be expected in line with the cerebellar deficit theory (Nicolson et al., 1995).

The cerebellar deficit hypothesis proposed that dyslexia could be explained by mild cerebellum impairment and offered an explanation for the main cognitive deficits found in readers with dyslexia. Traditionally the cerebellum has been seen as the brain's 'autopilot' as it is responsible for the coordination of actions, particularly those which are fast and skilled (Eccles et al., 1967). However, associations between its function, language, and automatisation of motor and cognitive skills, have also been found (Leiner et al., 1991; 1993; Desmond & Fiez, 1998; Kelly & Strick, 2003). A line of evidence for the cerebellar deficit theory of dyslexia was provided by means of clinical tests of cerebellar dysfunctions (Fawcett & Nicolson, 1999; Fawcett et al. 1996), brain imaging studies (Eckert, 2004; Nicolson et al., 1999), and by a post mortem study (Finch et al., 2002). Behaviourally, tasks such as throwing and catching a ball, walking backwards in a straight line (Haslum, 1989), toe tapping, arm shaking and postural stability (Fawcett & Nicolson, 1999), eye-blink conditioning (Nicolson et al., 2002) and time estimation (Nicolson et al, 1995) revealed deficits in children with dyslexia. Cerebellar impairment has been linked to the inability to develop automaticity of skills that are crucial for learning to read. Motor problems here are not seen as causal in reading problems but as an indicator of the cerebellum dysfunction (Nicolson et al., 2001). Most research, however, focuses on measuring the motor tasks while it is possible that some individuals with dyslexia may have the parts of the cerebellum that are not related to motor skills dysfunctional. The current investigation used only one motor measure, therefore its results cannot provide a clear answer as the whether or not the DtD performance requires the cerebellar input.

Although unable to provide empirical evidence at this stage, it is still possible to theorise whether or not the DtD task could be explained under the cerebellar deficit hypothesis. This could be done by looking at similar tasks previously used in the literature. Tasks such as the Annett peg-moving and rapid pointing both require speeded hand movements. The first task showed group differences in time taken to complete the series of movements (Fawcett & Nicolson, 1994), while the second showed differences when both speed and accuracy were taken into account (Stoodley et al., 2006). The DtD task also yielded similar results.

The DtD measures compromised in poor readers and adults with dyslexia could reflect a deficit in motor skill learning which would also be in line with the cerebellum and automatisation deficit theoretical frameworks. It could be argued, that the significantly greater total errors made by children identified as poor readers as well as deficits in TimeTotal (a measure of speed – accuracy trade-off) in adults with dyslexia were due to their poor ‘on-line’ motor skill learning, in line with some of previous research (Sela & Karni, 2012). The significantly better score of typical readers and non-dyslexic adults may be a reflection of the volitional skills learning processes as being more effective than in their counterparts with reading difficulties. The ‘off-line’ learning that reflects between-session gains (requiring time and sleep) was not investigated, however. This makes an area for further investigation and reflection on the procedural learning hypothesis (Nicolson & Fawcett, 2007).

According to the automaticity deficit framework, individuals with dyslexia can mask their incomplete motor skill automatisation by a process of conscious compensation (Nicolson & Fawcett, 1994) which allows them to achieve normal performance at the expense of greater effort. Once these compensatory strategies are blocked, by increasing task difficulty, the true automatisation deficit can be revealed. A different pattern of the DtD results, depending on its presumed difficulty, has been shown on scores obtained while using dominant vs non-dominant hand. The lack of group differences in the Direction Ratio measure in trials where the dominant hand was used may be either explained by the fact that all children needed some time to adjust to the rules of a new task and both groups of readers struggled equally. Another explanation would be that poor readers compensated more and concentrated more to do well on the task, therefore achieved comparable scores. This is in line with the automaticity deficit. However, when participants switched to the non-dominant hand, arguably a more demanding task in terms of motor skill, the group differences were found. Children who were indicated as typical readers and adults without dyslexia did not confuse the direction of the first line as much as those identified as poor readers as presumably the skills was automated by that time.

Researchers have recently begun to explore the possibility that an underlying implicit learning deficit may play a role in dyslexia (e.g., Nigro, Jiménez-Fernández, Simpson, & Defior, 2016; Stoodley, Ray, Jack, & Stein, 2008; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). This has been previously investigated in tasks examining children to implicitly acquire positional regularities embedded in both non-linguistic and linguistic stimuli (Nigro et al., 2016). Within this field paradigms such as the sequence learning task and the artificial grammar learning task have been mostly utilised. Although not made explicit, the DtD task patterns of dots follow a certain sequence that is repeated three times throughout the task. As participants are exposed more to the patterns, they should become gradually sensitive to the sequence. Typically, it would be expected that reaction times decrease with successive trials but increase when a randomly ordered pattern is introduced. In individuals with dyslexia, many studies have shown that there is no such increase observed indicating impaired sequences learning (Du & Kelly, 2013; Howard, Howard, Japikse, & Eden, 2006; Jiménez- Fernández, Vaquero, Jiménez, & Defior, 2011; Stoodley, Harrison, & Stein, 2006; Stoodley et al., 2008; Vicari et al., 2003). The Direction Ratio measure is an interesting one in this context as the differences found might be related to implicit learning of sequences of the patterns. As the patterns of the dots were repeated it is possible that implicit learning of the sequences by the time children saw six patterns took place. This learning was not as effective in poor readers though. In order to test this hypothesis future research should include reaction times for single patterns and an additional random pattern into the DtD task.

Considering the nature of the DtD task and similar tasks previously used by other researchers, such as Annet's peg moving and rapid pointing tasks, this finding may indicate that the DtD task may require a good level of hand-eye coordination. However, as the DtD task also requires one to dissociate between eye and the hand gaze, presumably it is a more sophisticated and complex task that draws on high level cognitive processing such as those related to attention. Impairments of automaticity may also contribute to the attentional problem, further complicating the picture.

Attentional problems in dyslexia are recognised in literature; however the precise nature of attention-related deficits is still debated. Researchers in the field proposed explanations that individuals with dyslexia have anomalous spatial distribution of visual attention, which was evidenced by their inattention to the left visual field and over-distractibility in the right visual filed (Facoetti & Molteni, 2001). This has been shown to be related to a right parietal dysfunction. Other researchers proposed different explanation. Bosse and colleagues (2007) suggested that individuals with dyslexia have reduced visual attentional resources. Serial attention deficits (Vidyasagar & Pammer, 1999) and parallel attention deficits (Lassaus-Sangosse, N'guyen-Morel, & Valdois, 2008) have also been documented and researched in the field. Different attentional networks in the brain had been recognised (Posner & Peterson, 1989) and they all have been found to be compromised in dyslexia. These are: the orienting of attention (Buchholz & Davis, 2005; Facoetti et al., 2003; Ruffino et al., 2010), executive functions and cognitive control (Bednarek et al., 2004; Brosnan et al., 2002; Kapoula et al., 2010; Poljac et al., 2010; Reiter, Tucha, & Lange, 2005).

Arguably, some of the above mentioned attentional deficits that are found in individuals with dyslexia may be also indicated by some of the DtD measures, which would have to be verified by further research. Nevertheless, one particular mechanism seems to be conceptually related to the first sector DtD measure; that is the attentional inhibition. Inhibitory control is one of the key components of executive functions that allows one to suppress previously activated cognitions and actions and to resist to any interference from irrelevant stimuli (Bjorklund & Harnishfegar, 1995; Zelazo & Muller, 2011). This mechanism is seen as a good predictor of efficacy in reading and writing acquisition (Altemeier, Abbott, & Berninger, 2008; Schmid, Labuhn, & Hasselhorn, 2011). Inhibitory control is important both at the start of reading acquisition as well as at the mastering stage (Kamza, 2017). A study by Bednarek et al. (2004) found that reading acquisition difficulties found in children with dyslexia are related to executive attention parameters. Relating back to the DtD test, particularly the Direction Ratio measure that was predictive of reading, it can be speculated that problems with initiation of the task seen in poor readers who tended to make the first movement in the opposite direction to the dot that needed to be joined were related to poor control of inhibition. This error in the planning of the movement may be explained by the interference from a previous trial where the first dot was located in a different location, interference from the top panel where the dots and lines were visualised and poor inhibition of the movement. Motor inhibition in the context of dyslexia however has not been studied extensively which makes this proposition even more speculative. Also as Johari and Behroozmand (2017) emphasised the way the brain initiates and controls movement has been long debated and the underlying mechanisms are still unclear. The authors found that movement inhibition was faster than initiation of movement which suggests that the latter requires longer processing time to coordinate activities across multiple regions in the brain. It would be interesting to explore whether this pattern would differ in individuals with dyslexia and whether that could be related to the DtD task.

The aforementioned cerebellum is believed to work with other brain areas to enhance their performance; it receives input from frontal association cortex and from primary motor cortex. Some researchers, however, suggested that it is not the cerebellum that is impaired, but the input it gets from other areas of the brain may be distorted. Particularly the visual pathways have been extensively studied in the context of dyslexia. The magnocellular theory (Stein, 2001) suggests that the cause of dyslexia lies in a deficit within the magnocellular-dependent visual pathway. The small deficits found in this pathway may cumulate and lead to more severe deficits in the posterior parietal cortex, in the motion processing area of the brain, the dorsal stream (Stein & Walsh, 1997). Evidence supporting the magnocellular-dorsal theory of dyslexia can be found in anatomy/physiology studies, in which abnormalities of the magnocellular layers in the brain (LGN) were well documented (Giraldo-Chica et al., 2015; Livingstone et al., 1991), brain imaging (Demb et al., 1998; Eden et al., 1996) and psychophysical (Lovegrove et al., 1980; Slaghuis & Ryan, 1999; Vidyasagar & Pammer, 1999) studies.

The current investigation used psychophysical methods of preferentially activating the visual pathways (magnocellular and parvocellular) and high level processing (dorsal and ventral streams) and showed that the DtD TimeTotal measure significantly correlated only with the magnocellular processing. This would make sense as the magnocellular cells are associated with visual guidance, limb movement and with directing visual attention (Stein & Walsh; Walsh & Richardson, 2000). The Direction Ratio measure, however, did not correlate with any of the visual tests which may indicate that different mechanisms, as those discussed above, are related to this measure. In relation to the MD theory, it needs to be pointed out that current research did not find strong evidence in its support. It would have been expected that scores on the tasks using stimuli preferentially activating the magnocellular and dorsal stream be lower in poor readers, while scores on control tasks (related to the parvocellular and ventral stream functioning) not differ. This was not the case; the poor readers were compromised on both tasks relating to the high level visual processing and on none of the low level processing. None of these, however related to the DtD measures.

Reading is a very complex task and learning to read is a demanding act involving the training of neural mechanisms that are believed to underlie an array of cognitive, perceptual, and motor skills originally devoted to other purposes (Vidyasagar & Pammer, 2010). The brain-based hypotheses, suggesting that the underlying causes of phonological problems are related to deficits in cerebellar functioning (Fawcett et al., 1996), and/or to deficits in low- and high-level visual processing (Stein, 2001), were the initial core theoretical frameworks used to understand the DtD task. The current investigations did not reveal any strong evidence for the visual deficit, therefore other possible mechanisms related to automaticity and attention have been here discussed. The DtD is also quite a cognitively and motor demanding task, therefore it involves a number of cognitive mechanisms and brain structures. It is argued here that different DtD measures reflect different skills (they are not strongly correlated with each other) and they show slightly different patterns of relationships with other baseline and vision measures. One of the most interesting set of measures in the DtD task is related to the first sector. It is speculated that the DtD task requires a number of pre-motor processes such as visual perception, attention, inhibition and initiation of a movement and recruitment of motor systems which would mostly be in line with automaticity and cerebellar deficits theories. The investigation and potential of the DtD task as a possible predictor of dyslexia was at the heart of this thesis, however, other interesting conclusions and theoretical implications in relation to developmental dyslexia in general can be also drawn. These are discussed next.

8.4 What have we learnt about dyslexia?

Phonological Processing measure on its own explained almost 41% of the reading variance in children. This corresponds to previous research which showed a significant link between phonological processing and reading (Bosse, Tainturies, & Valdois, 2006; Snowling, 2000). The current findings confirm that phonological processing is the strongest predictor of reading performance assessed prospectively. In pre-reading children, phonological processing also significantly contributed to the prediction model, aligning with previous research. The analysis of deficits found in poor/dyslexic readers contributed a lot to the discussion on the core deficits. The Phonological Processing deficit was found in 44% of poor readers and in 51% of adults with dyslexia that indicates that this is only one deficit and that it is neither sufficient, not necessary for reading problems to occur. These findings correspond to Pennington's (2006) multifactorial deficit hypothesis.

A number of important, novel findings related to definitions of dyslexia and how they affect our understanding of dyslexia emerged. Many debates and inconsistencies around dyslexia arise from a lack of clear operational definition of dyslexia in empirical research (Wagner, Francis, & Morris, 2005). The current findings show that depending on the cut-off points used to indicate poorly reading children, the prevalence of the reading difficulties drastically changes; from 3% (when -2 SD cut-off used) to 18% (-1 SD cut-off used). More importantly, the combinations of weaknesses manifested in poor readers also vary depending on the criterion used. When the most stringent criterion was used (-2SD), each of the three children who completed the baseline measures had a different combination of weaknesses. In particular, one child, who had the lowest score of the entire sample on reading, displayed six deficits. Only when the least stringent criterion was used (-1SD), children with single deficits were found. There were seven such children, three of which only had a deficit in DtD. The remaining children each showed a deficit in memory, RAN, and phonological processing.

The current findings are also interesting in the context of debates around the role of intelligence in dyslexia. The idea that low-level intelligence could result in problems with readings has been much debated in the literature (Hoskyn & Swanson, 2000; Stuebing et al., 2002). Although the full IQ was not measured here, tests of verbal (Similarities) and non-verbal (Block Design and Matrix Reasoning) reasoning were included to measure participants' general intellectual abilities. None of these contributed greatly to the models predicting reading performance; however, all of the three most severely poor readers, those scoring below 2SD of the sample mean on reading tests, had both verbal and non-verbal reasoning deficits. Of course, this needs to be interpreted with caution due to the study having such a relatively small sample of poor readers. Some studies have shown that the main deficits of dyslexia are consistent regardless of the IQ level (Black et al., 2011; Carroll et al. 2016; Siegel, 1989, 1992; Stanovich, 2005), which corresponds to the current findings showing that group differences in phonological processing, memory and RAN remained significant after controlling for verbal reasoning.

When looking at the features of the high-risk children and poor readers, the role of socioeconomic background emerged as an important factor that needs to be considered. The impact of socioeconomic status was not a main interest of the current research as the inclusion of a cross section of children from various backgrounds was primarily to maximize the representativeness of the sample. Nevertheless, current findings highlight the importance of the environment on children's development. Children from School 1, which was located in one of the most deprived areas in Scotland, were outperformed by their counterparts from schools in more affluent areas on all of the dyslexia-sensitive and reasoning measures. Only performance on the DtD task was not affected by School. Most of the poor readers in the sample were found in School 1, and prevalence (47%) of reading difficulties was higher than expected. However, the school was not a significant predictor of reading performance in any of predictive models. It is also important to emphasise that School 1 was rated "excellent" in recent school audits, so it is likely that the effects of school found were related to home rather than school environment. This, however, needs to be interpreted with caution as socioeconomic status of the children taking part in the study was not directly assessed. Although previous studies (Chaney, 2008; Whitehurst & Lonigan, 1998) agree with present findings, it is not entirely clear what the specific aspects of the low socioeconomic status that impact this development, whether it is parental education, genetics or exposure to the written word, are. Future research should also include socioeconomic factors of individual children's parents, such as income, employment, mental health or education.

8.5 Limitations and directions for future research

The limitations of specific studies contained in this thesis are discussed in their associated chapters. However, a general discussion about overarching limitations is now presented. Key aspects of the investigations across the research were correlational, which was important particularly for understanding the abilities the DtD task was associated with. However, this type of design does not allow one to imply causation. To alleviate the issue, the current studies were enhanced by the use of quasi-experimental designs in which children of high dyslexia risk, children that were indicated as poor readers and adults with dyslexia were compared to the respective control groups. Furthermore, a prospective investigation with more follow-ups would be desirable to investigate the progress of the children over the years.

The above comparative analyses, however, were also prone to error and bias. First, dyslexia risk was estimated by screening tool (Lucid Rapid) which turned out to be quite inaccurate, as described in the earlier chapters. Only half of the children who ended up being poor readers were flagged as at high risk of dyslexia by Lucid Rapid. This contrasts dramatically with the sensitivity level of 82% found by Brookes et al. (2011). Additionally, anecdotal evidence from the testing sessions indicated that some children did not like the tasks and wanted to stop which was not enabled by the software. This could have an impact on children's results. In terms of the adult sample, the LADS screening tool also was not very sensitive, indicating only 20% of adults with a formal diagnosis of dyslexia as at high risk of dyslexia.

Another limitation was that children in the prospective investigation were identified as poor readers based on their performance on two reading tests and applying a cut-off point. Although this is a common practice amongst researchers, it is rather simplistic in comparison to professional diagnosis. Further research should aim to follow up children with a full set of diagnostic tests in order to obtain the diagnosis, if at all possible. Future research could also incorporate the investigation of performance on the DtD task in IQ-reading discrepancy defined groups in order to aid the ongoing debate on the role of intelligence.

The issue of lack of professional diagnosis was recognized throughout the present research, which necessitated and justified the investigation of adults with a formal diagnosis of dyslexia by a specialist. As discussed in Chapter 7, the adult sample bias could also be an issue due to a high number of students and academic staff. One could reasonably assume that in order to be successful enough to attend the university, it would have been necessary to develop effective coping skills to compensate for their deficiencies (DuPre, Gilroy, & Miles, 2003). Moreover, there is also some speculation that dyslexia can be characterized as a continuum-based disorder, with difficulty levels ranging from mild to severe (Crisp & Lambon Ralph, 2006). The sample, therefore, could represent a milder form of dyslexia. Hence, the issue of generalisability to wider adult population must be raised as this study used an opportunity sample which was not representative of the wider population. Future research could include participants of various backgrounds and also ask what strategies they use to provide a better understanding of the role of remedial strategies in those with dyslexia. As a first investigation, however, the data are a helpful indicator of the efficacy of the DtD.

Another key concern was the low number of participants particularly in the study involving adults. The sample size of children at baseline was sufficient for the correlational study; however as it was unselected sample the number of children that were prospectively indicated as poor readers was relatively small. Although the use of unselected sample was justified and motivated by the desire to use a representative sample of children, this approach led to a smaller number of children with reading difficulties than it would have been the case if children at familial risk were included. Future research should, therefore, include even greater baseline sample in order to be able to investigate areas of weaknesses and deficits in a larger sample of poor readers and compare their abilities to typical readers.

If the above methodological limitations were addressed in future research it would be possible to comment on the usability of the DtD task with more certainty. In terms of the understanding of the DtD task, the initial assumptions, that it may require motor and visual-perceptual abilities, can be upheld only to some extent. It has been suggested throughout that the deficits shown in the DtD measures may be in line with the automaticity deficit theory of dyslexia, which future research should further investigate. Particularly, tests measuring more aspects of cerebellar functioning, motor planning, procedural learning and attentional demands included in future research are expected to be more informative. Particularly, the kinds of attention paradigms, such as crowding (e.g., Cassim et al. 2014), visual attention span (e.g., Bosse et al. 2007) or spatial orienting of visual attention (e.g., Facoetti et al., 2003; Facoetti et al., 2003) would be interesting to explore.

8.6 Conclusions

This thesis has shown that developmental dyslexia should not be seen as a homogeneous disorder that manifests itself in the same way in every person. **No one deficit that was found throughout the studies involving both adult and child samples is either sufficient nor necessary for reading difficulty to occur.** Other key findings from the studies involving a large, unselected sample of children demonstrated that **prevalence of high risk dyslexia is highly variable** (depending on the tool used, and the cut-offs). These findings lead to the conclusion that there is no one test that can reliably indicate risk of dyslexia in all children and adults. A need for a multifaceted set of screening tasks associated with various abilities stood out from the findings of the current thesis. **The DtD task showed a potential in helping to identify reading problems in children by adding a significant contribution to the predictive model and indicating some of the poor readers who would not be otherwise recognised as such on the basis of phonology-related or reasoning aspects**. While the current set of studies did not provide an entirely clear explanation as to why this is the case, it stimulates reflections on the current approach to screening measures and the nature of dyslexia. The inconsistencies around the operational definitions of dyslexia also emerge as potent factors impacting on a still fuzzy understanding of dyslexia.

The theoretical and practical implications of the current study are crucial to discuss now. In terms of the theoretical implications it is clear that the phonological deficit theory cannot be seen as a key explanation for dyslexia any longer. Perhaps phonological processing, along with other deficits that are in line with cognitive and biological explanations, may be understood as endophenotypes (as proposed by Snowling, 2008) suggesting that these deficits may manifest themselves in individuals with and without dyslexia and they should be seen as potential risk factors. Alternatively, different manifestations in poor readers may be interpreted as caused by different underlying mechanisms which would lead one to propose different types of dyslexia with either pure deficits or a different mixture of deficits. The latter point is paramount for practical implications for two reasons. First, the risk assessment of dyslexia cannot be based on only one type of deficit as this would lead to many children with different manifestations missed by such unidimentional screening tests. This point is strongly supported by this thesis; there were three poor readers who showed deficits in the DtD task but in none of the remaining tasks. If these children were to be screened by phonological tests they would not have been flagged as at risk. The second reason why these findings are important for practical implications is the potential effectiveness of interventions. It is argued that phonology–based interventions would not be suitable and successful for children whose reading is related to cerebellar, automaticity, attentional or visual problems (e.g., Lawton, 2016).

The conclusion of this thesis is that children who become poor readers may demonstrate a number of deficits in perceptual, motor, language, and cognitive tasks before they experience formal reading instruction at school. The type and combination of these deficits appears highly variable from child to child. Nevertheless, it is crucial to recognize these, as this would hopefully lead to the implementation of appropriate interventions as early as possible. Although phonological processing plays a great role in the prediction of reading difficulties, other aspects, such as motor and perceptual, also need to be considered and can be particularly useful for screening EAL children and adults.

Despite the progress achieved in recent years moving us closer to the overreaching goal of preventing reading failure and maximizing the potential of every pupil, it is still an ambitious and extremely difficult endeavour to comprehend the complexities of reading and reading problems.

'And so to completely analyze what we do when we read would almost be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilization has learned in all its history.'

Sir Edmund Huey (1908, p. 6)

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Publications

Ref: Piotrowska, B., Willis, A. (2014). *Visual-spatial-motor performance may predict reading difficulties in children and adults. Preliminary findings from a longitudinal study on young, pre-reading children*. Dyslexia Review, 25: 3, pp. 15-19.

Visual-spatial-motor performance may predict reading difficulties in children and adults: preliminary findings from a longitudinal study of young, pre-reading children.

In this article Barbara Piotrowska and Dr Alexandra Willis explore the idea that the phonological difficulties that characterise dyslexia may be underpinned by low-level sensorimotor deficits, and present preliminary findings of a longitudinal study that aims to examine this explicitly. They present preliminary evidence from a longitudinal study that suggests that a novel visual-spatial-motor task may be able to predict reading success.

Background

Developmental dyslexia affects around 10% of the British population, and is broadly defined as difficulties with word recognition, spelling, and decoding, despite adequate intelligence, education, and motivation (International Dyslexia Association, 2007). Although phonological difficulties are the primary features of dyslexia (Snowling, 2000), dyslexia is often associated with wider problems perceiving, attending to, organizing, integrating, timing, and sequencing information. Children and adults identified as having dyslexia, for example, often demonstrate deficits in a range of sensory and motor tasks, including visual motion perception (e.g.Kevan & Pammer, 2009) auditory timing (e.g.Goswami, 2011), visual-spatial attention (e.g. Lallier, Donnadieu & Valdois, 2013), and motor control (Fawcett, Nicolson & Dean, 1996). However, whether problems in sensory and motor processing *underlie* phonological difficulties in dyslexia (e.g. Vidyasagar & Pammer, 2010), or merely *co-exist* with them in many cases (e.g. Ramus, 2003), remains a topic of considerable debate.

Although the nature and causes of dyslexia are hotly debated, there is a widespread consensus that early identification and intervention are of central importance in both language remediation, and in limiting the low self-esteem and behavioural difficulties so often reported in unrecognized dyslexia. Unfortunately, the formal identification of reading and writing problems in UK schools typically occurs after children have failed to learn to read, and interventions only provided when a child falls significantly behind his or her classmates (Singleton, 2009). As dyslexia is a developmental disorder, it is counterinuitive to consider it manifesting itself only after the formal teaching of reading has been introduced.

Following *Special Educational Needs Code of Practice* (Department for Education, 2001), all teachers, from early years up to secondary school level, should be able to recognise the characteristics of dyslexia. When these characteristics appear and are identified by a teacher, the child is referred to the school's Support for Learning Teacher who is obligated to perform a series of actions, such as building a strengths and needs profile leading to a creation of an individualized program to address the child's weaknesses. While this procedure appears reliable, it has some pitfalls. Identifying dyslexia is far from straightforward. Typical characteristics of dyslexics are not always easily recognised. This may be due to coping strategies developed by children, or poor understanding of dyslexia amongst teachers. A recent report by Dyslexia Action (2012) showed that parents are often the ones who raise the concerns about their children, and suggests that training of education staff is very much needed in order to follow the procedures outlined in the Code of Practice. The identification of children with dyslexia is even more difficult in children who have English as an additional language (EAL). As all the existing screening tools for dyslexia are based on phonological and language skills, these children may be disadvantaged. Traditional assessments do not consider language proficiency and bilingualism. Also, the fact that the type of orthography in a child's first language determines the stage at which reading difficulties might emerge as well as their manifestations, is often overlooked (Cummins, 1984)

Longitudinal studies have shown that it may be possible to recognise children at risk of developing reading and writing problems as early as three years old (Lyytinen et al. 2006). However, schools do not tend to screen children before they start learning to read. There are several reasons for that. Firstly, it is due to lack of appropriate tools that are accessible to teachers. Secondly, the consequences of inaccuracy of existing tests may be harming for a child. If a pupil with learning difficulties is shown to be 'not at risk' by a screening tool, it is unlikely that he or she will be provided with appropriate support. There is also a well recognised danger of screening results influencing teachers' expectations of children (Singleton , 2009).

We have developed a simple, computer-based "dot-to-dot" (DtD) test which requires a combination of visual-spatial and motor skills, and which may help teachers and educational psychologists identify potential those at risk of dyslexia earlier and more quickly than existing tests. Unlike existing tests, ours does not depend on any phonological or general knowledge: as such, it may potentially be developed for use in pre-reading children, and in children and adults from a wide range of linguistic and cultural backgrounds, including those for whom English is an additional language.

In this article, we present some preliminary findings from the first phase of a longitudinal study designed to (**1**) address theoretical questions about whether or not sensorimotor deficits underlie dyslexia, or co-exist with it; and (**2**) explore the possibility of developing a novel screening tool which may, unlike existing tests, help identify dyslexia in children from a wide range of linguistic and cultural backgrounds before they fail to learn to read.

Our study

We argue that if low-level, sensorimotor deficits underlie developmental dyslexia, these deficits should be apparent in children even before they learn to read, and in children whose first language is not English. If so, it should be possible to develop a screening tool that assesses basic visual-spatial and motor skills in young children. Our study seeks to find out whether visual-spatial-motor performance, as determined by our dot-to-dot task: (1) is associated with phonological processing and rapid automatized naming in a cross-section of children and adults; (2) is compromised in adults with identified dyslexia and young children deemed at risk of dyslexia; and (3) precedes later reading difficulties in pre-reading children. We are attempting to address existing gaps in the research literature by adopting a large-scale, cross-sectional sampling approach (to capture a representative sample of children and adults), and conducting a longitudinal study of performance on our visual-spatial-motor task alongside various standardized psychometric measures and existing dyslexia screening tools

Methods

The design used in the study was cross-sectional and longitudinal. Data collection took place either at Edinburgh Napier University (adults) or at school (children). Informed consent to participate was obtained from all participants after the procedures were explained. Participants were told that they were under no obligation to take part, and that they could withdraw from the study at any time without giving a reason. In the case of child participants, consent was additionally provided by the head teacher of the school, and by their parent or guardian, on an opt-out basis. So far, only two children declined to take part, and only one child was opted out by their parents. In the case of adults, we also asked whether they had any history of language or motor problems, or a formal identification of dyslexia. Adults have so far only completed the dot-to-dot task (language and cognitive testing is currently ongoing); children completed both the dot-to-dot test and a series of standardized language and cognitive tasks, split over two sessions of 20-30 minutes each.

Participants
Fifty-two students and staff from Edinburgh Napier University aged between 17 and 46 (37 females; mean age = 24.0, SD 6.42 yrs) made up the sample of adults. Nineteen participants had previously been identified as having dyslexia by the University's specialist dyslexia team, and the remaining 33 reported having no language or motor impairments.

One-hundred-and-twenty-seven children aged between 4 and 10 yrs have completed the study so far, all from a single primary school in Edinburgh, UK. Data collection at two further schools is currently underway. Four year groups have been tested: *pre-school, P1, P3* and *P5*[12].

The Dot-to-Dot (DtD)Test
Participants were asked to look at a sequence of dots on a PC monitor and draw a line as quickly and accurately as possible between them on an adjacent touch-screen tablet using a stylus (Figure 1 presents the set up of the task). Single dots appeared sequentially, at a random location, as soon as the stylus moved sufficiently close to the previous dot. This task requires good hand-eye co-ordination, fine-motor control, and the ability to split visual attention between the display area (where the dots are displayed) and the drawing area underneath (where the line drawn by the stylus is displayed).

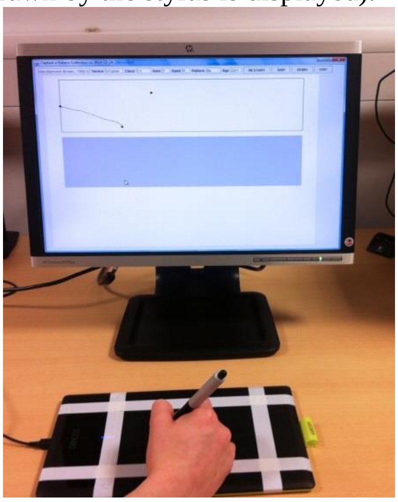

Figure 1: Experimental set up for the "Dot to Dot" task showing the display monitor, touch-screen tablet, and stylus. Participants looked at the top panel of the display and joined up the dots on the tablet below with the stylus. When the stylus gets to within a certain distance of the dot, the next dot appears in a random location. Participants must divide their attention in space between the display panel in front of them and the tablet below.

Participants completed three trials for each of 8 and 9 dot displays, using both the dominant and non-dominant hand. The sequence of trials was randomized.

[12] (1) pre-school: n=24, mean age=4.13 yrs, SD=0.34 yrs; (2) P1 (n=39, mean age=4.95 yrs, SD=0.39 yrs) (3) P3 (n=31, mean age=7.16 yrs, SD=0.58 yrs), and P5 (n=33, mean age=9.24 yrs. SD=0.43 yrs).

We measured: (1) the *maximum error* between the drawn line and the line of best fit in the first sector of the pattern (**DtD First Sector Max Error**); (2) the *total error* between the drawn line compared to the line of best fit over the whole pattern (**DtD Total Error**); and (3) the *time taken to complete the task* (**DtD Time**) (see Figure 2.)

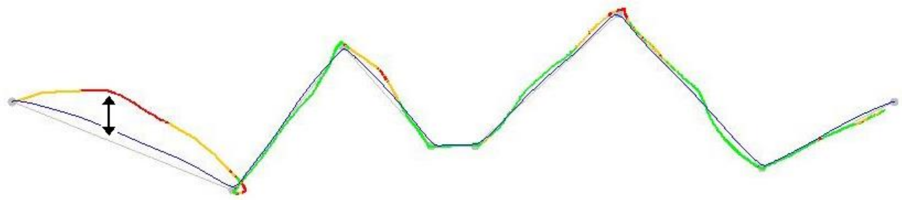

Figure 2: Example of the DtD task output for a single trial, for one participant (8-dot condition). The grey line shows the line of best fit, calculated by the software. The coloured line shows the line drawn by the participant. The double-headed arrow highlights the First Sector Max Error for this trial. Note that it is very large in this example; the yellow and red sections of the line indicate that the points fell beyond 1 and 2 SD of the mean, respectively, for the sample as a whole.

Language and Cognitive Tests
In order to examine whether performance on the dot-to-dot task was related to language and other skills believed to be compromised in dyslexia, participants also completed a commercially-available dyslexia screening test (**LUCID-Rapid**; LUCID software), and selected sub-tests of Fawcett & Nicolson's (1996) **Dyslexia Screening Test** series, and **Wechsler's Intelligence Scales** series.The younger children, (under 6 years old), completed subtests from Wechsler Pre-school and Primary Scale of Intelligence (WPPSI-IV; Wechsler, 2012) and Dyslexia Early Screening Test (DEST-2) and the older children (6 years and over), completed Wechsler's Intelligence Scale for Children (WISC-IV; Wechsler, 2004) and the Dyslexia Screening Test – Junior (DST-J).

Our test battery included:
(1) **phonological awareness** (*rhyme/alliteration* from DEST-2; *phonemic segmentation* from DST-J);
(2) **rapid automatized naming** (DEST-2/DST-J);
(3) **working memory** (the *digit span* subtest of the Wechsler series);
(4) **verbal reasoning** (the *similarities* subtest of the Wechsler series);
(5) **fluid / perceptual reasoning** (*block design* & *matrix reasoning* subtests of the Wechsler series); and
(6) **fine motor skills** (*bead-threading* subtest of the DEST/DST-J).

In addition, we obtained the results of the children's Baseline Literacy, Progress in English (PiE) and Progress in Literacy tests, which had been administered by their teachers as part of the school's curriculum.

Results
Adults
The adults' performance on the DtD task (dominant hand) is shown in Figure 3. Those with dyslexia produced significantly greater *maximum error* in the first sector of the pattern (DtD First Sector Max Error), on average, compared to those without[13]; in other words the line they drew to join up the first two dots were much further away from the perfectly straight line. They also made more errors in total (DtD Total Error), and took less time to complete the task (DtD time), but these differences were not statistically significant[14].

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[13] $t(50) = -2.04$; $p < 0.05$
[14] DtD Total Error: $t(50)=1.05$, $p=.30$; DtD Time: $t(50)=.53$, $p=.60$

These results suggest that accuracy on our DtD task is significantly lower in adults with identified dyslexia – at least in the first sector of the pattern – and suggest value in exploring young children's performance on this task to see if it can predict reading success or failure.

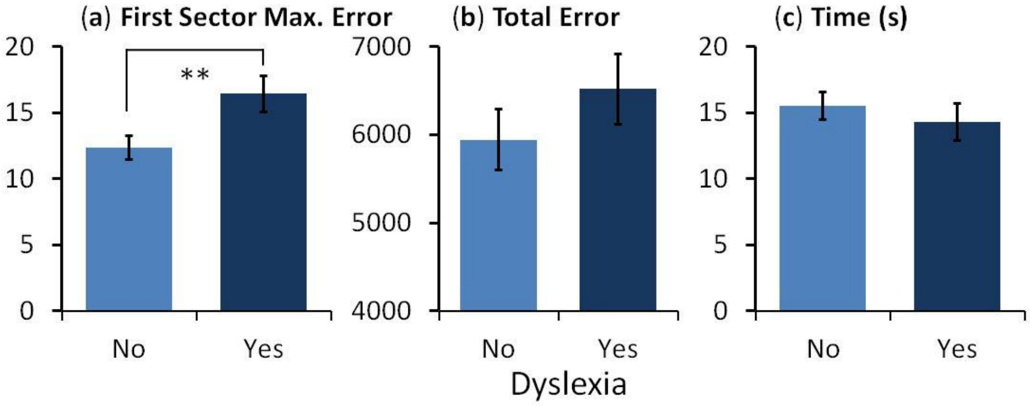

Figure 3: Adults' performance on our dot-to-dot task. (a) First Sector Max Error: the maximum error (in pixels, from the line of perfect fit between dots) made between dots 1 and 2; (b) Total Error: the mean sum of the difference (in pixels) between each point drawn by the participant compared with the corresponding pixel on the line of perfect fit; (c) Time: mean time (in s) taken to complete the pattern. Error bars indicate ±1 SEM. ** difference is significant at $p < 0.01$.

Children

We found that the First Sector Max Error and Total Error measures of performance on our DtD task (dominant hand) were significantly correlated (see Table 1) with both Phonological Awareness and Rapid Automatized Naming (arguably the best predictors of dyslexia), as well as Digit Span (a measure of working memory) and Bead Threading (a measure of fine motor control).

	Block Design	Matrix Reasoning	Similarities	Digit Span	RAN	Bead Threading	Phonological Awareness
DtD Time	.014	-.137	-.002	-.306**	-.066	-.249**	-.272**
DtD First Section Max Error	-.207*	-.324**	-.280**	-.607**	-.182*	-.415**	-.392**
DtD Total Error	-.201*	-.258*	-.237*	-.682**	-.272**	-.466**	-.491**

Table 1: Pearson's correlations for DtD (fot dominant hand), language and cognitive tests. * indicates that the correlation is significant (two-tailed): * $p < 0.05$; ** $p < 0.01$.

Further statistical analyses (multiple regressions) were conducted in order to investigate if the performance on the DtD task (First Sector Max Error for each hand), RAN, Bead Threading and Digit Span would predict *Phonological Awareness* scores (all measured by DEST-2/DST-J). The overall model proved significant[15]. What this means is that all these tests *together* could explain and predict 42%[16] of the variance in phonological awareness scores.

First Sector Maximum Error in the DtD task for dominant hand significantly predicted Phonological Awareness (measured with DEST-2/DST-J subtests) adding 45% to the model[17]. This finding indicates that the DtD measure is a significant predictor of Phonological Awareness.

Digit Span (working memory) and Bead Threading (fine motor skills) both significantly predicted Phonological Awareness, uniquely explaining 42%[18] and 25%[19] of the model. Both these tests added less prediction than the DtD measure. RAN and the First Sector Maximum Error for non-dominant hand marginally contributed to the model both explaining 19% of Phonological Awareness variance[20].

This finding is important as it shows that a child's performance on the DtD task (especially when we are looking at the lines in the first sector drown with the dominant hand) can predict their Phonological Awareness, which represents the core weakness in dyslexia, better than already known measures.

Groups of children classified as "very high" (n=19, 15%) and "low" (n=29, 23%) risk of dyslexia on the basis of their scores on LUCID-Rapid dyslexia screening tool were compared for each of the tasks (Figure 4). Children deemed at very high risk of dyslexia made significantly greater *maximum error* in the first sector of the pattern (dominant hand)[21] and made more *total error* over the whole pattern[22] compared with low-risk children: however, there was no significant difference in *time* taken to complete the task between the two groups[23].

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15 $F(5,102)=14.6$, $p<.001$
16 $R^2=.42$
17 B=-.08, SEB =.02, β=-.45, p<.001
18 B=.329, SEB =.09, β=.42, p=.001
19 B=-.47, SEB =.189, β=-.25, p=.013
20 RAN: B=-.03, SEB=.02, β=-.19, p=.06; First Sector Max Error B=-.03, SEB =.02, β=.20, p=.09
21 $t(45)=2.61$, $p=.014$
22 $t(45)=3.06$, $p=.004$
23 $t(45)=-.54$, $p=.59$

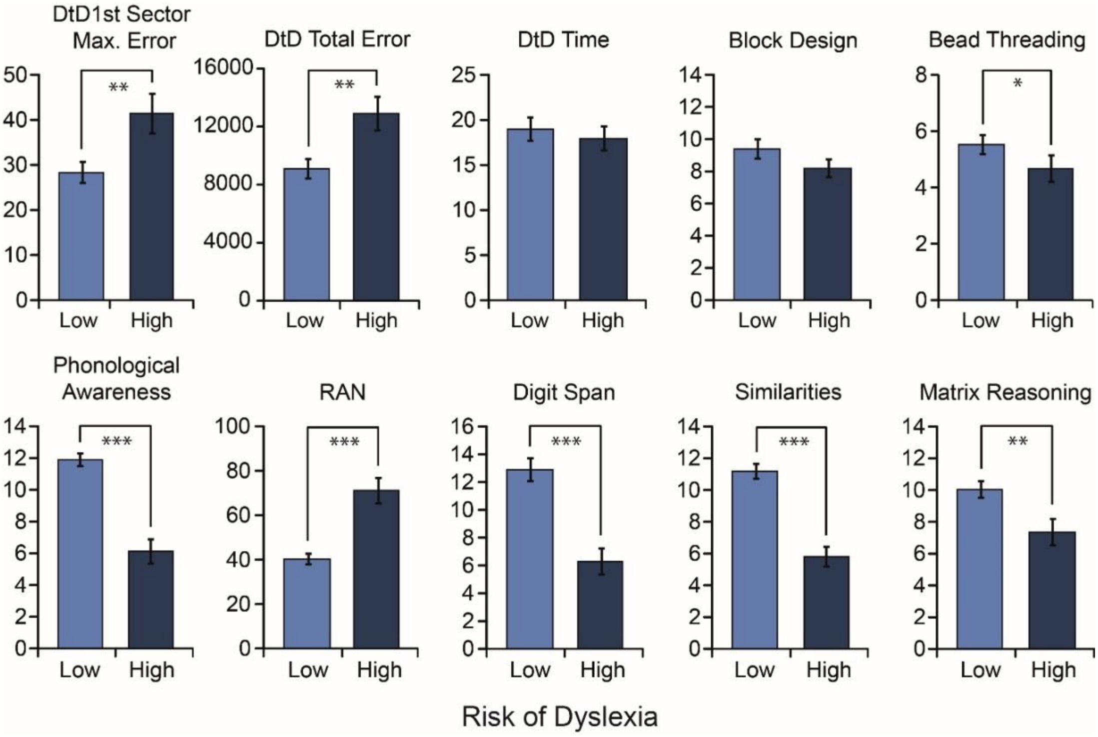

Figure 4: Children's performance on all tasks, grouped according to risk of dyslexia (low vs. high), as determined by the LUCID-Rapid Dyslexia Screening Tool. Error bars indicate ±1 SEM. Differences are significant at $p < 0.05$ (*); $p < 0.01$ (**); $p < 0.001$ (***).

The proportion of children deemed at "very high" and "high" risk of dyslexia, according to LUCID-Rapid was surprisingly high (17% and 23% respectively). We thought this may indicate that the specificity of the screening tool was not sufficiently high: however, P1 Baseline Literacy tests of all the children tested by the school (n=83) showed that reading scores across the sample were significantly skewed towards lower values (30% of children fell within the lowest 20% of Scottish children as a whole), and were therefore not representative of the wider population. Progress in Literacy scores, obtained when the children were in P2 (n=51), further showed that 45% of pupils at this school fell within the lowest 10% of performance nationwide.

Several factors could explain these findings. First, a high proportion of children (20%) had English as an additional language. Second, 50% of the children we tested received at least one type of additional support (that includes support for learning, speech and language therapies, behavioural support, etc.), which contrasts with 20% of pupils in primary schools across the country (Scottish Government, 2013). This school is located within one of the most economically and socially disadvantaged communities in Scotland, falling within the lowest 1st decile for the Scottish Index of Multiple Deprivation (SMID), in 2012. We have now broadened our study to two further primary schools chosen in consultation with the head of Additional Support for Learning, City of Edinburgh Council: one from a relatively affluent neighbourhood, and one from a mixed neighbourhood with a high proportion (85%) of English as an Additional Language families.

Conclusions

Both adults with identified dyslexia, and children deemed at high risk of dyslexia, performed significantly worse than their non-dyslexic / low-risk counterparts on our dot-to-dot task – especially in terms of *maximum error* in the first sector of the pattern, with the dominant hand. Performance on this measure was significantly correlated with Phonological Awareness and Digit Span and predicted the most of the variance in Phonological Awareness, which suggests the task may be useful in predicting future reading success. Follow-up studies will examine whether poorer performance on the DtD task in pre-reading children (nursery and P1) does indeed precede reading difficulties. We will also scrutinize a potential strength of our novel tool in dyslexia identification in children whose English is not the first language. As existing screening tools do not address and are not appropriate for this population, it will be the major focus of our study. In consequence, we will explore the possibility of developing the task for use as a dyslexia screening tool in children and adults from a range of linguistic backgrounds.

Acknowledgments
We would like to express our gratitude to our collaborator and designer of the dot-to-dot task, Professor Jon Kerridge, for an inspiration to conduct this study as well as his constant support throughout. Also, many thanks to Barbara's PhD supervisors, Dr Jennifer Murray and Dr Rory MacLean, for continued help and valuable feedback on this paper. We also appreciate Dr Stephen Martin's technical support. Last, but not least, we would like to express our gratitude to the schools, teachers and pupils for their enthusiastic participation in our research. The research is financially supported by a PhD studentship awarded to B. Piotrowska by Edinburgh Napier University.

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Appendices

Appendix A: Consent and information sheets

Consent and information letters sent to chidlrens' parents (for baseline and follow-up testing), Information sheets for children and adults, ethical approval from the City of Edinburgh Council.

November 2015

Dyslexia Research Project

Dear Parent or Carer,

Dalry Primary School has been selected as one of three primary schools in Edinburgh to participate in a research project conducted by a team of researchers at Edinburgh Napier University: Dr Alex Willis, Prof. Jon Kerridge, and Ms Barbara Piotrowska.

We have developed a simple, tablet-based task that we think may help identify problems with reading and writing earlier than existing tests – and perhaps before children even learn to read. This task involves simply joining up some dots on a touch-screen with a stylus, and only takes a few minutes to do. We are now conducting a large-scale research project to see if this test really can help identify children who may have problems reading and writing. Children are asked to complete a series of short "games", some on the computer and some on paper, over two 20-25 minute sessions. Most children who have taken part say they very much enjoyed it.

We need as many children to take part as possible in order to evaluate how well our new test might work. Mr XXXX has provided his consent to us asking all the children at XXXX whether or not they would like to take part. The researchers will explain what is involved to your child and reassure them that they do not have to take part if they don't want to. All information collected as part of this study will remain anonymous and strictly confidential.

If we don't hear from you, we will assume you provide your consent for your child to take part. If you **would not** like your child to take part in this research, please indicate this on the cut-off slip below and return it to school with your child by the end of this week.

If you would like any more information about this project, please email Alex at a.willis@napier.ac.uk or Barbara at B.Piotrowska@napier.ac.uk.

We are also looking for adults to take part in our study. If you are interested in taking part, please get in touch.

✂ ....

XXXXX Primary School

I **would not** like my child ______________________ (name), class ________

to take part in the dyslexia research project (Edinburgh Napier University).

Signed: ______________________ Name (PRINT): ______________________

Date: ______________________

School of Life, Sport & Social Sciences
Edinburgh Napier University
Sighthill Court
Edinburgh, EH11 4BN, UK
Tel: 08452 60 60 40

November 2015

Dyslexia Research Project

Dear Parent or Carer,

Dalry Primary School has been selected as one of three primary schools in Edinburgh to participate in a research project conducted by a team of researchers at Edinburgh Napier University: Dr Alex Willis, Dr Jennifer Murray, Prof. Jon Kerridge, and Ms Barbara Piotrowska.

Some time ago we have contacted you regarding a task we have developed that we think may help identify problems with reading and writing earlier than existing tests – and perhaps before children even learn to read. This task involves simply joining up some dots on a touch-screen with a stylus, and only takes a few minutes to do. The first part of our large-scale research project was when we asked children to complete a series of short 'games', including our new task, over two sessions. Now we would like to follow up those children and ask them to do some more games that will focus on readings and visual skills. Most children who have taken part say they very much enjoyed it.

Our aim is to follow up all the children who take part in the first session in order to evaluate how well our new test might work. Mr XXX has provided his consent to us asking the children at XXX whether or not they would like to take part. The researchers will explain what is involved to your child and reassure them that they do not have to take part if they don't want to. All information collected as part of this study will remain anonymous and strictly confidential.

If we don't hear from you, we will assume you provide your consent for your child to take part. If you **would not** like your child to take part in this research, please indicate this on the cut-off slip below and return it to school with your child by the end of this week.

If you would like any more information about this project, please email Alex at a.willis@napier.ac.uk or Barbara at B.Piotrowska@napier.ac.uk.

We are also looking for adults to take part in our study. If you are interested in taking part, please get in touch.

✂ ....

XXX Primary School

I **would not** like my child ______________________ (name), class ________

to take part in the dyslexia research project (Edinburgh Napier University).

Signed: ______________________ Name (PRINT): ________________________

Date: ____________________________________

School of Life, Sport & Social Sciences
Edinburgh Napier University
Sighthill Court
Edinburgh, EH11 4BN, UK
Tel: 08452 60 60 40

All about our Project: Joining up the Dots

Introduction

My name is Barbara, and my job is to find out why some people find it hard to read and write. We have made up a little game that children and adults can do on an i-Pad or a tablet. It is a bit like a dot-to-dot. We are doing a research project to see if this dot-to-dot game can tell us anything about how people learn to read and write.

We would like you and the other children in your class to take part in our project. We are asking lots of children from different schools in Edinburgh. You can choose if you want to do it or not. We have talked about this with your teachers, and they have said it's OK for us to ask you, and that it's up to you to decide. You can decide right now if you'd like to, or you can talk it over first with parents or friends or anyone else you feel comfortable talking to.

There may be some words you don't understand or things that you want me to explain more about because you are interested or concerned. Please ask me to stop at any time and I will take time to explain.

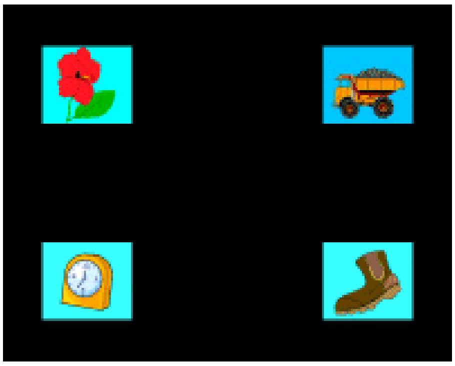
Do I have to take part?

You don't have to be in this project if you don't want to be. It's up to you. If you decide not to be in the project, it's okay and nothing changes. Even if you say "yes" now, you can change your mind later and it's still okay.

What is going to happen?

If you decide to take part, I will take you to a quiet place in the school and ask you to have a go at the dot-to-dot game, and also some other games. Some of them are on the computer, and some of them involve moving little things around on the table. They are all quite short. All the games together will take about 20 or 30 minutes. When it is finished, I will take you back to your classroom to join your teacher and friends. I will come back on another day and we'll do some more game/tests that are quite similar.

The "dot-to-dot"



The rhyming game

Is everybody going to know about this?

We will not tell other people that you are in this project and we won't tell anyone about what you did or said. Anything we find out about you will be put away and no-one except us will be able to see it.

Who can I talk to or ask questions to?

You can ask me questions now or later. I have written a number and email address where you can reach me. If you want to talk to someone else that you know, like your teacher, or mum or dad, that's OK too.

Barbara Piotrowska

Email: 09009490@live.napier.ac.uk
Phone: 0131 455 6423
Address: at the bottom of the page

Visual-Spatial-Motor Integration in Dyslexia

Information Sheet

Researchers: Ms Barbara Piotrowska, Ms Jessica Cadd, Dr Alex Willis, Prof. Jon Kerridge

Introduction

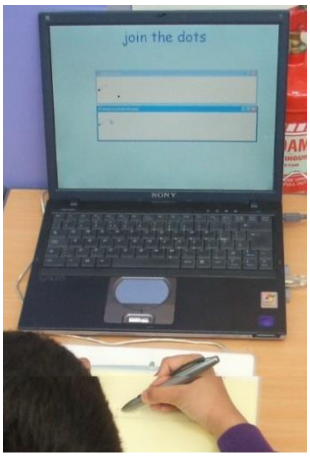
Please take time to read the following information carefully. Do ask if you would like more information, or if anything is unclear.

What is the aim of the study?

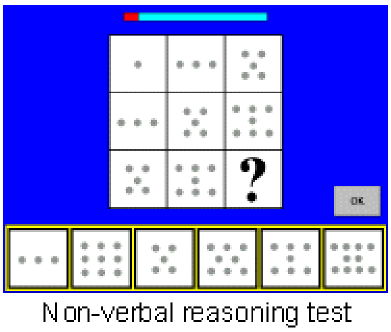
We have developed a simple, computer-based “dot-to-dot” task that we think might be useful in helping to diagnose young children with dyslexia – perhaps at an earlier stage than is possible using existing screening tests. In order to test this idea, we first need to see whether people with identified dyslexia perform differently on our dot-to-dot task than those without dyslexia.

What will happen if I agree to take part?

If you are happy to take part, we will agree a mutually convenient time for you to come along to the Perception Lab at Edinburgh Napier University, Sighthill. There, we will go over the procedure in more detail and ask you to sign a consent form. If you agree to participate, you will be asked to complete a series of short exercises designed to examine a range of general verbal and non-verbal abilities (using standard psychometric tests), as well as performance on our “dot-to-dot” task. The whole process should take no longer than 1 hour to complete. While completing these tasks, you will be asked to wear a pair of lightweight eye tracking glasses which will record your eye movements.



1. The “dot-to-dot” task



3. A non-verbal task: which of these patterns fits best in the box with a question mark?

2. A motor task: how many wooden beads can you thread on a string in 30 s?

Do I have to take part?

No. Participation is entirely voluntary. Even if you have signed the consent form, you are free to withdraw at any time during the study without giving a reason.

What are the possible benefits of taking part?

The study will increase our understanding of how dyslexic and non-dyslexic individuals process visual information. If we find there is a difference between dyslexic and non-dyslexic groups, we will develop the "dot-to-dot" system into a screening tool that could be used to help diagnose children with dyslexia at an earlier stage than is currently possible – perhaps even before they learn to read. Participants may also find that taking part makes them more aware of their own visual and motor skills.

Is participation in this study confidential?

All information which is collected in this study will be kept strictly confidential and will only be used for the purposes of the research described here. Only members of the research team will have access to the data. We expect to publish the aggregated results in academic journals, but these publications will not contain any information that could be used to identify participants.

Thank you for taking time to read this information sheet.

If you would like to take part, or have any questions, please contact:

Ms Barbara Piotrowska
09009490@live.napier.ac.uk

·EDINBVRGH·
THE CITY OF EDINBURGH COUNCIL

Dr Alexandra Willis
Edinburgh Napier University
School of Life, Sport and Social Sciences
Sighthill Court
EDINBURGH
EH11 4BN

Date	6 January 2014
Your ref	
Our ref	SCS/JAI
Direct dial	0131 469 3162

Dear Dr Willis

I am writing in response to your application requesting permission to undertake research in schools in The City of Edinburgh.

Your request has been considered, and I am pleased to inform you that you have been given permission in principle to undertake your research. I must stress that it is the policy of this Authority to leave the final decision about participation in research projects of this kind to Head Teachers and their staff, so that approval in principle does not oblige any particular establishment to take part.

I request that you forward a copy of your completed findings to me when they become available. In this case an electronic summary of your thesis would be preferred. Your work may be of interest to a number of staff in the Children and Families Department.

I would like to thank you for contacting the Children and Families Department about your work, and wish you every success in the completion of your project.

Yours sincerely

JAInnes

JULIE INNES
Administrative Officer

Business Support, Schools and Community Services, Children and Families
Level 1.2, Waverley Court, 4 East Market Street, Edinburgh, EH8 8BG
Tel 0131 469 3162 Fax 0131 529 6213 E-mail julie.innes@edinburgh.gov.uk

Appendix B: Detailed statistical data analyses

Table B-1
Missing data: dyslexia-sensitive and intelligence tests

	N	Mean	SD	Missing		No. of Extremes[a]	
				Count	%	Low	High
Phonological Processing	382	< 0.001	0.999	50	11.6	0	0
Auditory Sequential Memory	382	< 0.001	0.999	50	11.6	0	0
Visual Memory/Phonic Skill	348	< 0.001	0.999	84	19.4	0	0
Digit Span	407	< 0.001	0.999	25	5.8	5	16
Random Automatised Naming	390	< 0.001	0.999	42	9.7	1	11
Bead Threading	404	< 0.001	0.999	28	6.5	0	1
Block Design	407	< 0.001	0.999	25	5.8	5	16
Matrix Reasoning	407	< 0.001	0.999	25	5.8	1	0
Verbal Reasoning	398	< 0.001	0.999	34	7.9	0	0

Note. [a] Number of cases outside the range (Q1 - 1.5*IQR, Q3 + 1.5*IQR).

Table B-2
Missing data: the DtD test for dominant hand and non-dominant hand

	N	Mean	SD	Missing		No. of Extremes[a]	
				Count	%	Low	High
DH First sector max. err.	369	0.070	0.999	63	14.6	0	14
DH Time	369	0.053	0.999	63	14.6	0	10
DH Total err.	369	0.078	0.999	63	14.6	0	13
DH SD2	369	0.025	0.999	63	14.6	0	2
DH Direction ratio	370	-0.007	0.999	62	14.4	0	0
DH FirstDown First sector max. err.	369	0.060	0.999	63	14.6	0	16
DH FirstDown Direction ratio	360	-0.016	0.999	72	16.7	0	80
DH FirstUp First sector max. err.	369	0.056	0.999	63	14.6	0	14
DH FirstUp Direction ratio	247	0.011	0.998	185	42.8	0	0
DH TimeTotal	369	0.066	0.786	63	14.6	0	13
NDH First sector max. err.	287	0.180	0.998	145	33.6	0	12
NDH Time	287	0.165	0.998	145	33.6	0	12
NDH Total err.	287	0.212	0.998	145	33.6	0	8
NDH SD2	287	0.054	0.998	145	33.6	0	2
NDH Direction ratio	287	-0.065	0.998	145	33.6	0	1
NDH FirstDown First sector max. err.	292	0.177	0.998	140	32.4	0	17
NDH FirstDown Direction ratio	280	-0.126	0.998	152	35.2	0	3
NDH FirstUp First sector max. err.	287	0.128	0.998	145	33.6	0	9
NDH FirstUp Direction ratio	245	-0.018	0.998	187	43.3	0	0
NDH TimeTotal	287	0.189	0.744	145	33.6	0	17

Note. [a] Number of cases outside the range (Q1 - 1.5*IQR, Q3 + 1.5*IQRSD2 = points over 2 SD; T = time; DR = direction ratio; FirstUp = pattern with the first dot located above the starting point; FirstDown = pattern with the first dot located below the starting point; DH = dominant hand; NDH = non-dominant hand.

Table B-3

Dyslexia risk group differences on the main DtD measures for dominant hand

DtD	DD risk	*N*	*M*	*SD*	*F (df)*	*p (q); η²*
First sector max. err.	High	82	0.287	1.035	3.563	.030
	medium	110	0.094	1.073	(2, 295)	(.021-.022)
	Low	106	-0.093	0.785		
Time	High	82	-0.049	0.809	.150	.860
	medium	110	0.014	0.962	(2, 295)	
	Low	106	0.020	0.991		
Total error	High	82	0.264	0.961	2.2427	.090
	medium	110	0.107	1.069	(2, 295)	
	Low	106	-0.041	0.774		
SD2	High	82	0.248	0.934	3.401	.035
	medium	110	-0.004	0.969	(2, 295)	(.024)
	Low	106	-0.108	0.921		
Direction ratio	High	82	-0.197	0.992	3.549	.030
	medium	110	-0.002	1.017	(2, 295)	(.021-.022)
	Low	106	0.197	1.019		
TimeTotal	High	82	0.107	0.687	.586	.557
	medium	110	0.060	0.868	(2, 295)	
	Low	106	-0.010	0.674		
FirstDown First sector max. err.	High	82	0.189	1.011	1.591	.205
	medium	110	0.100	1.112	(2, 295)	
	Low	106	-.062	.811		
FirstDown Direction ratio	High	81	-.117	.863	1.139	.322
	medium	105	-.021	1.015	(2, 286)	
	Low	103	.109	1.141		
FirstUp First sector max. err.	High	82	.320	1.183	**4.476**	.012* (.017);
	medium	110	.040	.910	(2, 295)	η^2=.029
	Low	106	-.102	.825		
FirstUp Direction Ratio	High	54	-.322	1.096	**3.457**	.014*[a] (.019);
	medium	78	.045	.926	(2, 193)	η^2=.044
	low	64	.122	.909		

Note. * significance at the B-H adjusted level *critical q values provided for the lowest p values in brackets;* [a] *p* value provided here comes form Kruskal-Wallis test (χ^2 (2) = 8.595) as the distribution of this measure vialoted normality checks and the result differed from ANOVA's result (p = .033); SD2 = points over 2 SD.

Table B-4

Dyslexia risk group differences on the main DtD measures for non-dominant hand

DtD	DD risk	*N*	*M*	*SD*	*F (df)*	*p (q); η²*
First sector max. err.	high	66	0.328	1.112	1.998	.138
	medium	94	0.248	1.128	(2, 251)	
	low	94	0.055	0.752		
Time	high	66	0.198	1.020	.311	.733
	medium	94	0.181	1.001	(2, 251)	
	low	94	0.090	0.889		
Total error	high	66	0.234	0.901	1.556	.213
	medium	94	0.354	1.080	(2, 251)	
	low	94	0.098	0.977		
SD2	high	66	0.209	0.920	1.804	.167
	medium	94	-0.002	0.991	(2, 251)	
	low	94	-0.088	1.016		
Direction ratio	high	66	-0.043	0.977	1.281	.280
	medium	94	-0.177	1.029	(2, 251)	
	low	94	0.060	1.034		
TimeTotal	high	66	0.216	0.739	1.354	*.260*
	medium	94	0.268	0.796	(2, 251)	
	low	94	0.101	0.666		
FirstDown First sector max. err.	high	66	0.273	1.040	.703	.496
	medium	94	0.257	1.168	(2, 252)	
	low	94	0.108	.811		
FirstDown Direction ratio	high	64	-.170	.851	.345	*.708*
	medium	92	-.157	1.066	(2, 345)	
	low	92	.052	1.008		
FirstUp First sector max. err.	high	66	.319	1.356	2.980	*.053*
	medium	94	.182	.952	(2, 251)	
	low	94	-.059	.714		
FirstUp Direction Ratio	high	54	-.068	1.096	.909	*.405*
	medium	82	-.127	.943	(2, 211)	
	low	78	.082	.993		

Note. * significance at the B-H adjusted level; SD2 = points over 2 SD.

Table B-5

Analysis of differences between the baseline and followed up sample of children in the DtD scores

DtD	sample	*N*	*M*	*SD*	*t (df)*	*p*
DH First sector max. err.	baseline	369	0.070	0.999	-.084	.933
	followed	231	0.077	1.038	(598)	
DH Time	baseline	369	0.053	0.999	-.068	.946
	followed	231	0.059	1.062	(598)	
DH Total error	baseline	369	0.078	0.999	-.469	.639
	followed	231	0.118	1.024	(598)	
DH SD2	baseline	369	0.025	0.999	-.283	.777
	followed	231	0.049	1.019	(598)	
DH Direction ratio	baseline	370	-0.007	0.999	-.518	.605
	followed	231	0.036	0.981	(599)	
DH TimeTotal	baseline	369	0.066	0.786	-.331	.741
	followed	231	0.088	0.871	(598)	
DH FirstDown First sector max. err.	baseline	369	0.060	0.999	-.025	.980
	followed	231	0.062	1.051	(598)	
DH FirstDown Direction ratio	baseline	360	-0.016	0.999	-.311	.756
	followed	224	0.010	1.036	(552)	
DH FirstUp First sector max. err.	baseline	369	0.056	0.999	-.146	.884
	followed	231	0.068	1.028	(598)	
DH FirstUp Direction Ratio	baseline	247	0.011	0.998	-.489	.625
	followed	156	0.060	0.979	(401)	
NDH First sector max. err.	baseline	287	0.180	0.998	.375	.708
	followed	187	0.180	1.045	(472)	
NDH Time	baseline	287	0.165	0.998	-.009	.993
	followed	187	0.129	1.026	(472)	
NDH Total error	baseline	287	0.212	0.998	-.083	.934
	followed	187	0.205	1.049	(472)	
NDH SD2	baseline	287	0.054	0.998	-.140	.889
	followed	187	0.068	1.047	(472)	
NDH Direction ratio	baseline	287	-0.065	0.998	-.318	.751
	followed	187	-0.035	1.013	(472)	
NDH TimeTotal	baseline	287	0.189	0.744	.304	.762
	followed	187	0.167	0.790	(472)	
NDH FirstDown First sector max. err.	baseline	292	0.177	0.998	.416	.678
	followed	191	0.138	1.030	(481)	
NDH FirstDown Direction ratio	baseline	280	-0.126	0.998	-.245	.807
	followed	182	-0.103	0.965	(460)	
NDH FirstUp First sector max. err.	baseline	287	0.128	0.998	-.545	.586
	followed	187	0.180	1.059	(472)	
NDH FirstUp Direction Ratio	baseline	245	-0.018	0.998	-.233	.816
	followed	159	0.005	0.998	(402)	

Note. SD2 = points over 2 standard deviations; DH = dominant hand; NDH= non-dominant hand.

Table B-6

Analysis of differences between the baseline and followed up sample of children in dyslexia sensitive and reasoning measures

DtD	DD risk	*N*	*M*	*SD*	*t (df)*	*p*
Phonological Processing	baseline	362	0.039	0.842	-.634	.526
	followed	229	0.083	0.798	(589)	
Digit Span	baseline	397	0.000	0.999	-1.406	.160
	followed	251	0.113	0.987	(646)	
RAN	baseline	390	0.000	0.999	.289	.773
	followed	247	-0.024	1.047	(635)	
Bead Threading	baseline	404	0.000	0.999	.389	.697
	followed	254	-0.031	1.002	(656)	
Auditory Sequential Memory	baseline	382	0.000	0.999	-.613	.540
	followed	241	0.051	1.016	(621)	
Visual Memory/Phonic Skill	baseline	348	0.000	0.999	-1.086	.278
	followed	225	0.093	1.016	(571)	
Block Design	baseline	407	0.000	0.999	-1.036	.301
	followed	255	0.083	1.020	(660)	
Matrix reasoning	baseline	407	0.000	0.999	-.039	.969
	followed	255	0.003	1.004	(660)	
Verbal Reasoning	baseline	398	0.000	0.999	.006	.995
	followed	250	-0.001	0.994	(646)	

Table B-7

Spearman's correlations of the DtD, dyslexia screening and reasoning scores with reading (nonsense and speeder reading combined)

Co-variable	*N*	*r*	*p (q)*
NDH Time	207	**-0.289***	<0.001 (<.020)
DH First sector max. error	207	**-0.281***	<0.001 (<.020)
DH Total error	207	**-0.272***	<0.001 (<.020)
DH FirstUp First sector max. error	207	**-0.258***	<0.001 (<.020)
DH SD2	207	**-0.234***	0.001 (<.024)
DH FirstDown First sector max. error	207	**-0.234***	0.001 (<.024)
DH Time	207	**-0.213***	0.002 (<.028)
DH TimeTotal	207	**-0.213***	0.002 (.028)
NDH Direction ratio	171	**-0.202***	0.008 (.029)
NDH SD2	171	**-0.197***	0.010 (.031)
NDH TimeTotal	171	**-0.168***	0.028 (.032)
NDH FirstUp First sector max. error	171	-0.148	0.053
NDH First sector max. error	171	-0.133	0.082
NDH Total error	171	-0.105	0.172
NDH FirstDown First sector max. error	171	-0.102	0.180
NDH FirstDown Direction ratio	171	0.052	0.167
DH Direction ratio	207	0.050	0.474
DH FirstUp Direction ratio	207	0.044	0.138
DH FirstDown Direction ratio	207	0.011	0.874
NDH FirstUp Direction ratio	171	<0.001	0.997
Bead Threading	230	0.101	0.127
Digit Span	229	**0.400***	<0.001 (<.020)
RAN	226	**-0.293***	<0.001 (<.020)
Phonological Processing	210	**0.595***	<0.001 (<.020)
Auditory seq. memory	222	**0.414***	<0.001 (<.020)
Verbal memory/Phonic skill	207	**0.407***	<0.001 (<.020)
Matrix Reasoning	231	**0.316***	<0.001 (<.020)
Block Design	231	**0.328***	<0.001 (<.002)
Verbal Reasoning	227	**0.427***	<0.001 (<.020)

Note. * significance at the B-H adjusted level *critical q values in brackets;* SD2 = points over 2 standard deviations; DH = dominant hand; NDH= non-dominant hand.

Table B-8

Spearman's correlations of DtD, dyslexia screening and reasoning scores with reading (nonsense and speeder reading combined) for the pre-reading sample

Co-variable	*N*	*r*	*p(q)*
DH Total err.	111	**-0.290***	0.002 (.012)
DH TimeTotal	111	**-0.230***	0.015 (.016)
DH SD2	111	**-0.227***	0.017 (.017)
DH First sector max. error	111	**-0.222***	0.019 (.019)
DH FirstDown First sector max. error	111	-0.216	0.023 (.021)
DH FirstUp First sector max. error	111	-0.203	0.033
NDH FirstUp First sector max. error	79	-0.185	0.103
NDH Direction ratio	79	0.162	0.154
NDH FirstDown First sector max. error	79	-0.151	0.185
DH Time	111	-0.130	0.173
NDH FirstDown Direction ratio	77	0.125	0.277
NDH SD2	79	-0.124	0.275
NDH First sector max. error	79	-0.123	0.279
NDH FirstUp Direction ratio	66	-0.089	0.478
NDH TimeTotal	79	-0.076	0.506
DH FirstDown Direction ratio	110	0.079	0.411
NDH Total err.	79	-0.073	0.522
NDH Time	79	-0.068	0.551
DH Direction ratio	111	0.018	0.851
DH FirstUp Direction ratio	68	0.015	0.905
Bead Threading	132	0.177	0.042
Digit Span	131	**0.380***	<0.001 (<.010)
RAN	128	-0.242	0.006 (.014)
Phonological Processing	115	**0.549***	<0.001 (<.010)
Auditory seq. memory	128	**0.373***	<0.001 (<.010)
Verbal memory/Phonic skill	116	**0.350***	<0.001 (<.010)
Matrix Reasoning	133	0.165	0.058
Block Design	133	**0.300***	<0.001 (<.010)
Verbal Reasoning	129	**0.454***	<0.001 (<.010)

Note. * significance at the B-H adjusted level *critical q values in brackets;* SD2 = points over 2 standard deviations; DH = dominant hand; NDH= non-dominant hand.

Table B-9

DtD scores differences between dyslexia and control groups.

	Dyslexia(N)	Mean rank	z score	Mann-Whitney U test
DH Time	Yes (37)	*39.14*	0.654	U=745, p = 0.513
	No (37)	*35.86*		
DH First sector max. error	Yes (37)	*39.04*	0.616	U=741.5, p = 0.538
	No (37)	*35.39*		
DH Total error	Yes (37)	*38.62*	0.449	U=726, p = 0.654
	No (37)	*36.38*		
DH Direction Ratio	Yes (37)	22.96	-1.611	U=180.5, p = 0.137
	No (37)	19.50		
DH SD2	Yes (37)	36.11	-0.557	U=633, p = 0.578
	No (37)	38.89		
DH TimeTotal	Yes (37)	43.68	2.470	U=795, p = 0.232
	No (37)	31.32		
DH First sector max. error FirstDown	Yes (19)	*22.26*	-0.322	U=233, p = 0.748
	No (26)	*23.54*		
DH Direction Ratio FirstDown	Yes (19)	19.50	-1.487	U=180.5, p = 0.137
	No (26)	24.78		
DH First sector max. error FirstUp	Yes (19)	23.05	0.023	U=245, p = 0.982
	No (26)	22.96		
DH D. Ratio FirstUp	Yes (15)	18.23	0.697	U=161, p = 0.730
	No (26)	17.45		
NDH Time	Yes (37)	*41.02*	1.427	U=816.5, p = 0.154
	No (37)	*33.93*		
NDH First sector max. error	Yes (37)	*40.82*	1.330	U=807.5, p = 0.184
	No (37)	*34.18*		
NDH Total error	Yes (37)	*39.70*	0.881	U=766, p = 0.378
	No (37)	*35.30*		
NDH Direction Ratio	Yes (37)	*22.00*	-0.448	U=228, p = 0.654
	No (37)	*23.73*		
NDH SD2	Yes (37)	39.68	0.870	U=765, p = 0.384
	No (37)	35.32		
NDH TimeTotal	Yes (37)	43.68	2.470	**U=913, p = 0.008***
	No (37)	31.32		
NDH First sector max. err. FirstDown	Yes (19)	*25.21*	0.965	U=289, p = 0.334
	No (26)	*21.38*		
NDH Direction Ratio FirstDown	Yes (19)	18.18	0.342	U=156.5, p = 0.392
	No (26)	21.41		
NDH First sector max. error FirstUp	Yes (19)	24.74	0.758	U=280, p = 0.448
	No (26)	21.73		
NDH D. Ratio FirstUp	Yes (15)	22.00	0.162	U=203, p = 0.196
	No (26)	17.17		

Note. *significance at the level calculated using the HB procedure; SD2 = points over 2 SDs; DH = dominant hand; NDH = non-dominant hand.

Table B-10

Dyslexia and control groups' performance on reasoning and dyslexia sensitive tests

	Dyslexia(N)	Mean rank	z score	Mann-Whitney U test	η^2
Similarities	Yes (17)	*16.79*	-2.081	U=132.5, p = 0.037	
	No (25)	*24.70*			
Block design	Yes (17)	22.70	-0.775	U=182.5, p = 0.438	
	No (25)	19.74			
Matrix Reasoning	Yes (17)	16.79	-2.067	U=132.5, p = 0.039	
	No (25)	24.70			
Non-verbal reasoning (L)	Yes (18)	20.14	-1.075	U=191.5, p = 0.282	
	No (26)	24.13			
Verbal Reasoning (L)	Yes (15)	15.50	-0.320	U=112.5, p = 0.770	
	No (16)	16.47			
Word Recognition	Yes (18)	*28.19*	2.518	U=336.5, p = 0.012	
	No (26)	*18.56*			
Word Construction	Yes (18)	*31.14*	3.772	**U=389.5, p < 0.001***	**0.331**
	No (26)	*16.52*			
Working Memory (L)	Yes (18)	*29.56*	3.521	**U=361, p < 0.001***	**0.288**
	No (26)	*17.62*			
Digit span (W)	Yes (17)	13.91	-3.331	**U=83.5, p = 0.001***	**0.264**
	No (25)	26.66			
RAN	Yes (17)	20.79	-0.325	U=200.5, p = 0.745	
	No (25)	21.98			
Bead Threading	Yes (17)	22.44	0.419	U=228.5, p = 0.675	
	No (25)	20.86			
Phonemic segmentation	Yes (17)	*12.18*	-4.314	**U=54, p < 0.001***	**0.443**
	No (25)	*27.84*			

Note. Dyslexia and control groups' performance on intelligence subtests derived from WAIS-III IQ scale (similarities, block design, matrix reasoning, digit span), and dyslexia predictors derived from LADS (non-verbal reasoning, verbal reasoning, word recognition and construction) and from DAST (RAN and phonemic segmentation). *significance at the level calculated using the HB procedure.

Table B-11

Spearman correlation matrix for the DtD (dominant hand), dyslexia sensitive and reasoning measures

DH DtD	Word recognition	Word construction	Backward Digit Span	Digit Span	RAN	Phonemic S & S	Non-verbal reasoning	Verbal reasoning	Similarities	Block design	Matrix reasoning	Bead Threading
Time	.159 (N=59)	.251 (N=59)	.071 (N=59)	-.270 (N=57)	-.119 (N=57)	-.115 (N=57)	-.149 (N=59)	-.032 (N=36)	.015 (N=57)	-.239 (N=57)	-.095 (N=57)	.006 (N=57)
First sector max error	.028 (N=59)	.108 (N=59)	.114 (N=57)	-.018 (N=57)	-.081 (N=57)	-.155 (N=57)	.027 (N=59)	.044 (N=36)	-.220 (N=57)	-.194 (N=57)	.042 (N=57)	-.183 (N=57)
Total error	.106 (N=59)	.112 (N=59)	.005 (N=59)	-.012 (N=57)	-.190 (N=57)	-.131 (N=57)	.064 (N=59)	.078 (N=36)	-.126 (N=57)	-.076 (N=57)	.067 (N=57)	-.107 (N=57)
SD 2	.105 (N=59)	.152 (N=59)	.082 (N=59)	-.049 (N=57)	-.073 (N=57)	-.126 (N=57)	.156 (N=59)	.039 (N=36)	-.157 (N=57)	-.003 (N=57)	.048 (N=57)	-.093 (N=57)
Time Total	.248 (N=59)	.252 (N=59)	.082 (N=59)	-.206 (N=59)	-.316 (N=59)	-.235 (N=59)	-.120 (N=59)	-.119 (N=59)	-.164 (N=59)	-.228 (N=59)	-.052 (N=59)	-.115 (N=59)
Direction Ratio	-.054 (N=50)	.130 (N=50)	-.046 (N=50)	.131 (N=48)	.148 (N=48)	.061 (N=48)	.118 (N=50)	-.068 (N=36)	-.105 (N=48)	.009 (N=48)	.015 (N=48)	-.105 (N=48)
FirstDown First sector max. err.	.076 (N=50)	.114 (N=50)	.126 (N=50)	.021 (N=48)	-.181 (N=48)	-.115 (N=48)	.013 (N=50)	-.087 (N=36)	-.211 (N=48)	-.190 (N=48)	.042 (N=48)	-.166 (N=48)
FirstDown Direction ratio	.045 (N=59)	.033 (N=59)	-.025 (N=50)	-.173 (N=57)	.116 (N=57)	-.022 (N=57)	.106 (N=59)	-.084 (N=36)	-.059 (N=57)	.220 (N=57)	-.022 (N=57)	-.003 (N=57)
FirstUp First sector max. err.	-.135 (N=50)	.075 (N=50)	.074 (N=50)	-.069 (N=48)	-.130 (N=48)	-.246 (N=48)	-.079 (N=50)	.218 (N=36)	-.153 (N=48)	-.362 (N=48)	-.073 (N=48)	-.247 (N=48)
FirstUp Direction ratio	-.051 (N=59)	-.052 (N=59)	-.030 (N=59)	-.120 (N=57)	.329 (N=57)	-.008 (N=57)	.170 (N=59)	.191 (N=36)	-.090 (N=57)	.188 (N=57)	-.028 (N=57)	.270 (N=57)

Note. Number of participants in brackets; * significance at the B-H adjusted level; SD2 = points over 2 SDs

Table B-12
Spearman correlation matrix for the DtD (non-dominant hand), dyslexia sensitive and reasoning measures

NDH DtD	Word recognition	Word construction	Backward Digit Span	Digit Span	RAN	Phonemic S & S	Non-verbal reasoning	Verbal reasoning	Similarities	Block design	Matrix reasoning	Bead Threading
Time	.284 (N=59)	.279 (N=59)	-.028 (N=59)	-.221 (N=57)	-.230 (N=57)	-.016 (N=59)	.002 (N=59)	-.150 (N=36)	-.042 (N=57)	-.157 (N=57)	.053 (N=57)	-.040 (N=57)
First sector max error	.191 (N=59)	.325 (N=59)	-.286 028 (N=57)	-.220 (N=57)	-.065 (N=57)	-.096 (N=57)	.058 (N=59)	.201 (N=36)	-.192 (N=57)	-.247 (N=57)	.124 (N=57)	-.103 (N=57)
Total error	.061 (N=59)	.162 (N=59)	.075 (N=59)	-.081 (N=57)	-.243 (N=57)	-.127 (N=57)	-.045 (N=59)	.110 (N=36)	-.049 (N=57)	-.270 (N=57)	.078 (N=57)	-.014 (N=57)
SD 2	.129 (N=59)	.211 (N=59)	.096 (N=59)	-.178 (N=57)	-.014 (N=57)	-.175 (N=57)	.047 (N=59)	.039 (N=36)	-.115 (N=57)	-.176 (N=57)	.019 (N=57)	.048 (N=57)
Time Total	.209 (N=59)	.282 (N=59)	.050 (N=59)	-.233 (N=59)	-.381 (N=59)	-.113 (N=59)	-.111 (N=59)	-.045 (N=59)	-.022 (N=59)	-.367 (N=59)	.101 (N=59)	-.018 (N=59)
Direction Ratio	-.100 (N=50)	.010 (N=50)	.038 (N=50)	.253 (N=48)	.174 (N=48)	.176 (N=48)	-.049 (N=50)	-.046 (N=36)	.089 (N=48)	-.139 (N=48)	-.026 (N=48)	193 (N=48)
FirstDown First sector max. err.	.021 (N=50)	.159 (N=50)	.189 (N=50)	-.139 (N=48)	-.016 (N=48)	-.016 (N=48)	.066 (N=50)	.199 (N=36)	-.098 (N=48)	-.324 (N=48)	.112 (N=48)	-.160 (N=48)
FirstDown Direction ratio	-.005 (N=59)	-.056 (N=59)	-.065 (N=50)	.055 (N=57)	.271 (N=57)	.043 (N=57)	.137 (N=59)	-.035 (N=36)	-.094 (N=57)	.182 (N=57)	.009 (N=57)	.050 (N=57)
FirstUp First sector max. err.	.194 (N=50)	.364 (N=50)	.262 (N=50)	-.064 (N=48)	-.157 (N=48)	-.112 (N=48)	-.084 (N=50)	.003 (N=36)	-.023 (N=48)	-.177 (N=48)	.017 (N=48)	-.072 (N=48)
FirstUp Direction ratio	.039 (N=59)	-.089 (N=59)	-.136 (N=59)	-.048 (N=57)	.081 (N=57)	.079 (N=57)	.176 (N=59)	.106 (N=36)	.017 (N=57)	.224 (N=57)	.058 (N=57)	.036 (N=57)

Note. Number of participants in brackets; * significance at the B-H adjusted level

Appendix C: Summary of the key hypotheses and findings in the thesis

Table C1

Summary of all of the hypotheses, findings and interpretations covered in the thesis

Hypotheses	Observed results	Theoretical interpretation	Implications and other comments
Chapter 4			
(1) Performance on the DtD task, the established dyslexia screening tests, and verbal (Similarities) and non-verbal reasoning (Matrix Reasoning and Block Design) tests will significantly differ between children at high, medium and low risk of dyslexia as assessed by Lucid Rapid.	**FirstUp FSME & FirstUp DR DH** measures could distinguish between high and low risk children, after controlling for verbal reasoning – the significant differences disappeared. Dyslexia indicators could distinguish between risk groups; as expected. Non-verbal reasoning sig. differentiated between low – medium and high – low	Lucid Rapid estimates risk of dyslexia in line with phonological deficit theory without taking the intelligence level into considerations; DtD shows potential in indicating children at risk	Lucid problematic therefore the risk assessed here needs to be verified with reading tests
Performance on the DtD task will be related to the performance on some of the dyslexia-sensitive tasks (PP, RAN, memory and motor tasks), the motor task and to verbal and non-verbal reasoning	These two measures showed weak correlations (<.2) with other measures (with BD, VR, VM, & MR)	DtD cannot be understood in line with the PAD theory, also no correlation with BT indicates that it's not a purely motor task.	No strong correlations between the measures distinguishing the risk groups and dyslexia indicators revealed therefore further research needed
Chapter 5			
Will baseline measures (DtD task, dyslexia screening tests and reasoning measures) be correlated with reading ability in children?	Correlated with reading: DtD measures for *DH*: **First sector max. error, Time, Total error, SD2, FirstDown first sector max. error, FirstUp first sector max.**	Phonological processing significantly correlated with reading in line with PAD; The fact that DtD also correlated with reading, despite of not being related to PP,	Reading is a complex task and its deficits cannot be fully understood by only looking at phonological and language

Hypotheses	Observed results	Theoretical interpretation	Implications and other comments
	error, and TimeTotal; NDH: **Time, SD2, Direction ratio, and TimeTotal.** Other sig. correlations with: Auditory sequential memory, Verbal memory/phonic skill, digit span, RAN, phonological processing, block design, matrix reasoning and verbal reasoning	signifies that other skills, beyond the PP, are also needed for successful reading. This also provides evidence against the hard PAD view.	aspects. * only 53% of poor readers were identified by Lucid Rapid as being at high risk – previous chapter's results need to be interpreted with caution then.
How effectively do the baseline measures, which significantly correlated with reading, predict children's reading abilities? Would different measures be more indicative of poor reading in pre-reading children (nursery and beginning of P1) than in the full sample overall?	DH **TimeTotal explained 4.4%** of variance in reading scores; together with **NDH DR 8%** explained. PP explained 40.8%, together with RAN 43% explained. NDH DR added extra 2.6% on top of PP and RAN (all explained **45.9%**). BD added 1.7% but disappeared after controlling for PP. **Pre-readers**: PP – 30%, **DH TotalError** added 5.1%.	DtD doesn't explain much of the variance but still remains an important predictor; arguably more important than other established measures (e.g., memory). PP as the best predictor, in line with PAD. RAN also a unique contributor, in line with double deficit hypothesis. WM possibly related to PP and RAN. Making sense of the DtD: no correlation with BT (BT possibly not the best task for cerebellar functioning); Other possible explanations: motor skill learning ('on-line' learning) in line with automaticity & cerebellar deficits; impaired visually guided motion and attention allocation mechanisms in line with the magnocellular-dorsal stream deficit hypothesis?	DtD cannot be used as a sole dyslexia indicator as it explained arguably very little variance but still statistically significant. This implies that the dominant theory cannot fully account for the reading difficulties. The implications of the findings are that there is no one single test that could reliably indicate the risk of dyslexia and multiple tests, with DtD being a useful addition, are necessary for accurate identification. Risk prediction even more difficult in pre-reading children (only 35% of variance in reading predicted)
How effectively do the measures that can statistically distinguish between poor and typical readers predict which children will become poor readers and which will be typical readers? The sensitivity and specificity of the set of best predictors will be assessed.	Group diff: **DH: FSME, TotalError, TimeTotal, FirstDown FSME, FirstUpFSME, NDH DR** & all dyslexia sensitive + reasoning tests. Prediction: **DH: FSME & NDH DR**: Sensitivity -14.3%, specificity - 100%. **PP & NDH DR**: Sensitivity - 98.5%, specificity - 36.8%.		

Hypotheses	Observed results	Theoretical interpretation	Implications and other comments
Is there evidence for multiple deficits in reading disorder, or is there one common deficit?	16% of poor readers show deficits in 1 area. Majority of participants showed multiple deficits. No one common deficit for all.	The findings provide strong evidence for the multiple deficit model in line with previous research (Pennington, 2006, Carroll et al. 2016)	
Chapter 6			
Will performance on vision tasks be correlated with the DtD, reading measures and reasoning measures?	DtD for DH correlated with M; DR for NDH did not correlate with anything. CF correlated with verbal and non-verbal reasoning. VR also with M	DtD weakly related to magnocellular processing, which itself could not distinguish between poor and typical readers. Under the MD theory it would be expected there would be group differences in the magnocellular and dorsal sensitivity tasks and no difference in control tasks associated with the parvocellular and ventral pathways (as per previous research Cornelissen, 1998; Stein & Walsh, 1997). In the current study poor readers compromised only on high-level visual processing which provides only partial evidence for MD theory.	The visual tasks used may be problematic due to possibly insufficient control of light in the room and children's head movements. This also implies that although such tests were indicated in previous research as useful, they cannot be reliably used in school settings
Will performance on vision tests be associated with MD sensitivity significantly differ between poor readers and typical readers	poor readers performed significantly poorer than the typical readers on the **coherent form task** (medium effect size). Poor readers sig poorer than the typical readers on the **coherent dot motion task** (small effect size).		

Hypotheses	Observed results	Theoretical interpretation	Implications and other comments
Chapter 7			
Will the performance on dyslexia screening, the DtD and reasoning measures differ between adult participants with and without developmental dyslexia?	sig diff: DtD TimeTotal for NDH; Word Contruction, Working Memory, Digit Span, Phonemic segmentation;	TimeTotal measure accounts for speed and accuracy trade-off; the measure did not correlate with any of the other measures showing that it cannot be construed under phonological deficit theory, but more likely to be in line with automaticity, cerebellar, attentional deficits	Phonological processing and word construction measures were sufficient to correctly classify 90% of cases which is better than the full LADS test. This should be considered in practice. Key limitation – sample not representative
Will the performance on various dyslexia screening tests be related to reasoning tests and the DtD task in adults?	no significant correlations found		
How well the DtD task can classify individual into those with and without dyslexia. Which of the dyslexia screening and DtD measures will be the best predictors of dyslexia in adults?	DtD - correctly classified 63.5%; but did not add anything on top of the Phonological processing and word construction (both correctly classified 90%). Lucid Lads sensitivity 68%, specificity 72% - poor	Evidence for phonological deficit theory and multiple deficits theories in adults.	
Is there evidence for multiple deficits in dyslexia, or is there one common deficit? What proportion of adults shows weaknesses in each area?	Most adults (54%) showed deficits in two areas, 4 (24%) adults showed a single deficit (2 in memory, 1 Ran, 1 PP - so in line with PAD), only 2 dyslexic had DtD deficit but in combination with other weaknesses.		

Note. DH = dominant hand; NDH = non-dominant hand; DR = Direction Ratio; PP = Phonological Processing; PAD = Phonological Awareness Deficit; M = Magnocellular, P = Parvocellular; CM = Coherent Motion; CF = Coherent Form; BT = Bead Threading; VR = Verbal Reasoning