Sentence processing in dyslexia: An examination of eye movements and comprehension

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Abstract

This thesis aimed to investigate the comprehension and eye movements of adults and adolescents with dyslexia while reading sentences with complex syntax. We focused on the processing of sentences with temporary syntactic ambiguity (Chapter 2), sentences that contain relative clauses (Chapter 3), as well as active and passive, plausible and implausible sentences (Chapter 4). The final experiment reported in this thesis involved the examination of the way that dyslexic and non-dyslexic adolescents comprehend and process all three types of sentences that were the focus of the adult studies (Chapter 5). We also compared the similarities and differences between the adult and adolescent samples, in order to attempt to provide some exploratory insight into the trajectory that the development of sentence processing and comprehension follows from adolescence to adulthood. Results showed that dyslexic adults show poorer comprehension than controls in sentences with syntactic ambiguity, and in passive and implausible sentences. However, dyslexics showed similar comprehension accuracy to controls in sentences that contained relative clauses. Despite the type of sentence examined, dyslexic adults showed consistently longer reading times than non-dyslexics. Dyslexic adolescents showed similar result patterns to dyslexic adults. More specifically, they showed consistently longer reading times in all types of sentences and poorer comprehension in garden-path and passive sentences. This highlights the differences in development of comprehension and processing of sentences between non-dyslexic and dyslexic individuals of all ages. Throughout this thesis, we additionally examined the role of several cognitive factors (working memory, processing speed, verbal intelligence) in comprehension and processing of sentences. Working memory in general appeared to be more associated with group differences than the other two factors. The findings of the studies presented in this thesis provide invaluable insights into the manifestation of dyslexia as a cognitive-developmental disorder in the processing and comprehension of sentences in adolescence and adulthood.

Keywords: dyslexia, eye movements, sentence processing, sentence comprehension, cognitive factors

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Author's declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

The research presented in Chapter 2 has been communicated to the scientific community by publication in the journal *Dyslexia*. Parts of this thesis have been presented at conferences as oral and poster presentations.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the School of Psychology Ethics Committee at the University of East Anglia.

Chapter 1

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Introduction

Definition of Dyslexia

Early definitions of dyslexia from the World Federation of Neurology recognised dyslexia as a reading disorder that manifests itself in the presence of average intelligence, instruction and socioeconomic status (Critchley, 1970). Definitions like this one have been widely criticised due to the fact that they focus on what dyslexia is not, without providing many inclusionary criteria (Fletcher, 2009).

Later definitions of dyslexia that have evolved through research and contemporary definitions from the International Dyslexia Association (IDA), have defined developmental dyslexia as a specific learning disability with a neurobiological origin. Dyslexia appears in childhood and is primarily characterised by difficulties in accurate and/or fluent word recognition, decoding and spelling, despite adequate intelligence, instruction and opportunity to learn (Bishop & Snowling, 2004; Lyon, Shaywitz, & Shaywitz, 2003; Peterson & Pennington, 2012). This definition focuses on inclusionary criteria that highlight that dyslexia occurs due to a specific cognitive deficit and in the absence of other disabilities that could justify the difficulties in reading. Furthermore, in this definition, there is no reference to intellectual abilities or socioeconomic status (Fletcher, 2009).

Dyslexia is a complex disorder and despite the fact a single universally accepted definition has not yet been achieved, there is agreement on the factors that can contribute to dyslexia (Reid, 2016). Rose (2009) describes dyslexia as a learning difficulty primarily affecting the skills involved in accurate and fluent word reading and spelling, which has characteristic features of difficulties in phonological awareness, verbal memory and verbal processing speed (Rose, 2009; Snowling & Hulme, 2008). Rose also highlights that dyslexia is best thought as a continuum occurring across a range of intellectual abilities (Lyon et al., 2003; Rose, 2009; Shaywitz, 2003). As such, children with dyslexia show phonological deficits regardless of whether their reading level matches their IQ and chronological age, or not (Fletcher et al., 1994). Furthermore, Reid (2016) suggests that dyslexia is a processing difference, often characterised by difficulties in literacy acquisition affecting reading, writing and spelling. Reid (2016) also emphasises the individual differences and variation among people with dyslexia and that it is essential to consider learning styles, learning and work context when planning intervention and accommodations.

Reid and Everatt (2009) highlighted some factors that current research has agreed upon, that is, they contribute to dyslexia and they have influenced our understanding of dyslexia. Each one of the following factors can and has had an impact on how dyslexia is perceived, and how assessment and interventions are planned and delivered. Some of these factors are related to brain structure and functions (Galaburda & Rosen, 2001; Hynd et al., 1995) as well as genetic correlations (Gilger, 2008) and genetic factors (Stein, 2008). Some additional factors are associated with cognitive abilities and processes, like processing speed (Wolf & Bowers, 1999), difficulty in automatising skills and tasks (Fawcett & Nicolson, 1992), working memory difficulties (Jeffries & Everatt, 2004) and phonological deficits (Snowling, 2000).

Estimates of the prevalence of dyslexia in the population vary between three and 20 percent depending on the definition of dyslexia used in the various studies (Esser & Schmidt, 1994; Feeg, 2003; Miles, 2004; Peterson & Pennington, 2012; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Shaywitz, 2003). The difference in these estimates is likely due to the differences in populations studied and the criteria used for defining dyslexia. For example, a re-examination of the British Births Cohort Study suggested that the UK prevalence rate was between three and six percent, depending on whether diagnostic criteria included children who were underachieving in reading or who showed positive signs of dyslexia (Miles, 2004). Dyslexia is also found across different languages despite differences in orthography and phonology (see reviews, Marketa Caravolas, 2008; Peterson & Pennington, 2012).

Related Disorders and Comorbidity Issues

Epidemiological studies suggest that dyslexia co-occurs with other disorders, like Attention Deficit/Hyperactivity Disorder (ADHD/ADD) as much as 30-40% of the time (August & Garfinkel, 1990; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005). ADHD occurs in approximately 3-7% of the population, and according to the DSM-V, it is primarily characterised by pervasive and impairing symptoms of inattention, hyperactivity, and impulsivity (American Psychiatric Association, 2013; Barkley, 1997). Both dyslexia and ADHD are characterised by deficits in various cognitive functions and especially in developing efficient reading skills (Germanò, Gagliano, & Curatolo, 2010).

In light of the challenges that dyslexia poses for individuals and society, educators and researchers alike are focused on identifying underlying risk factors that account for the presence of symptoms and may allow for earlier identification of dyslexia and more appropriate interventions.

Aetiology of Dyslexia

Genetic Factors and Heritability

At the biological level, genetic analyses can identify and examine specific gene effects that contribute to disorders, like dyslexia, and subsequently help to identify possible biological mechanisms that may be responsible for the differences in brain functions that affect cognitive and behavioural development. A considerable amount of research has been focused on the genetic basis of dyslexia.

Family studies on dyslexia have shown that the disorder clusters within families (DeFries, Singer, Foch, & Lewitter, 1978). According to Gilger, Pennington and DeFries (1991) the risk of a son being dyslexic, if he has a dyslexic father is around 40%. Furthermore, 50 and 75% of children with one or two parents with a reading difficulty have been found to be at risk of dyslexia (Wolff & Melngailis, 1994) and siblings show a greater incidence of reading difficulties than children without familial dyslexia (Pennington et al., 1991). Pennington and Smith (1983) as well as Vogler, DeFries and Decker (1985) further suggested that the risk to sons with fathers who have dyslexia is 40% and to sons of mothers with dyslexia the risk was estimated to be 35%. On the other hand, the risk to daughters of a dyslexic parent of either sex was 17-18%.

Twin studies have also confirmed that this familial clustering is influenced to a large extent by genes in addition to the contribution of the shared environment within families. Research with identical, monozygotic twins has shown concordance rates for dyslexia of 68% compared to 38% in non-identical dizygotic twins (DeFries & Alarcón, 1996). If the dyslexia status was influenced to a greater extent by environmental factors, the heritability estimates for the different twin groups would be more similar. Many of these studies have been focused on the heritability of reading skills and sub-skills, and particularly the phonological component.

It is important to note that there is a significant number of factors and studies identifying different areas of the genotype and relating this to the different aspects of reading and literacy (the phenotype). Multiple studies have shown strong evidence that genes do have an impact on dyslexia and that there are and will be children who are genetically at risk of dyslexia (Muter & Snowling, 2009; Snowling et al., 2007). This point is essential as it can provide pointers for early identification and diagnosis.

Dyslexia has been one of the common but unusually challenging phenotypes to explain genetically. Gilger et al. (1991) have highlighted the importance and the complexity of utilising and relying on data and results from genetic studies. They suggested the following genetic regions as the most prominent ones to be associated with dyslexia: 1p36, 2p16-p15, 2p11, 6p22.2, 7q32, 11p15.5, 15q21, 13, 16, 2q (Reid, 2016). They have also pointed out that these regions can be responsible for different aspects of reading and writing processes, such as, reading and verbal ability, single-word reading, spelling, phoneme awareness, phonological decoding, pseudo- and non-word reading and writing, IQ, language skills, rapid naming and verbal short-term memory.

Many of the gene studies indicate the presence of a possible site of dyslexic genes. Several susceptibility genes have been suggested, many of which point to common but previously unsuspected biological mechanisms, such as neuronal migration (Kere, 2014). These identified genetic and neurobiological mechanisms contribute to establishing the complex neurocircuitry that may subserve abilities such as phonological and visual processing, as well as learning. Disruptions in this neurocircuitry could result in impairments that are associated disorders of language and reading functions (Rendall, Tarkar, Contreras-Mora, LoTurco, & Fitch, 2017).

The first attempts to identify genetic loci influencing susceptibility were based on genetic linkage mapping in unusually large families with dominance inheritance patterns or multiple small families, and therefore, introducing the risk of genetic heterogeneity. It is worth mentioning at this point that despite the fact that the genetic linkage studies have been based on families in multiple countries and thus speaking different languages, the results of genetic mapping have remained largely consistent (Kere, 2014).

The first candidate susceptibility genes for dyslexia were identified in the early 2000’s and the studies were based on rare chromosomal translocations localising within the implicated genetic loci on chromosome 15 (DYX1, gene DYX1C1) (Taipale et al., 2003) and chromosome 3 (DYX5, gene ROBO1) (Hannula-Jouppi et al., 2005). The dyslexia susceptibility 1 candidate 1 gene (DYX1C1) was initially identified by a study of a family with dyslexic father and three out of four children, all of whom carried the gene. The role of DYX1C1 in dyslexia has been verified and replicated by multiple studies around the world with large data sets (Kere, 2014). Furthermore, positive association between the above gene and the presence of dyslexia have been reported not only for users of alphabetic writing systems, but also for Chinese (Lim, Ho, Chou & Waye, 2011).

The DYX1C1 gene has been specifically shown to be associated with deficits in short-term memory in individuals with dyslexia. More specifically, DYX1C1 variants have been associated with core component features of dyslexia, including deficits in verbal short-term memory (Marino et al., 2007), non-verbal short-term memory (Dahdouh et al., 2009), orthographic choice tasks and non-word reading (Bates et al., 2010). Recent research on mice was also able to replicate the findings about the associating between the DYX1C1 and memory deficits. Rendall et al. (2017) conducted behavioural assessments on mice with DYX1C1 conditional (forebrain) homozygous knockouts and compared their scores to the behavioural scores of mice with DYX1C1 conditional heterozygous knockouts and to the scores of wild-type mice. Mice with the homozygous DYX1C1 knockout showed deficits on memory and learning, but not on auditory or motor tasks. These findings affirm existing evidence that DYX1C1 may play an underlying role in the development of neural systems important to learning and memory, and disruption of this function could contribute to the learning deficits seen in individuals with dyslexia (Rendall et al., 2017).

Parallel efforts employed genetic fine-mapping based on assessing associations at increasing resolution, and yielded two candidate dyslexia genes on chromosome 6 (DYX2, genes DCDC2 and KIAA0319) (Cope et al., 2005; Francks et al., 2004; Meng et al., 2005; Schumacher et al., 2006), chromosome 2 (DYX3, genes C2Orf3 and MRPL19) (Anthoni et al., 2007) and somewhat later on chromosome 18 (DYX6, genes MC5R, DYM and NEDD4L) (Fisher et al., 2002; Scerri et al., 2010).

Environmental Factors

The environment is another influential factor in learning and this implies that social and cultural factors can affect the outcomes of the learning experience. The environment includes the learning context in the home, the school and the community, all of which have an influence on learning and teaching (Reid, 2016). More specifically, research has demonstrated that environmental influences are stronger for reading comprehension compared to spelling and word recognition and that they are less salient for phoneme awareness and phonological decoding compared to word recognition. However, it was also shown that shared environment has a stronger impact on intelligence compared to word reading ability (Gayán & Olson, 2001). These findings suggest that environmental influences vary across components of literacy skills.

Further environmental factors, such as home literacy environment, family stressors and child health have also been the focus of research in dyslexia and in reading-related skills. Children at family risk of dyslexia and children with preschool language difficulties experience more environmental adversities and health risks compared to controls in recent studies (Dilnot, Hamilton, Maughan, & Snowling, 2017). Generally, the risks associated with family risk of dyslexia and with language status were additive. Home literacy environment and child health were predictors of reading readiness of the children who participated in the study, while home literacy environment and family stressors were predictors for attention and behaviour (Dilnot et al., 2017). The research findings point more towards the direction of the conceptualisation of strong correlations between genetic and environmental factors.

Theories of dyslexia

Development of Reading

In understanding the nature of dyslexia, it is important to consider the processes of child development which contribute to reading proficiency. The goal of literacy development is to be able to comprehend written texts present in the child's environment and produce written texts in order to communicate with others. When learning to read, a child gradually understands that there are relationships between letters (graphemes) and sounds (phonemes) in spoken language which can be used to decode new words either through letter decoding and blending, or through reference to words with similar spellings (Ehri & McCormick, 1998; Kuhl, 2004). Children gradually become better at decoding larger language units and over time are able to decode words until reading becomes efficient and automatic (Ehri, 1992; Ehri & McCormick, 1998). Spelling ability builds on these same phoneme-grapheme decoding and correspondence skills and sight word vocabulary.

Reading and spelling are significantly linked to pronunciation of words, relying on the ability to segment spoken words into phonemes and map them onto graphemes (Ehri, 1992). The ability to make sense of someone else's spoken words and phrases (speech perception) develops long before reading or writing skills. At birth, babies can distinguish phonemes from any language (Kuhl & Rivera-Gaxiola, 2008) and over the first year of their life, through exposure to the speech sounds of their native language, infants lose the ability to discriminate sounds not present within their environment (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). Children continue to learn speech by listening and observing people around them, beginning to recognise words and associate them with events or objects in their environment (Kuhl, 2004).

Particular sound-based features of language allow children to identify likely word candidates, guided by previous experience in their native language (Kuhl & Rivera-Gaxiola, 2008). These features include the sounds, the gaps between sounds and the temporal and spectral characteristics of speech sounds. The speech recognition system is able to process these features in order to create and manage speech, despite the speech stream being perceived as a coherent stream of sound (Whalen & Liberman, 1987). On an evolutionary timescale, this type of sound-based processing of speech has been used functionally over a much longer period than the analysis of visual graphemic word forms (for reading), allowing a higher degree of specialisation for such sound-meaning translations.

Speech perception therefore differs from the processes of learning to read and write, where the discontinuous sound stream has to be segmented at appropriate points which correspond to letters or letter strings (Davis & Johnsrude, 2007). This task is made more difficult because the phonemes represented by letters are different to the segments used to create meaning during speech perception. In order to perceive words within this stream, regularities, such as stressed syllables and acoustic boundaries, are used in conjunction with lexical knowledge to derive segments which relate to meanings (Davis & Johnsrude, 2007). As such, when reading text, the distinctive features of speech that by convention relate to each letter have to be consciously extracted from the speech signal, a process which is more difficult for people who have difficulties in phonological representations (Leppänen et al., 2010).

The building blocks of reading and spelling are therefore many and complex, requiring multiple pairings of sounds, word forms, and behavioural experiences, until skills become automated and proficiency develops. Consequently, the Morton and Frith (1995) framework shown in Figure 1 incorporates multiple cognitive mechanisms at the intermediate level which can interact with various environmental factors, giving rise to the behavioural literacy outcomes seen in a child in the classroom. This complex route to reading helps to explain why research is targeted at a variety of cognitive processes that at first glance appear somewhat removed from the core deficit in word recognition.

Although the primary deficit in dyslexia is in word decoding, a range of other cognitive skills enable the development of reading and spelling abilities. These cognitive elements are supported by various functional processes in the brain and they are influenced by genetic and environmental factors during development. The environmental factors include language exposure, schooling and nutrition. As such, dyslexia has often been considered within the framework outlined by Morton and Frith (1995), which highlights the interactions between the cognitive, biological and environmental levels that contribute to the observed behavioural symptoms used for diagnosis of dyslexia (Figure 1).

The causal modelling framework is seen as a useful guide as it incorporates the neurological and cognitive/learning dimensions with those related to practice or educational dimensions and these areas cover the research dimensions in dyslexia. Furthermore, the framework takes into account the role of environmental factors and particularly how the environment can influence the other dimensions. Although dyslexia manifests in the classroom mainly as a difficulty in reading and spelling, the recognition of these additional factors (biological, cognitive and environmental) has lead research to focus also on processes other than the main deficits.

Frith (2002) suggests that a causal modelling framework including three levels of description (behavioural, cognitive and biological) can shed light in some of the issues regarding the concept of dyslexia. Frith (2002) further highlighted that the framework should be seen as being fluid, flexible and incorporating overlapping dimensions. This means that some aspects such as phonological processing can have an impact on all three, neurological, cognitive and educational dimensions.

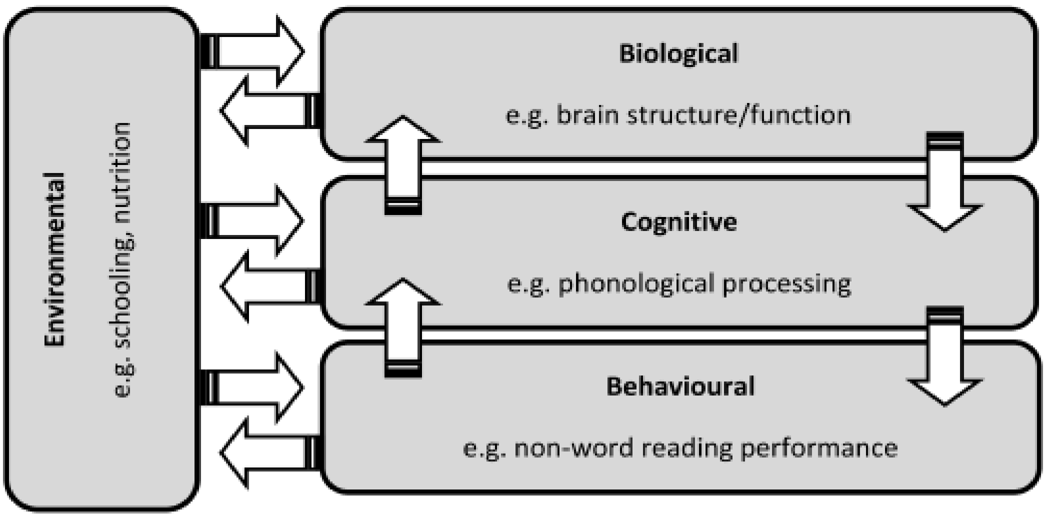

Figure 1. Key factors in dyslexia across different levels of analysis.[1]

Phonological Deficit Theory

During the past decades in research, there have been two distinct approaches to the study of dyslexia. The first approach has been concerned with explaining dyslexia in terms of deficits in underlying cognitive processes. Work in this field has focused on processes that are assumed to be necessary for learning to read, for example, memory and perceptual processes. The second approach has instead

[1] Figure adapted from (Morton & Frith, 1995) showing the various factors which can contribute to the development of dyslexia and examples at each level.

focused directly on the written language skills of dyslexic children. The assumption here has been that qualitative differences between the reading and spelling strategies of dyslexic and normal children will give insight into the nature of the dyslexics' difficulties (Hulme & Snowling, 1992, 1988; Snowling, 1987).

There has been substantial evidence that the acquisition of phonological skills is crucial for successful reading and that difficulties in acquiring phonological skills are the cause of dyslexia. This perspective has derived from research evidence that difficulties in phonological processing, particularly when related to phonological decoding, have been a major distinguishing factor between dyslexics and non-dyslexics from early literacy learning to adulthood (Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgesen, 1987) and that early phonological training improves word literacy and reduces the likelihood of literacy difficulties (Bryant & Bradley, 1985). The difficulties that children with dyslexia have are typically the result of a deficit in the phonological component of language (Cain, 2010). There is a growing body of theories, which attribute dyslexia to a specific deficit in phonological skills, but there are other theories that propose alternative causes.

The most influential cause of dyslexia seems to be the failure to acquire phonological awareness and skill in alphabetic coding (Vellutino et al., 2004). Phonological awareness has a direct effect on word reading ability and as a result, weak phonological decoding might also lead to difficulties in storing and retrieving words from long-term memory. But it is stated that these deficiencies might be the result of other deficits in speech perception and production (Cain, 2010; Hulme & Snowling, 2009; Vellutino et al., 2004).

Children with dyslexia have also shown difficulties in naming tasks on expressive vocabulary, but they had normal scores in word-picture match tasks, which give a measure of receptive vocabulary (Hulme & Snowling, 2009). These naming difficulties are consistent with predictions that semantic information is adequately represented in working memory, but phonological information is poorly symbolised. This is linked to theories on poor verbal short-term memory as studies have found that poor readers can remember fewer verbal items in a list and this could show a deficit in reading nonwords (Griffiths & Snowling, 2002). Therefore, while a typically developing child can make connections between representations of graphemes and phonemes, the dyslexic child would make mappings between whole words and their pronunciations in extreme cases, which shows deficiencies in phonological skills. Children who find it difficult to distinguish sounds within verbally presented words would be predicted to have problems learning the alphabetic principle that letters correspond to particular sounds. These would be the children who are most likely to be dyslexic based on the phonological deficit hypothesis.

Research has also highlighted the fact that the phonological deficit might surface only as a function of certain task requirements, notably short-term memory, conscious awareness, and time constraints (Ramus, 2003; Ramus et al., 2003; Ramus & Szenkovits, 2008). Instead it has been proposed that individuals with dyslexia have a deficit in access to phonological representations, which is causing the additional sensory and cognitive deficits. Furthermore, the consideration of additional deficits present in individuals with dyslexia has led researchers to conclude that phonological deficits alone seem unlikely to be able to account for the complexity and heterogeneity of developmental dyslexia (Castles & Friedmann, 2014).

Double-Deficit Theory

Another prominent cognitive model of dyslexia is the double-deficit hypothesis (Wolf & Bowers, 1999), which attributes dyslexia to two core deficits: phonological processing and rapid naming (Vellutino et al., 2004). Phonological processing refers to the speed and accuracy of grapheme-to-phoneme access (Wagner & Torgesen, 1987), and rapid automatised naming (RAN) refers to the ability to quickly name a series of letters or numbers, and is one of the best predictors of reading fluency (Jones, Branigan, & Kelly, 2009).

According to the double-deficit hypothesis, dyslexia is the result of slow naming speed that confounds orthographic processing, reading fluency, and deficiencies in phonological skills (Hulme & Snowling, 2009; Pennington, Cardoso-Martins, Green, & Lefly, 2001). By using RAN tasks, speed of processing can be measured and high scores on these tasks show disruption of the processes that support induction of orthographic patterns and slow word recognition (Vellutino et al., 2004; Wolf & Bowers, 1999). Naming speed is regarded as a crucial precursor of word reading fluency and is also related to later reading comprehension skills of children (Oakhill & Cain, 2012). Additionally naming speed is a strong predictor of early word reading development (Caravolas et al., 2012) and an important marker of dyslexia across the lifespan (Snowling, Muter, & Carroll, 2007).

Magnocellular Visual System Deficit

Singleton (2012) has pointed out the association between dyslexia and visual stress, as the estimated prevalence of visual stress in dyslexics is in the region of 50% (Whiteley & Smith, 2001). Furthermore, the research on the magnocellular visual system can also be related to visual stress. There are two types of cells found in the neural tracts between the retina and the visual cortex: magnocells, which are large cells that code information about contrast and movement, and parvocells, which are smaller and code information about detail and colour. Cooperation between those two systems enables individuals to perceive stationary images while moving their eyes across a scene or a page of text. When reading, the eyes do not move smoothly across the page but in a series of saccades, which are very quick jumps, in order to fixate successive portions of the text. During saccades, which typically take about 20-40 milliseconds, vision is supressed (Reid, 2016).

Stein (2008) suggests that the development of magnocellular neurons is impaired in children with dyslexia. He argues that the different qualities of visual targets, especially during reading, are analysed by separate, parallel pathways that work simultaneously moving forward in the visual brain. Stein shows that there are two main kinds of retinal gaglion cell, whose axons project all the visual information to the brain. The cells in the magnocellular layers have been found to be smaller and more disordered in children with dyslexia than in typically-developing children (Galaburda & Livingstone, 1993). These differences in the visual system are proposed to relate to reading ability due to the need for rapid visual attention, visual search and eye movements during orthographic processing, with correlations found between motion coherence performance and orthographic sensitivity (Talcott et al., 2000).

It is suggested that the great variety of visual, phonological, kinaesthetic, sequencing, memory and motor symptoms that are seen in different dyslexics may arise from differences in particular magnocellular systems that are most affected by the particular mix that individuals with dyslexia inherit (Stein, 2008). However, it is worth noting that not all those diagnosed with dyslexia present visual deficits, and on the other hand, some people who are not dyslexic present evidence of visual deficits.

Cerebellar Deficit Hypothesis

Further links between neurobiological factors in dyslexia have been identified in the cerebellum and its cognitive processes. In terms of its formation, the cerebellum is one of the first brain structures that begins to differentiate, but it is one of the last to achieve maturity as the cellular organisation of the cerebellum continues to change for many months after birth. According to Fawcett and Nicolson (2008), the cerebellum is a brain structure particularly susceptible to insult in the case of premature birth and such insults can subsequently lead to a range of motor, language and cognitive problems.

Nicolson et al. (2001) proposed that the automatisation deficit arises from a difference in the cerebellum, leading to movement, timing and coordination differences that might affect writing and articulation in dyslexia. The cerebellum is involved in numerous facets of cognitive processing including language processing, receiving inputs from the majority of cortical areas allowing refinement of signals prior to them being relayed back to cortical areas (Booth, Wood, Lu, Houk, & Bitan, 2007; Strata, Thach, & Ottersen, 2009). In support of this theory, children with dyslexia have been found to show reduced cortical volume in the right anterior lobes of the cerebellum and reduced grey matter asymmetry in the cerebellum (Eckert et al., 2003). Similarly, functional differences in the cerebellum are found in adults with dyslexia during literacy related and implicit learning tasks of the kind implicated in the automatisation hypothesis (Brunswick, McCrory, Price, Frith, & Frith, 1999; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006). However, recent evidence has indicated that there might not be any anatomical differences of the cerebellum in adults with dyslexia (van Oers et al., 2018).

The specificity of the cerebellar hypothesis has been questioned because the functional differences in the cerebellum may be the result of alterations in function in other brain areas, such as in the visual cortex (Zeffiro & Eden, 2000). Furthermore, structural and functional brain differences in dyslexia are not limited to the cerebellum (Brunswick et al., 1999). Reservations about the theory have also been raised because the motor impairments in dyslexia may simply represent the overlap between dyslexia and other disorders such as ADHD (Rochelle, Witton, & Talcott, 2009) with some studies failing to replicate Nicolson and Fawcett's findings of motor impairments in children with dyslexia (Ramus, Pidgeon, & Frith, 2003). Indeed, a meta-analysis of studies examining the balance deficits in dyslexia concluded that the deficits were unlikely directly related to reading ability, but more likely associated with the presence of ADHD (Rochelle & Talcott, 2006).

Multi-Factorial Perspective

There has been no universal acceptance of any of these theories, despite the fact that some of them, like the phonological-deficit theory, have dominated the research field more than the others. The difficulty in exploring and identifying the aetiology of dyslexia is not surprising given that children with dyslexia are very different and they can present a variety of levels of difficulty in a range of different areas and skills. They are a heterogeneous group due to the complexity of factors, which could affect the development of literacy skills (as detailed in Figure 1). It is evident that the presence of dyslexia is influenced by a range of risk factors which interact with environmental factors and cognitive development to determine the outcome of the disorder (Thomas & Karmiloff-Smith, 2002). As a result, the heterogeneity means that it is unlikely that all individuals with dyslexia will show the same difficulties in all tasks that are associated with dyslexia and that measure behavioural outcomes predicted by the theories (Ramus, 2003; Rosen, 2003).

Therefore, the theories of dyslexia can only attempt to explain particular aspects of impairment. More recently, conceptualisations of dyslexia take account of its multi-factorial nature and for the fact that dyslexia commonly co-occurs with other disorders (Snowling, 2008). This adapted perspective is in contrast with the single-deficit models, such as the phonological-deficit theory, which focus on one main area of impairment, and as such, are alone insufficient explanatory models (Pennington & Bishop, 2009; Snowling, 2008). Instead, multiple factors with overlapping effects are more likely (Pennington & Bishop, 2009), as further highlighted by the evidence from behavioural research on genetics (Plomin & Kovas, 2005).

Despite this position, there is still much merit in investigating risk factors that contribute to dyslexia at any level of the framework, providing investigations recognise this broader phenotype perspective and the complex route to reading and literacy development. Research on risk factors does not weaken the significance of any particular contributing risk factor within the framework of reading development (Hulme, Snowling, Caravolas, & Carroll, 2005), but can contribute to our understanding of other levels of explanation.

Working Memory framework

The theoretical concept of working memory assumes that a limited capacity system, which temporarily maintains and stores information, supports human thought processes by providing an interface between perception, long-term memory and action (Baddeley, 2003; Conway, Jarrold, Kane, Miyake, & Towse, 2012). There have been many approaches to the study of working memory, using a range of empirical and theoretical techniques and several, but complementary approaches to working memory. Some of these approaches emphasise the role of attentional control in memory (Cowan, 2008), while others have attempted to explain working memory in terms of models that were originally developed for long-term memory (Nairne, 1990; Neath, 2011).

The term ‘working memory’ was initially introduced by Miller, Galanter and Pribram (1960) and was further adopted by Baddeley and Hitch (1974) to emphasise the differences between their three-component model and earlier unitary models of short-term memory. Daneman and Carpenter (1980) later developed a task in which individuals were required to combine storage and processing, first by reading a series of unrelated sentences, and then by recalling the final word of each sentence. Working memory span was defined as the maximum number of sentences for which this task could be performed perfectly. They found a high correlation between working memory span and reading comprehension, a result that has been replicated many times (Daneman & Merikle, 1996). Similar results occur when sentence processing is replaced by other tasks, such as arithmetic calculation (Turner & Engle, 1989) or colour – word association (Bayliss, Jarrold, Gunn, & Baddeley, 2003).

The phonological deficit hypothesis for dyslexia has an important component that is linked to short-term and working memory. More than 30 years of research on dyslexia have shown that there are potentially three distinct dimensions to the phonological deficit. These include poor phonological awareness, poor verbal short-term memory and slow lexical retrieval (Pugh & McCardle, 2011; Wagner & Torgesen, 1987). Here, we are going to focus on the account of working memory framework in relation to dyslexia.

Previous research by Ramus and Szenkovits (2008; Szenkovitz & Ramus, 2005) indicated that individuals with dyslexia potentially have intact phonological representations but they experience difficulties due to the limited capacity and processes of their working memory. They concluded that there might be an alternative hypothesis that could suggest that the phonological difficulties that individuals with dyslexia show might be due to deficits in working memory, particularly in the input and/or output phonological buffers, or the phonological loop between input and output sublexical representations according to Baddeley’s (2003) model.

Another influential conceptualisation of working memory, which is particularly significant for dyslexic individuals is that of a limited resource that can be flexibly allocated to support either processing or storage (e.g., Daneman & Carpenter, 1980; Just & Carpenter, 1992). According to one model in this theoretical tradition, developmental increases in complex memory performance reflect improvements in processing speed and efficiency that release additional resources to support storage (Case, Kurland, & Goldberg, 1982). It could indicate that working memory skills indexed by complex memory tasks represent an important constraint on the acquisition of skill and knowledge in reading. Furthermore, the severity of deficits in the areas of reading in dyslexic children was closely associated with working memory skill. Gathercole, Alloway, Willis and Adams (2006) proposed that this association arises because working memory acts as a bottleneck for reading tasks.

Research by Jeffries and Everatt (2004) also indicated that dyslexics seem to show deficits in recall tasks involving the phonological loop. The phonological loop is specialised for the maintenance of verbally coded material and is estimated to retain about as much material as can be articulated within 1.5 to 2 seconds (Baddeley, 2017). It is hypothesised to consist of two parts: a phonological store that holds speech-based information and an articulatory control process that is based on inner speech (Baddeley, 2003). The store retains phonological representations of verbal information that decay over time. The articulatory control process refreshes the memory trace by means of subvocal rehearsal. Their results indicated that dyslexics may have a central executive difficulty as their deficits were in tasks which required no verbal recoding which seemed to preclude the cause being a phonological loop deficit (Jeffries & Everatt, 2004).

Kibby, Marks, Morgan and Long (2004) further highlighted that children with reading disability have an impaired phonological loop but intact visual–spatial sketchpad and central executive functioning. In terms of the phonological loop, the deficit appears to be specific to the phonological store, which is in line with previous findings (e.g. Ramus et al., 2004). An alternative possibility is that individuals with reading disability do not have an abolished phonological store but one that functions with reduced efficiency. They would then have difficulties in storing verbal material, regardless of whether that material is presented orally or visually (Kibby et al., 2004).

With respect to sentence comprehension and processing, individuals with dyslexia tend to show more difficulties in reading and comprehending sentences that have a more demanding working memory load (Robertson & Joanisse, 2010). Apparent syntax deficits in dyslexia could be caused by an underlying phonological deficit, which impedes the temporary storage of verbal material. Previous research has highlighted that dyslexic readers perform more poorly in sentence reading tasks due to the high storage and processing demands (Robertson & Joanisse, 2010; Schulz et al., 2008; Wiseheart, Altmann, Park, & Lombardino, 2009).

In this thesis, we have focused on further examining the role of working memory in comprehension of syntactically complex sentences in dyslexia. We expected that the difficulties individuals with dyslexia experience due to limited sources in terms of storage and processing of working memory, would also result in difficulties in comprehension of the sentences we examined. As described by Gathercole et al. (2006), the fact that working memory acts as a bottleneck for reading tasks was an element that we predicted it would result in comprehension difficulties for dyslexics in the processing of syntactically complex sentences.

Verbal Efficiency and Synchronisation Hypotheses

According to Perfetti's Verbal Efficiency theory (VET) (1985, 1988), in order for a dyslexic reader to compensate for difficulties in decoding, they have to rely more on working memory and vocabulary knowledge. Because comprehension processes are demanding on cognitive resources, skilled readers have more automatic access to lexical storage in long-term memory. When readers can recognise words automatically, this frees cognitive processes, like attention and working memory, for higher-level comprehension (LaBerge & Samuels, 1974). VET also focuses on automaticity of decoding text and further expands the notion to higher-level reading processes, like syntactic parsing, and proposition assembly and integration (Logan, 1988).

The Synchronisation Hypothesis suggests that the various brain systems and functions need to be in synchronisation in order for accurate integration of information in word decoding to occur (Breznitz, 2006; Breznitz & Misra, 2003). Furthermore, this hypothesis emphasises the timing in which information from bottom-up sources is provided to higher levels in order for comprehension to proceed fluently.

With respect to dyslexia, as both theories focus on the importance of the processes involved in word decoding, they assume that the poor word decoding of individuals with dyslexia has a negative effect on multi-word and multi-sentence comprehension. It is also suggested that dyslexic readers experience asynchrony in language comprehension, which results in slow downs and overall difficulties leading to impaired comprehension accuracy (Breznitz, 2006; Perfetti, 1988; Perfetti & Hart, 2001; Perfetti & Hogaboam, 1975).

Sentence comprehension in dyslexia

The current literature on sentence processing in dyslexia is quite limited. This is important because we do not know whether dyslexic readers show difficulty in sentence processing and sentence comprehension, over and above single-word decoding difficulties (cf. De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hyönä & Olson, 1995). There are considerable differences between reading single words and reading sentences. Comprehending sentences requires the ability to combine words together into meaningful phrases and extract compositional meaning

(Fodor, 2001), and is therefore, considerably different and more complex than single-word reading (Perfetti, 2007).

To date, there has only been one study that has examined the comprehension of passive sentences and sentences containing subject and object relative clauses in dyslexia. Wiseheart, Altmann, Park, and Lombardino (2009) tested adults with and without dyslexia on the above types of sentences. Participants were shown two images side-by-side on a computer screen, and they were asked to select the image that corresponded to the sentence. For sentences with relative clauses, Wiseheart et al. (2009) showed that dyslexic readers had poorer comprehension accuracy compared to the control group. Controls were 93% accurate on subject relatives and 97% on object relatives, while dyslexics were 84% accurate on subject relatives and 84% accurate on object relatives. Note that the pattern for the object relatives in controls was in the opposite direction of what is most commonly reported in the psycholinguistics literature. Wiseheart et al. (2009) argued that dyslexics showed poorer comprehension accuracy compared to controls, as subject and object relatives place high demands on working memory and the individuals with dyslexia in their sample had lower working memory than did controls. This was further confirmed in an analysis in which working memory was covaried, as the effect of group was no longer significant.

To examine the comprehension of active and passive sentences, Wiseheart et al. (2009) used non-biased reversible sentences (e.g. *The queen kissed the king.* vs. *The king was kissed by the queen*), which means that there was no bias between the potential doer of the action and patient of the action. The same procedure was followed as the experiment with sentences with relative clauses. Wiseheart et al. (2009) showed that dyslexic readers were marginally slower in their response times and had poorer comprehension accuracy on passive sentences compared to the control group. Controls were 98% accurate on actives and 95% accurate on passives. In contrast, participants with dyslexia were 98% accurate on actives and 83% accurate on passives. In their conclusions, Wiseheart et al. (2009) argued for a frequency-based (or exposure-based) explanation. In general, people encounter passives much less frequently that actives, and given dyslexics difficulties with reading and their inherent aversion to reading, the frequency differential for people with dyslexia would be even greater (Dick & Elman, 2001).

On the other hand, Bishop and Snowling (2004) have provided an alternative account about dyslexia and difficulties in sentence processing. They highlighted previously held perceptions that the main difficulties in dyslexia reflect a deficit within the language system and especially in phonology (e.g. Shaywitz et al., 2002). In previous cases that children with dyslexia have shown semantic or syntactic deficits, they have been regarded as secondary consequences of phonological impairment (Shankweiler & Crain, 1986). As Bishop and Snowling (2004) regarded sentence comprehension difficulties as symptoms separate from dyslexia as a cognitive disorder, it is vital that we try to understand a bit more about the sentence processing difficulties that dyslexics show.

Our predictions are based on the plethora of previous research on the processing difficulties that dyslexics demonstrate when encountering reading tasks. First of all, the single-word reading difficulties that dyslexics experience would have an additive effect on their speed and quality in sentence reading. Since working memory deficits have been viewed as a symptom of impairments in phonological awareness and as Robertson and Joanisse (2010) showed, it is expected that dyslexic readers will show more difficulties with sentences that require a higher working memory load. Due to the fact that working memory acts as a bottleneck for reading tasks for dyslexics (Gathercole et al., 2006), we would also expect their processing to slow down and to show longer reading times.

Eye Movements in Dyslexia

Eye tracking allows researchers to investigate online processing in reading and the majority of existing research focused on typically-developing skilled adult readers (for a review, see Rayner, 1998). There have been however several studies that have examined the eye movements of individuals with dyslexia, from investigating the basis of Pavlidis' (1981) theory that atypical eye movements are the cause of dyslexia (Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Olson, Kliegl, & Davidson, 1983) to the association between oculomotor control, visuo-spatial deficit and dyslexia (Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013) and differences in saccadic eye movements (Fischer, Biscaldi, & Otto, 1993; Heiman & Ross, 1974).

It is widely accepted that differential eye movement patterns in dyslexia are not the cause of reading difficulties, but instead, reflect the underlying disorder (Olson et al., 1983). Previous eye movement studies on dyslexia have shown that dyslexic readers tend to make longer fixations, shorter saccades, and a greater proportion of regressive eye movements compared to typically-developing readers (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Eden, Stein, Wood, & Wood, 1994; Hawelka, Gagl, & Wimmer, 2010; Hutzler & Wimmer, 2004; Olson et al., 1983; Rayner, 1978, 1985). Further studies on eye movements of individuals with dyslexia during reading of single words and nonwords (e.g. De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Thaler et al., 2009), sentences (Hawelka, Gagl, & Wimmer, 2010; Horowitz-Kraus & Breznitz, 2011; Manon Wyn Jones, Kelly, & Corley, 2007) and texts (e.g. De Luca et al., 1999; Hyönä & Olson, 1995) have shown that dyslexic readers tend to make longer fixations, shorter saccades, and a greater proportion of regressive eye movements compared to non-dyslexic readers.

Hawelka et al. (2010) also showed that dyslexic readers' eyes tend to land closer to the beginning of words, compared to typically-developing readers, whose eyes tend to land closer to the middle of words. They also argued that readers with dyslexia rely more on the grapheme-phoneme conversion route rather than whole-word recognition, which is characteristic of more automated (skilled) reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). However, Hawelka et al. (2010) tested German, which has a shallower and more regular orthography than English (Landerl, Wimmer, & Frith, 1997).

In another study, Hyönä and Olson (1995) examined word length and word frequency. They showed that dyslexics had a greater number of fixations on a target word, an increased number of regressions out of a word, and longer fixation durations, demonstrating crucial difficulties in processing words in text. In contrast, research on eye movements in reading has mainly focused on sentence-level online processing and offline comprehension, and so much is known about semantic and syntactic factors that affect eye movement behaviour. However, little dyslexia research has been conducted into the processing demands of particular words in sentence contexts.

Furthermore, imaging methods with higher temporal resolution, such as electroencephalography (EEG) and magnetoencephalography (MEG) have been used to measure the activation of particular brain areas in individuals with dyslexia. For example, N400 is an ERP component associated with how easily a word's meaning can be integrated with context (Kutas & Federmeier, 2011) and the P600 component is activated by syntactic violations (Hagoort, Brown, & Groothusen, 1993). Qian et al. (2018) argued that the semantic P600 effect provides evidence for both syntactic and semantic processing routes, while the absence of the N400 effect could suggest a stronger link with the Good Enough Processing hypothesis.

Schulz et al. (2008) combined event-related potentials (ERP) and functional magnetic resonance imaging (fMRI) to examine semantic processing deficits in children with and without dyslexia. They found that sentence reading was indicated by activation in the left-lateralised language network, while semantic processing involved the activation of left-hemispheric regions in the inferior frontal and superior temporal cortex. Semantic processing was also accompanied by a N400 effect after 240 ms with consistent left anterior source lateralisation. Dyslexic children in particular showed decreased activation in anterior parietal and frontal regions during sentence reading and decreased activation in inferior parietal regions and during the N400 effect for semantic processing.

Outline and Thesis Purposes

In the present thesis, several psycholinguistic and cognitive factors will be considered in terms of dyslexic readers' comprehension and processing of sentences, with respect to syntax and semantics. As it will be described in greater detail in forthcoming chapters, syntax involves the organisation of words and phrases in a sentence to convey meaning (Rayner, Carlson, & Frazier, 1983). This organisation reveals the structure of grammar in which the strings of language have been formed according to the distinct rule systems. The field of semantics involves the processing of compositional aspects of meaning of words, sentences and text, as well as the analysis of the relations between words (Heim & Kratzer, 1998).

One of the main components of any examination of language processing is understanding the way that sentences of a language are syntactically processed. There has been a large body of research in psycholinguistics that has focused on the analysis of syntactically ambiguous sentences (e.g. Clifton & Ferreira, 1989; Ferreira & Clifton, 1986; Frazier & Rayner, 1987; Warner & Glass, 1987). Garden-path sentences (like *While Anna dressed the baby played on the bed.*) reveal readers' preferences for resolving syntactic ambiguities when incorrect syntactic decisions are initially made. The difficulty of comprehending garden-path sentences arise from the fact that they require revision in order for the reader to correctly interpret the thematic roles of each component of the sentence. Waters and Caplan (1996) therefore argued that garden path sentences are expected to have a more demanding load on working memory and result in slower processing compared to non-garden path sentences.

Chapter 2 is the first experimental chapter of this thesis, in which we examined the processing of garden path sentences. For the control group, we expected to see similar performance as it has been described in previous research with typically developing readers and garden-path sentences (e.g., Ferreira, Christianson and Hollingworth, 2001). More specifically, we expected non-dyslexic participants to show poorer comprehension for garden path sentences compared to non-garden path sentences, as well as longer reading times on the disambiguating verb in ambiguous sentences compared to unambiguous ones (Christianson, Williams, Zacks, & Ferreira, 2006).

With respect to the dyslexic group, we predicted that the syntactic complexities of garden-path sentences would have even higher demands on working memory load and due to the bottleneck created in reading tasks, it would result in poorer comprehension than the control group. Regarding the reading times, we expected that the potential reanalysis of garden-path sentences would have an additive effect to the phonological processing deficit experienced by dyslexic readers, which will result in sentence processing difficulties and therefore longer reading times than the controls (Bishop & Snowling, 2004). Part of our rationale for Chapter 2 were also the theories of verbal efficiency and synchronisation (Breznitz, 2003; Perfetti, 1988). The difficulties in automatic word decoding that individuals with dyslexia experience is expected to have a negative effect on their multi-word and multi-sentence comprehension.

In Chapter 3, we present our study on the processing of sentences with relative clauses, which has a theoretical basis on the role of working memory and the Surprisal theory (Hale, 2001; Levy, 2008). The first main issue that arises in the processing of these types of sentences is the violation of predictive expectations, which have been computationally assessed via Surprisal (Hale, 2001; Levy, 2008) and is very closely related to linguistic prediction (for reviews see Ferreira & Lowder, 2016; Kuperberg & Jaeger, 2016). The second key issue is with respect to working memory, as in object relative clauses, the object noun phrase must be held in memory until the reader encounters the relative clause verb that it is associated with (Gennari & MacDonald, 2008; Gibson, 1998; Gordon et al., 2001; Grodner & Gibson, 2005; Just & Carpenter, 1992; Lewis & Vasishth, 2005; Traxler et al., 2002; Waters & Caplan, 1996).

Therefore, in order to resolve the long-distance dependency, the reader is expected to sustain a substantial demand on cognitive resources, especially in terms of working memory, which led us to expect that our non-dyslexic participants would show more difficulties in comprehending object relative clauses than subject relative clauses. Due to this characteristic of sentences with relative clauses, we expected that dyslexic participants' bottleneck on working memory demands would result in more difficulties in processing and comprehending these types of sentences compared to non-dyslexic participants.

Previous studies have highlighted the difficulties in comprehension of sentences with object relative clauses partially due to the fact that they are less frequently encountered compared to subject relative clauses (Roland, Dick, & Elman, 2007). Previous research by Wiseheart et al. (2009) has demonstrated that adult readers with dyslexia have difficulties in comprehension of sentences that contain centre-embedded relative clauses, particularly when they were object relative clauses.

With respect to passive sentences, previous research on comprehension and processing of noncanonical sentences, like passive sentences, has shown that English native speakers show difficulties in comprehension when those sentences are implausible (e.g. *The dog was bitten by the man*) (Ferreira, 2003). Ferreira further argued that readers employ the noun-verb-noun strategy more frequently than the semantic plausibility strategy. In the study reported in Chapter 4, we used active and passive, plausible and implausible sentences and we expected that the control participants would show similar results to Ferreira's (2003). More specifically, they would present more difficulties in comprehension of passive implausible sentences compared to all other conditions. With respect to dyslexia, we predicted that readers with dyslexia would show more difficulties in comprehending both passive and implausible sentences. This could be a secondary result of the phonological difficulties associated with dyslexia, as well as due to the bottleneck in working memory, which will make it more for dyslexic participants to recall the correct interpretation of implausible sentences. Our hypotheses for this chapter were primarily based on the Good Enough Theory (Ferreira & Patson, 2007).

In Chapter 5, we report our final experimental study which was focused on the sentence processing and comprehension of dyslexic and non-dyslexic adolescents, as well as on a comparison with the results from the adult studies, presented in Chapters 2 – 4. All three types of sentences examined in Chapters 2 – 4 were also used for the experiment in Chapter 5.

Family studies in dyslexia have noted that the behavioural profile of children with dyslexia changes with age, from the pattern of delayed language development in the pre-school years to a more specific profile of phonological difficulties in the school years (Scarborough, 1990; Snowling, Muter, & Carroll, 2007). Children in school (from 6 years old and upwards) show impairments in phonological awareness (Swan & Goswami, 1997), phonological processing (Snowling, 1995), verbal short-term and working memory (Bruck, 1990), non-word repetition (Snowling, 1987), and verbal naming (Bowers & Wolf, 1993; Swan & Goswami, 1997). Despite the fact that only a few studies have focused on dyslexia in adolescence, Snowling et al. (2007) conducted a longitudinal study on children at family risk of dyslexia. When the participants were assessed in early adolescence for literacy and language skills, as well as print exposure, a significant proportion of the ‘at-risk’ group showed reading and spelling impairments. Regarding print exposure, they found that adolescents in the ‘at-risk’ group read less than controls, and generally showed more reading difficulties at school than do typically-developing adolescents.

For this study, we aimed at examining the development of sentence comprehension and processing from adolescence to adulthood. Our rationale was further based on Keith Rayner’s (1998) hypothesis that non-dyslexic adolescents would show similar eye movement patterns as dyslexic adults, which was our prediction for the results of this study for all three types of sentences. More specifically, we expected that non-dyslexic adolescents will show difficulties in comprehension of garden-path sentences, sentences with object relative clauses, passive and implausible sentences. Their comprehension and reading times results will be similar to the ones of dyslexic adults and these difficulties would be due to their infrequent exposure to these types of syntactic constructs (Snowling et al., 2007). We expected that the dyslexic adolescents would show even more difficulties in comprehension and processing of all types of sentences, primarily due to the fact that their phonological difficulties will hinder their sentence reading performance. However, our final results contradicted Rayner's hypothesis about dyslexic adults and adolescents.

All three types of sentences have been widely used as a way to explore the mechanisms of language comprehension, which was one of the main aims of this thesis, as well as provide additional evidence about the way that individuals with dyslexia process and comprehend sentences with complex syntax. We decided to focus on examining the comprehension of these types of sentences as they require the readers to interpret the thematic roles in the sentences and at the same time, especially for garden-path sentences, implausible and passive sentences to use semantic heuristics to extract the correct meaning of the sentences. The readers' knowledge of plausible events in the real world is another factor that could interfere with comprehension of those sentences, so we were interested in examining whether dyslexia would be an additional factor that could have an additive impact on comprehension.

In the sentence processing tasks of all experiments, we included an intervening arithmetic problem between the presentation of each sentence and the comprehension question. This maths problem consisted of either an addition or a subtraction (e.g. 45 + 67 = 112) and the participants were asked to respond whether they thought the equation was correct or not. The rationale for including the additional maths task was the fact that we wanted to assess the representation that comprehenders generated of the sentences, without allowing them to have direct access to the sentence or having the sentence being the most recent item presented. We expected that the presence of the maths problem would clear the immediate contents of working memory, therefore resulting in the participants responding to the comprehension questions on the basis of a more long-term representation/trace of the sentences. Finally, due to the slower phonological decoding increasing the working memory demands for dyslexics, we wanted to ensure that the participants' responses to the comprehension question would be affected as little as possible by the bottleneck in working memory processes.

Chapter 2

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Syntactic ambiguity resolution in dyslexia: An examination of cognitive factors underlying eye movement differences and comprehension failures

Abstract

This study examined eye movements and comprehension of temporary syntactic ambiguities in individuals with dyslexia, as few studies have focused on sentence-level comprehension in dyslexia. We tested 50 participants with dyslexia and 50 typically-developing controls, in order to investigate (1) whether dyslexics have difficulty revising temporary syntactic misinterpretations and (2) underlying cognitive factors (i.e. working memory and processing speed) associated with eye movement differences and comprehension failures. In the sentence comprehension task, participants read subordinate-main structures that were either ambiguous or unambiguous, and we also manipulated the type of verb contained in the subordinate clause (i.e. reflexive or optionally transitive). Results showed a main effect of group on comprehension, in which individuals with dyslexia showed poorer comprehension than typically-developing readers. In addition, participants with dyslexia showed longer total reading times on the disambiguating region of syntactically ambiguous sentences. With respect to cognitive factors, working memory was more associated with group differences than was processing speed. Conclusions focus on sentence-level syntactic processing issues in dyslexia (a previously under-researched area) and the relationship between online and offline measures of syntactic ambiguity resolution.

Introduction

Dyslexia or reading disability is a cognitive disorder of genetic origin that affects an individual’s acquisition of reading skill, despite adequate intelligence and opportunities to learn (Bishop & Snowling, 2004; Fisher et al., 2002; Snowling, 1987). It affects approximately 5-10% of the population and characteristic features of dyslexia are difficulties in phonological awareness, short-term/working memory, and verbal processing speed (Reid, 2016; Snowling, Duff, Petrou, Schiffeldrin, & Bailey, 2011).

More recently, research has identified additional areas of difficulty, such as reduced short-term/working memory capacity (Chiappe, Siegel, & Hasher, 2000), slow processing speed (Shanahan et al., 2006) and reduced visual-attention span (Prado, Dubois, & Valdois, 2007). The main focus of the current study was sentence-level language comprehension, and in particular, processing of sentences containing a temporary syntactic ambiguity.

Theories of Dyslexia – Language Comprehension

There are several reasons to suspect that individuals with dyslexia will show difficulties/deficits in sentence processing (e.g. poor word identification skills, and reduced working memory). Two theoretical models which have implications for sentence processing in dyslexia are the Verbal Efficiency Hypothesis (Perfetti, 1985, 1988, 1992, Perfetti & Hart, 2001, 2002; Perfetti & Hogaboam, 1975; Perfetti, Landi, & Oakhill, 2005) and the Synchronisation Hypothesis (Breznitz, 2001, 2003; Breznitz & Misra, 2003). These two theories share some underlying assumptions. The similarities are that both assume (1) that poor word decoding adversely effects multi-word and multi-sentence comprehension, and (2) that poor word identification is a result of a failure of automaticity (Logan, 2006; Samuels & Flor, 1997). As a result, word decoding in individuals with dyslexia is a slow, time-consuming process that requires more cognitive effort compared to typically-developing readers. In skilled readers, the processes supporting word decoding become automatised (LaBerge, 1981; LaBerge & Samuels, 1974; Logan, 1988, 1997). This frees up cognitive resources, according to Verbal Efficiency – attention and working memory – which can then be applied to higher-level (comprehension) processes. In contrast, the Synchronisation Hypothesis focuses more on the timing in which information from bottom-up sources is provided to higher levels in order for comprehension to proceed fluently, particularly in cases in which different brain regions are involved. Thus, synchronisation assumes that individuals with dyslexia experience asynchrony in language comprehension, which results in slow downs and overall difficulties leading to impaired comprehension accuracy.

One issue to bear in mind is that these two theories have been most often used to explain deficits in text comprehension rather than sentence comprehension. However, the same issues apply to comprehension at the sentence level. For example, a reader needs to engage in propositional-level creation, especially for sentences containing multiple clauses. Sentence comprehension also involves "structure building", that is, syntactic processing (or parsing). To break the process down step-by-step, a reader must first decode individual words (lexical access), which involves semantic encoding or retrieving word meanings from the lexicon.

The parser then must perform its functions, assigning words to grammatical roles and assembling a coherent syntactic and semantic representation. This will ultimately lead to propositional-level content, and a situation model that the sentence is describing. One difference between sentence comprehension and text comprehension is that there is more of an emphasis on incremental interpretation (i.e. how the reader integrates new words with those that have come before). In text comprehension models, for example Latent Semantic Analysis (Landauer & Dumais, 1997), there is less emphasis on processes operating within a sentence, rather than between sentences.

The Verbal Efficiency Hypothesis has been supported by several studies. For example, Perfetti and Hart (2002) examined a large-scale dataset of readers whose word decoding and comprehension skills were assessed. A factor analysis on these measures showed two significant factors, one loading on phonology, spelling, and decoding and the second on meaning and comprehension. Moreover, when the dataset was broken down into sub-groups. Perfetti and Hart (2002) determined that there were many more individuals who showed “good” decoding and “poor” comprehension compared to individuals with “good” comprehension and “poor” decoding, which suggests a more likely causal role for decoding on comprehension. In addition, many studies across development show that there are reasonably strong positive correlations between word identification and comprehension (for a review see, Perfetti, 2007).

In summary, beginning readers and individuals with dyslexia use too many cognitive resources for decoding words, due to a lack of automaticity. According to Verbal Efficiency, processing is slow and can overload attentional and working memory resources. According to Synchronisation, a lack of automaticity results in timing issues such that information is not available when it is needed in order to support fluent reading comprehension. However, it is important to note that the current study does not adjudicate between these two theoretical perspectives, but instead, throughout the paper we compare and contrast their assumptions with respect to the predictions and findings of the current study.

Eye Movements in Dyslexia

Eye tracking allows researchers to investigate online processing in reading and the majority of existing research focused on typically-developing skilled adult readers (for a review, see Rayner, 1998). It is widely accepted that differential eye movement patterns in dyslexia are not the cause of reading difficulties, but instead, reflect the underlying disorder (Olson, Kliegl, & Davidson, 1983). Comparatively fewer eye movement studies have focused on dyslexia, and they have shown that dyslexic readers tend to make longer fixations, shorter saccades, and a greater proportion of regressive eye movements compared to typically-developing readers (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Eden, Stein, Wood, & Wood, 1994; Hawelka, Gagl, & Wimmer, 2010; Hutzler & Wimmer, 2004; Olson et al., 1983; Rayner, 1978, 1985). Hawelka et al. (2010) also showed that dyslexic readers' eyes tend to land closer to the beginning of words, compared to typically-developing readers, whose eyes tend to land closer to the middle of words. They also argued that readers with dyslexia rely more on the grapheme-phoneme conversion route rather than whole-word recognition, which is characteristic of more automated (skilled) reading (Coltheart et al., 2001). However, Hawelka et al. (2010) tested German, which has a shallower and more regular orthography than English (Landerl, Wimmer, & Frith, 1997).

In another study, Hyönä and Olson (1995) examined word length and word frequency. They showed that dyslexics had a greater number of fixations on a target word, an increased number of regressions out of a word, and longer fixation durations, demonstrating crucial difficulties in processing words in text. In contrast, research on eye movements in reading has mainly focused on sentence-level online processing and offline comprehension, and so much is known about semantic and syntactic factors that affect eye movement behaviour. However, little dyslexia research has been conducted into the processing demands of particular words in sentence contexts, and in cases where there is syntactic ambiguity.

Additionally, there have been very few systematic studies investigating whether dyslexic readers show difficulty in sentence processing and sentence comprehension, over and above single-word identification (cf. De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hyönä & Olson, 1995). This is significant because there are considerable differences between reading single words and reading sentences. As mentioned above, comprehending sentences requires the ability to combine words together into meaningful hierarchical structures in order to extract global meaning (Fodor, 2001), and is therefore, considerably different and more complex than single word reading (Perfetti, 2007).

Research in sentence comprehension aims to discover how people understand language and a useful way to examine this is by using sentences that contain a temporary syntactic ambiguity, such as While Anna dressed the baby that was small and cute played on the bed. Sentences like these are known as garden-path sentences (Ferreira et al., 2001). In the example, readers tend to interpret the baby as the direct object of dressed. However, the second verb (played) makes clear that this interpretation is incorrect, and that in fact, Anna dressed herself. Comprehension errors are frequent and systematic with these types of sentences (Christianson et al., 2001). Christianson et al. (2001) investigated the hypothesis that full reanalysis of a local syntactic ambiguity is a necessary part of the process of deriving the correct interpretation of a garden-path sentence. They found that participants would often maintain the initial misinterpretation of a garden-path sentence, and at the same time, they would correctly reanalyse the main clause of the sentence, leading them to only partially reanalyse the garden-path (Patson, Darowski, Moon, & Ferreira, 2009). In these cases, the syntactic roles that were initially and incorrectly assigned continued (or lingered) into the final interpretation of the sentence. In other cases, participants would fully reanalyse the sentence and correct their initial misinterpretations, which results in a final interpretation which has a syntactic structure that is fully consistent with the input string (Christianson et al., 2001).

These assumptions are linked to traditional reanalysis theories in sentence processing, according to which there are two ways of handling temporary ambiguity (Fodor & Inoue, 1998; Frazier & Fodor, 1978; Frazier & Rayner, 1982; Gibson, 1998). In the first, the disambiguating part of the sentence is detected and reanalysis occurs, bringing the structure into compliance with the grammar and generating the correct semantic interpretation (Slattery, Sturt, Christianson, Yoshida, & Ferreira, 2013). In the second, the ambiguity is not noticed or the incorrect interpretation is chosen and thus, the disambiguating information does not trigger full but partial reanalysis. In either case, one would not expect to observe the classic eye movement patterns of syntactic reanalysis, namely longer fixation times on the disambiguating region, often accompanied by regressive eye movements from the disambiguating word and re-reading of the ambiguous word/phrase (Christianson, Luke, Hussey, & Wochna, 2017; Frazier & Rayner, 1982).

Sentences containing local ambiguities (i.e. garden-path sentences), have been investigated for decades by psycholinguists as a way to explore the mechanisms of language comprehension (Frazier & Rayner, 1982; Warner & Glass, 1987). Garden-path sentences, like the example, reveal people's preferences for resolving syntactic ambiguities when incorrect syntactic decisions are initially made (Slattery et al., 2013).

There have been few controlled eye movement studies of reading in dyslexia, and only a handful have specifically examined sentence-level processing. Wiseheart, et al. (2009) investigated the effects of syntactic complexity on written sentence comprehension and working memory in people with dyslexia. They observed significantly longer response times and lower accuracy in interpreting sentences with syntactic ambiguity, suggesting that syntactic processing deficits may be characteristic of dyslexia (Wiseheart et al., 2009). They also highlighted that poor working memory accounts for deficits in sentence comprehension. However, due to a lack of further research, the nature of syntactic ambiguity resolution in dyslexia remains unclear.

Cognitive Factors in Dyslexia

As mentioned above, apart from phonological awareness and rapid naming skills, additional skills have been identified as areas of difficulty for individuals with dyslexia. The ones that we focused on this study were working memory (Chiappe et al., 2000) and processing speed (Shanahan et al., 2006), and those two skills have been identified as possible cognitive factors that play a crucial role in the reading and comprehension of sentences with complex syntax. For example, the Verbal Efficiency Hypothesis explicitly suggests a close relationship between word decoding skills and demands on working memory capacity (Perfetti, 2007).

Working memory is assumed to have processing as well as a storage function, which indicates that it has a crucial role in reading comprehension (Daneman & Carpenter, 1980). In order to read and understand a sentence, people need to be able to store and process information at the same time, as they must combine prior knowledge and information provided by the text to make inferences, and to structure the sequence of the events within the sentence (Oakhill & Cain, 2012). More specifically, in tasks which involve reading comprehension, the reader is required to store semantic and syntactic information. Some of that information can be maintained in working memory and can then be used to integrate and clarify subsequent material, and is especially important for things such as resolving long-distance dependencies and pronoun resolution (Fiorin & Vender, 2009; Hussey, Ward, Christianson, & Kramer, 2015). The role of working memory in reading comprehension is especially important in individuals with dyslexia, since deficits in short-term and working memory are characteristic of individuals with dyslexia at all ages (Chiappe et al., 2000; Jeffries & Everatt, 2004).

With regards to processing speed, it has been emphasised that when the rate of processing of visual information is disrupted/reduced, then it impacts processing of orthographic representations, which are essential for language comprehension (Wolf, Bowers, & Biddle, 2000). However, examining the effect of processing speed in language comprehension in dyslexia has several complications. The majority of studies that showed slow processing speed in dyslexia have used verbal tasks, such as the RAN task and the Stroop task (e.g. Bonifacci & Snowling, 2008; Georgiou & Parrila, 2013; Norton & Wolf, 2012; Shanahan et al., 2006, Wiseheart & Wellington, 2018). As a result, slow processing may be linked to poor phonological processing. There is also a possibility that slowdowns may have an effect on reading via working memory (Daneman & Carpenter, 1980). More specifically, slower reading requires readers to maintain information in memory for a longer period of time, which increases the chances of decay and/or interference (Van Dyke & McElree, 2006).

Current Study

The first goal of the current study was to investigate how readers with dyslexia process syntactic ambiguity, and the second goal looked at how working memory and speed of processing affect online and offline sentence comprehension. Previous studies have suggested that working memory (Chiappe et al., 2000) and processing speed (Bonifacci & Snowling, 2008) are two critical cognitive factors for comprehension deficits in dyslexia. Sentences with more complex syntax require the reader to maintain information in working memory, as well as placing higher demands on processing resources in individuals with dyslexia (Perfetti, 2007). Working memory deficits would reduce the amount of information that can be actively maintained and remembered, and as a result, comprehension should be adversely affected (Caplan & Waters, 1999; Daneman & Carpenter, 1980; DeDe, Caplan, Kemtes, & Waters, 2004; Just & Carpenter, 1992; King & Just, 1991; Lewis, Vasishth, & Van Dyke, 2006; Waters & Caplan, 1996; 2004). Regarding processing speed, complex sentences require more time to process, which can be associated with comprehension failures (Breznitz, 2006; Caplan, DeDe, Waters, Michaud, & Tripodis, 2011).

In the current study, a test battery of cognitive measures was administered, including several measures of working memory and processing speed. The garden-path sentence processing task included eye-tracking and comprehension questions (see Table 1). We also manipulated the type of subordinate clause verb. The verb was either optionally transitive or reflexive. Reflexive verbs have been shown in previous research to be easier to revise than optionally transitive verbs (i.e. it is easier to switch to a transitive reflexive interpretation than to switch to an intransitive interpretation). This difference is due to semantics, and so, if individuals with dyslexia have difficulty with reflexive verbs, then it would suggest a semantic processing issue, due to the fact that in reflexive verbs have the same semantic agent and patient (see also Nation & Snowling, 1998; 1999).

In the sentence comprehension task, we expected participants with dyslexia to show poorer comprehension compared to controls, as well as showing differential eye movement patterns. More specifically, we expected dyslexic readers to show eye movement patterns characteristic of dyslexia. These include longer fixation durations (Heiman & Ross, 1974), more regressions out of the disambiguating region (Hawelka et al., 2010; Heiman & Ross, 1974), and approximately, twice as many fixations as controls. In the key region the sentence, which includes the disambiguating verb and the spill over region (i.e. the word following the disambiguating verb – N + 1), we expected eye movement patterns characteristic of syntactic ambiguity resolution (i.e. longer fixations durations and more regressions out). Moreover, these eye movement patterns would be associated with whether participants fully resolved the ambiguity, that is, we expected there to be significant correlations between eye movement measures and comprehension. It was, therefore, predicted that participants with dyslexia, would show longer reading times, particularly with ambiguous sentences. Regarding cognitive factors, we expected processing speed to have a general effect on reading times, while working memory would have a larger effect on fixation durations at the disambiguating verb and at the N+1 word and on comprehension question accuracy.

Table 1

Example stimuli: Sentences were ambiguous or unambiguous and there were two types of subordinate clause verbs (i.e. reflexive and optionally-transitive).

Reflexive verbs
1. While Anna dressed the baby that was small and cute played on the bed. (Ambiguous)
2. While Anna dressed, the baby that was small and cute played on the bed. (Unambiguous)
Comprehension question
3. Did Anna dress the baby?
Optionally-transitive verbs
4. While Susan wrote the letter that was long and eloquent fell off the table. (Ambiguous)
5. While Susan wrote, the letter that was long and eloquent fell off the table. (Unambiguous)
Comprehension question
6. Did Susan write the letter?

In summary, this study addressed two main research questions. The first was whether dyslexia is associated with deficits in syntactic ambiguity resolution, and the second was how do cognitive factors (i.e. working memory and processing speed) impact online and offline processing of syntactic ambiguity resolution.

Method

Participants

Fifty adults with self-reported dyslexia were recruited via advertisements and 50 undergraduate psychology students were tested as typically-developing control participants (see Table 2). Both groups were recruited from the campus of the University of East Anglia. All participants with dyslexia verified that they had diagnostic assessments for dyslexia in the past. All were native speakers of British English with normal or corrected-to-normal vision. Dyslexics were reimbursed £15 for their time, and controls were compensated with participation credits.

Table 2

Means and standard deviations for demographic variables, Rapid Automatised Naming, working memory, and processing speed for the two diagnostic groups.

	Controls (N = 50)	Dyslexics (N = 50)	*t-value*	*Cohen's d*
Variable	Mean(SD)	Mean(SD)		
Age (years)	20.7 (3.1)	24.7 (5.1)	t(98) = -4.62*	d = .92
Gender (% male)	10.0	20.0	t(98) = -1.15	d = .23
RAN Letters (seconds)	13.3 (2.4)	15.1 (2.9)	t(98) = -3.35*	d = .67
RAN Numbers (seconds)	13.4 (3.0)	13.9 (2.9)	t(98) = -.89	d = .18
Working Memory				
Digit span forward	96.0 (11.7)	84.3 (9.8)	t(98) = 5.40**	d = -1.08
Digit span backward	95.9 (9.1)	90.7 (8.6)	t(98) = 2.95*	d = -.59
Digit span sequencing	102.4 (12.7)	92.4 (10.7)	t(98) = 4.25**	d = -.85
Letter-number sequencing	96.7 (6.6)	87.1 (7.4)	t(98) = 6.84**	d = -1.37
Reading span	51.6 (11.8)	39.5 (14.1)	t(98) = 4.68**	d = -.94
WM Composite	.54 (.84)	-.54 (.86)	t(98) = 6.34**	d = -1.27
Processing Speed				
Symbol search	109.7 (12.6)	105.5 (13.9)	t(98) = 1.58	d = -.32
Coding	104.4 (11.3)	95.9 (10.7)	t(98) = 3.87**	d = -.77
Cancellation	99.8 (11.3)	92.2 (14.1)	t(98) = 3.30*	d = .66
PS Composite	.35 (85)	-.35 (1.02)	t(98) = 3.75**	d = -.75

Note. *$p < .01$, **$p < .001$. RAN = rapid automatised naming, WM = working memory, PS = processing speed. Reported scores for RAN tasks and Reading span are raw scores. Standard scores are reported for all other tasks.

Standardised Measures

Rapid Automatised Naming. All participants completed both a letter and a number RAN test (Denckla & Rudel, 1976; Norton & Wolf, 2012) using the Comprehensive Test Of Phonological Processing (CTOPP 2). The RAN task requires participants to name a series of letters or numbers sequentially out loud as quickly and accurately as possible. The time taken to complete an array was recorded with a stopwatch. Participants completed one letter and one number array for practice, and two served as the critical trials (i.e. one letter array and one number array). The score for each task was the total time that was needed to complete the task, higher scores indicate worse performance. Each array consisted of four rows of nine items. Letters and numbers were presented in Arial font, and all items appeared on the same side of white A4 paper. The standardised procedures of administration for this task were followed as described in the test manual. Independent samples *t*–tests revealed significantly longer naming times for the dyslexic group on the letter array (see Table 2), which is consistent with prior studies (e.g. Wolf & Bowers, 1999). The reliability of the CTOPP-2 subtests have been demonstrated by average internal consistency that exceeds .80 (Wagner, Torgensen, Rashotte, & Pearson, 2013).

Working Memory. Working memory was measured using the digit and letter span tasks (i.e. digit span forward, digit span backward, digit span sequencing, and letter-number sequencing) from the 4^{th} edition of the Wechsler Adult Intelligence Scale (WAIS-IV) (Wechsler, 2014). In the digit span forward task, participants were given increasing sequences of numbers, and they were asked to repeat them back in the same order. In digit span backward, they had to repeat them back in reverse order. In digit span sequencing, participants listened to increasing sequences of numbers and they were asked to repeat them back in ascending order. Finally, in the letter-number sequencing, participants were given increasing length mixed sets of numbers and letters, which then they were required to repeat back by first listing the numbers of the set in ascending order and then the letters in alphabetical order. In each task, the score was the total number of sets of digits and/or letters that the participants could recall accurately. The standardised procedures of administration for these subtests were followed as described in the test manual.

Processing speed. Processing speed was measured using speeded subtests of WAIS-IV (i.e. coding, symbol search, and cancellation tasks). In coding, participants were given a grid with numbers from one-to-nine, each one corresponded to a specific shape. Then they had to replace every number in 144 cells with the shape corresponding to it in a set amount of time. In the symbol search task, participants were required to identify whether one of the two given target symbols for every item can be found in an array of five symbols in a set amount of time. Finally, in cancellation, participants were required to scan a structured arrangement of coloured shapes and mark the targets while avoiding the distractors. For all subtests, higher values correspond to faster processors and the score for each of these tasks was the total number of items that the participants could identify accurately. The standardised procedures of administration for these subtests were followed as described in the test manual. With respect to the reliability of the WAIS-IV, the manual reports average internal reliability coefficients for subtests that range from .78 to .94 (Benson, Hulac, & Kranzler, 2010).

Reading Span. A reading span task was also used as a measure of working memory, as it has been shown to assess both processing and storage functions (Daneman & Carpenter, 1980; Unsworth, Heitz, Schrock, & Engle, 2005). Participants were required to read silently a set of sentences of 13-16 words in length and then verify whether or not the sentence was semantically correct. After each sentence, participants were presented with an isolated letter that needed to be recalled at the end of the set. The task consisted of 15 trials (3 trials of each set of 3-7 letters that needed to be recalled) (Unsworth et al., 2005). The reading span task developed by Engle's Working Memory Laboratory, and reported reliability range between .70 and .79 for the reading span (Conway et al., 2005).

Sentence Processing

To investigate syntactic processing, we used 40 sentences with two different types of verbs, 20 with reflexives and 20 with optionally transitive verbs (see Table 1). The sentences were based on the long/plausible items used in Christianson et al. (2001), Experiment 3. Each participant saw 20 ambiguous and 20 unambiguous sentences, and items were rotated in a Latin Square Design. All filler sentences were grammatically correct and consisted of five sets of 16 sentences. The first set were subordinate-main structures in which the subordinate clause was transitive. The second set were main-subordinate sentences. The third set were transitive sentences containing a relative clause at the end of the sentence. The fourth set were transitive sentences that contained an embedded relative clause that modified the subject noun phrase. The fifth set were coordination structures, in which two transitive sentences were conjoined with *and.* Half of these had a comma between *and* and the preceding word and half did not. The final set were 20 passive sentences. Half of these were implausible and half were plausible.

Apparatus

Eye movements were recorded with an EyeLink 1000 eye-tracker, sampling at 1000 Hz (SR Research, Ontario, Canada). Viewing distance was 70 cm from eyes to a 45 cm computer monitor, and at this distance, 1.0° of visual angle subtended 1.22 cm, which corresponded to approximately four or five letters. Head movements were minimised with a chin rest. Eye movements were recorded from the right eye. The sentences were presented in 12 pt. Arial black font on a white background.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 × 2 (Sentence Structure × Verb Type × Group) mixed model, in which sentence structure and verb type were within subjects and group was between subjects. Participants completed three practice trials, 40 experimental trials, and 100 fillers. Trials were presented in a random order for each participant.

Participants were provided with a set of instructions that detailed the experimental procedure. They were then seated at the eye tracker and asked to respond to on-screen instructions using the keyboard. At the beginning of each trial, a message appeared asking the participant to press a button when they were ready to continue. After the participant pressed the button, they were required to fixate a drift-correction dot. The experimenter then initiated the trial. The sentence appeared after 500 ms, and the initial letter of each sentence was in the same position, in terms of *x* and *y* coordinates, as the drift correction dot (i.e. on the left edge of the monitor and centred vertically).

The entire sentence was presented on a single line on the screen. The participant read the sentence silently and then pressed the spacebar on the keyboard. Following a delay of 500 ms, an arithmetic problem (either addition or subtraction) appeared on the screen (e.g. 45 + 67 = 112). The problem was presented for 3000 ms and was followed by a screen prompting the participant to press the green button on the keyboard if the solution was correct, or the red button if it was incorrect. Feedback on the accuracy of the response to the math problem was given. After the feedback, participants were asked a comprehension question, such as *"Did Anna dress the baby?"*. For the ambiguous sentences, accurate "no" responses indicate the extent to which participants fully revise the temporary syntactic ambiguity. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were ten items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was α = .60.

The rationale for including the additional arithmetic problem was the fact that we wanted to assess the representation that comprehenders generated of the sentences, without allowing them to have direct access to the sentence. We expected that the presence of the mathematical problem would clear the immediate contents of working memory, therefore resulting in the participants responding to the comprehension questions on the basis of a more long-term representation/trace of the sentence.

The testing session for each participant lasted approximately 2 hours, with several breaks between tasks to avoid fatigue. The tests were delivered in the following order for each participant: digit span forward, coding, digit span backward, reading span, sentence processing, RAN digits, RAN letters, digit span sequencing, symbol search, letter-number sequencing and cancellation.

Data Screening and Analysis

Outliers were defined as means greater than 3 *SDs* from the mean. Outliers were replaced with the mean of that variable (McCartney, Burchinal, & Bub, 2006). This avoids listwise deletion and the corresponding reduction in power (Schafer & Graham, 2002). There were five outliers in the dataset (two in letter-number sequencing, one in coding, and two in cancellation), which were assessed via standardised values. Two of the outliers were participants with dyslexia and three were non-dyslexic.

In order to keep the analyses as straightforward as possible we submitted the working memory and processing speed tasks (separately) to a factor analysis in which we saved the retained factors as variables. For both working memory and processing speed, the factor analysis produced only a single factor, and thus, we used these composite (or latent) variables in our analyses examining "cognitive factors". The composite means are also presented in Table 2.

We analysed the comprehension and reading time data using standard mixed ANOVAs with subjects ($F1$) and items ($F2$) as random effects. For reading times, we examined the critical disambiguating word (i.e. main clause verb), and to assess whether the experimental manipulations might have a spill-over effect, we also examined the fixations on the word that followed (i.e. N+1 region). We first report the comprehension results, and second the eye movements. For the critical disambiguating word and the one following it (N+1), we report four dependent measures: first pass reading time, total reading time, proportion of trials with regression, and regression-path durations. *First pass reading time* is the sum of all fixations on a word from when a reader first enters a region to when they leave that region either forward or backward. *Total reading time* is the sum of all fixations on a word. *Regressions out* are the sum of all right-to-left eye movements from a word. *Regression path duration* is the sum of all fixations from the first time the eyes enter a region until they move beyond that region.

To assess the effects of working memory and processing speed (i.e. the cognitive factors), we conducted ANCOVAs in which each cognitive factor was co-varied separately. We were specifically interested in whether any group effects (dyslexic vs. control) changed with the inclusion of the covariate, and we were particularly interested in instances in which a group effect went from significant to non-significant with the inclusion of a covariate, suggesting overlapping/shared variance.[2]

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[2] We chose to use ANCOVA because of the variable input procedures. With ANCOVA, the covariate is entered first, and hence we were particularly interested in whether there was a group effect after variance in working memory is removed.

Results

Comprehension Accuracy

For comprehension accuracy, there were significant main effects of sentence structure $F1(1,98) = 59.37$, $p <.001$, ($\eta^2 = .38$); $F2(1,38) = 106.14$, $p < .001$, verb type $F1(1,98) = 264.19$, $p <.001$, ($\eta^2 = .73$); $F2(1,38) = 29.81$, $p < .001$, and group $F1(1,98) = 6.93$, $p < .05$, ($\eta^2 = .07$), $F2(1,38) = 74.62$, $p < .001$. The unambiguous sentences had higher accuracy than ambiguous sentence (.58 vs. .39), and sentences with reflexive verbs had higher accuracy than sentences with optionally transitive verbs (.62 vs. .36). Participants with dyslexia had poorer comprehension compared to controls (.44 vs. .54). There was also a significant sentence structure × verb type interaction $F1(1,98) = 56.19$, $p < .001$, ($\eta^2 = .37$); $F2(1,38) = 29.77$, $p < .001$ (see Figure 1, bottom panel). This interaction was driven by performance in the unambiguous-reflexive condition, which was substantially higher than both unambiguous-optional $t1(98) = -16.32$, $p < .001$, ($d = -1.52$), $t2(38) = 7.30$, $p < .001$ and ambiguous-reflexive conditions $t1(98) = -9.60$, $p < .001$, ($d = -1.09$), $t2(19) = -9.56$, $p < .001$. However, the other two paired comparisons were also significant (ambiguous-optional vs. unambiguous-optional $t1(98) = -3.47$, $p < .01$, ($d = 0.37$); $t2(19) = -4.28$, $p < .001$, and ambiguous-optional vs. ambiguous-reflexive $t1(98) = -7.79$, $p < .001$, ($d = 0.55$), $t2(38) = 2.97$, $p < .01$). This pattern is consistent with previous studies using similar materials (Christianson et al., 2001; Christianson, Williams, Zacks & Ferreira, 2006; Engelhardt, Nigg, Carr & Ferreira, 2008; Engelhardt, Nigg & Ferreira, 2017; Ferreira et al., 2001; Qian, Garnsey, & Christianson, 2018). None of the other interactions were significant.

As a follow up, we conducted one-sample *t*-tests to assess whether performance was significantly different from chance (i.e. 50/50), and the ones that were significant are indicated with an asterisk in Figure 1 (see top panels). Control participants were less accurate than chance in the ambiguous-optional condition $t(49) = -3.01$, $p < .01$, and were significantly above chance in the unambiguous-reflexive condition $t(49) = 11.92$, $p < .001$. Dyslexic participants were less accurate from chance in three conditions (i.e. ambiguous-optional $t(49) = -8.85$, $p < .001$, ambiguous-reflexive $t(49) = -2.18$, $p < .05$, unambiguous-optional $t(49) = -4.77$, $p <$

.001), and were significantly above chance in the unambiguous-reflexive condition $t(49) = 5.10$, $p < .001$.

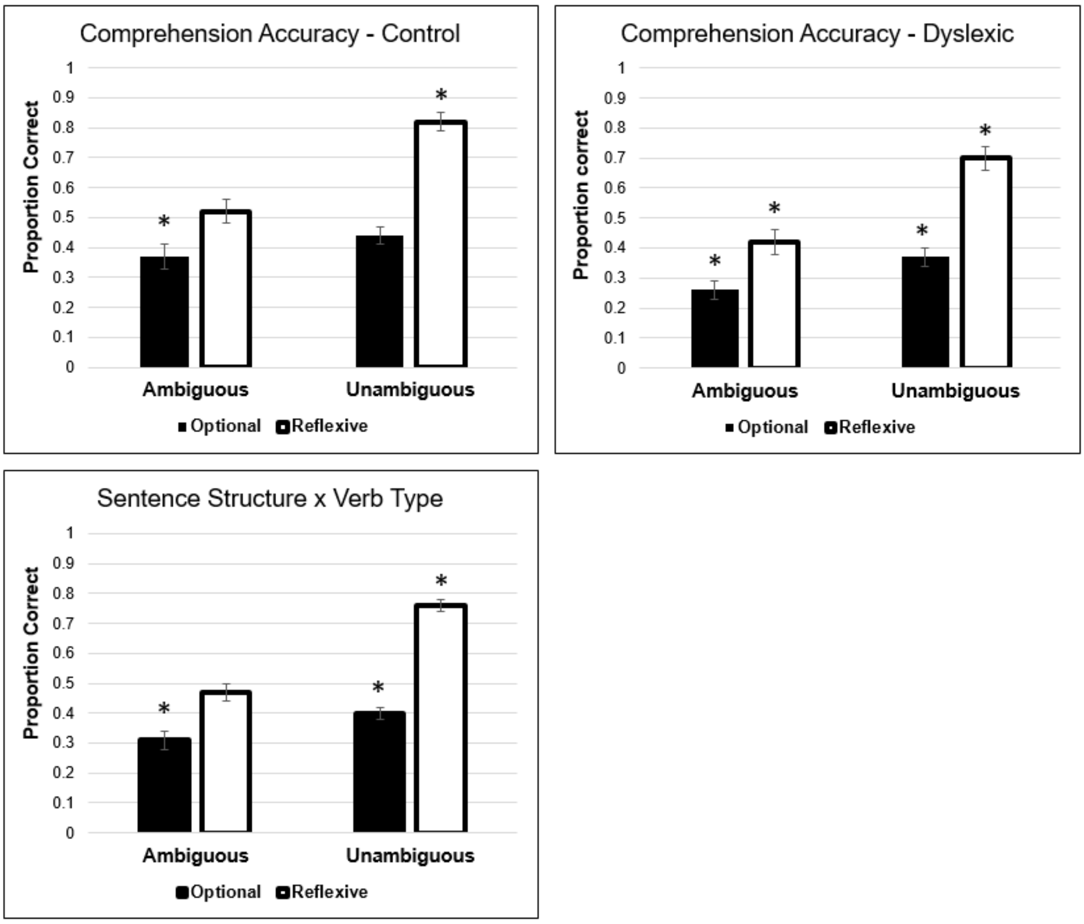

Figure 1. Top panels show the comprehension accuracy for controls (left) and dyslexics (right). The bottom panel shows the comprehension accuracy for sentence structure by verb type interaction. Error bars show the standard error of the mean. (*) indicate the significant one-sample *t*-tests.

Cognitive Factors. When working memory was included as a covariate in a 2 × 2 × 2 (Sentence Structure × Verb Type × Group) ANCOVA, the main effect of group was no longer significant (see Table 3). The other significant effects remained unchanged. Thus, our data suggests that group differences in comprehension were linked to working memory, and in particular, individuals with higher working memory abilities showed higher comprehension accuracy. In contrast, when processing speed was co-varied the main effect of group remained significant (see Table 3). Results however, did show a significant interaction between sentence structure and processing speed. We return to this interaction in the Discussion.

Table 3

Mixed ANCOVA analysis for risk factors on comprehension

Working Memory	
Sentence Structure	F(1,97) = 58.38, p < .001, η^2 = .37
Verb Type	F(1,97) = 262.59, p < .001, η^2 = .73
Group	F(1,97) = 1.66, p = .20, η^2 = .02
Working Memory	F(1,97) = 3.10, p = .08, η^2 = .03
Sentence Structure x Verb Type	F(1,97) = 57.31, p < .001, η^2 = .37
Processing Speed	
Sentence Structure	F(1,97) = 60.77, p < .001, η^2 = .39
Verb Type	F(1,97) = 261.97, p < .001, η^2 = .73
Group	F(1,97) = 4.13, p < .05, η^2 = .04
Processing Speed	F(1,97) = 1.50, p = .22, η^2 = .02
Sentence Structure x Verb Type	F(1,97) = 56.41, p < .001, η^2 = .37
Sentence structure x P. Speed	F(1,97) = 4.32, p < .05, η^2 = .04

Summary. Results indicated that dyslexic participants had lower comprehension compared to controls. (The correlations between group and the within subject conditions are presented in Table 4.) When working memory was co-varied, the main effect of group was no longer significant, which indicates an effect of individual differences in working memory on comprehension accuracy (Caplan & Waters, 1999; Christianson et al., 2006; DeDe et al., 2004).

Table 4

Bivariate correlations between diagnostic group, working memory, processing speed, comprehension, and reading times

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Dyslexia	-	-.54**	-.35**	-.22*	-.17	-.17	-.24*	.26**	.22*	.13	.21*	.39**	.39**	.29**	.35**
2. WM Factor		-	.52**	.21*	.16	.17	.34**	-.34**	-.20*	-.27**	-.21*	-.23*	-.22*	-.24*	-.16
3. PS Factor			-	.13	.00	.27**	.27**	-.25*	-.09	-.16	-.14	-.17	-.16	-.15	-.23*
4. Comp. Ambig – optional				-	.75**	.42**	.33**	-.15	-.22*	-.29**	-.20	-.05	-.14	-.02	-.06
5. Comp. Ambig – reflexive					-	.36**	.36**	-.12	-.20*	-.29	-.15	.01	-.13	.01	.02
6. Comp. Unambig – optional						-	.57**	-.36**	-.28**	-.26**	-.17	-.03	.12	.09	-.04
7. Comp. Unambig – reflexive							-	-.29**	-.28**	-.28**	-.21*	.14	.19	.08	.10
8. First Pass Ambig – optional								-	.61**	.55**	.48**	.47**	.28**	.24*	.34**
9. First Pass Ambig – reflexive									-	.60**	.58**	.30**	.26**	.30**	.27**
10. First Pass Unambig – optional										-	.51**	.15	.25*	.32**	.21*
11. First Pass Unambig – reflexive											-	.28**	.24*	.24*	.42**
12. Total RT Ambig – optional												-	.68**	.60**	.66**
13. Total RT Ambig – reflexive													-	.54**	.60**
14. Total RT Unambig – optional														-	.65**
15. Total RT Unambig – reflexive															-

Note. *p < .05, **p < .01. Dyslexia coded 0 = control and 1 = dyslexic, WM = working memory, PS = processing speed, comp. = comprehension accuracy, RT = reading time.

Eye Movements - Disambiguating Verb

First pass reading times showed a significant main effect of group $F1(1,98) = 6.87$, $p < .05$, ($\eta^2 = .07$); $F2(1,38) = 36.57$, $p < .001$, in which dyslexic participants had longer first pass reading times compared to controls (see Table 5). None of the other main effects or interactions were significant. Total reading times showed a significant main effect of group $F1(1,98) = 21.49$, $p < .001$, ($\eta^2 = .26$); $F2(1,38) = 100.59$, $p < .001$ with dyslexic participants having longer total reading times compared to controls (see Table 5). There was also a significant main effect of sentence structure $F1(1,99) = 33.58$, $p < .001$, ($\eta^2 = .26$); $F2(1,38) = 39.54$, $p < .001$ and a main effect of verb type that was significant by-subjects $F1(1,99) = 11.82$, $p < .001$, ($\eta^2 = .11$); $F2(1,38) = 1.35$, $p = .25$. The ambiguous sentences and sentences with reflexive verbs had longer reading times.

Table 5

Mean reading times (msec) and regressions for disambiguating verb and N+1 by group and experimental condition.

	First Pass RT		Total Reading Time		Reg. Out		Reg. Path Duration	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Controls								
GP opt	294.1	75.3	574.3	198.8	.28	.18	728.4	354.2
GP ref	309.2	71.2	601.2	175.5	.32	.18	858.1	460.5
NGP opt	301.4	69.4	513.7	136.9	.22	.16	590.0	294.1
NGP ref	301.5	73.4	548.9	169.1	.28	.18	685.6	473.6
Mean	301.5	57.1	559.5	129.0	.28	.13	715.5	308.9
Dyslexics								
GP opt	342.8	102.6	770.0	268.3	.25	.19	801.1	488.1
GP ref	346.2	96.8	807.3	301.4	.32	.19	1026.3	595.0
NGP opt	322.3	87.8	616.1	197.3	.24	.17	670.0	448.6
NGP ref	337.1	89.6	699.6	232.1	.30	.17	708.1	407.3
Mean	337.1	77.1	723.3	213.9	.28	.12	801.4	361.6

Disambiguating verb

Controls									
GP opt	270.0	87.0	298.1	149.0	.59	.22	1632.0	1163.2	
GP ref	270.7	89.6	310.1	159.9	.64	.25	1620.5	851.5	
NGP opt	284.0	84.3	311.9	137.0	.51	.21	1215.2	604.4	
NGP ref	269.0	79.2	273.2	110.6	.58	.23	1222.6	658.4	N + 1 word
Mean	273.4	64.4	298.3	111.0	.58	.15	1422.6	660.1	
Dyslexics									
GP opt	274.5	77.2	408.6	221.4	.56	.19	2115.1	1158.5	
GP ref	270.6	76.5	393.6	208.3	.54	.23	1986.6	1315.0	
NGP opt	292.8	84.0	342.8	157.6	.52	.20	1491.2	900.0	
NGP ref	298.0	90.3	326.8	165.4	.52	.25	1404.0	976.0	
Mean	284.0	54.0	368.0	160.5	.53	.15	1749.2	834.0	

There was also a significant sentence structure × group interaction $F1(1,98) = 5.30$, $p < .05$, ($\eta^2 = .05$); $F2(1,38) = 5.01$, $p < .05$ (see Figure 2, left panel). Paired comparisons showed significant differences between controls and dyslexics for both the ambiguous $t1(98) = 4.62$, $p < .001$, ($d = 0.92$); $t2(39) = -8.04$, $p < .001$ and the unambiguous sentences $t1(98) = 3.78$, $p < .001$, ($d = 0.76$); $t2(39) = -6.04$, $p < .001$. Both controls $t1(49) = 3.13$, $p < .05$, ($d = -0.39$); $t2(39) = 2.66$, $p < .05$ and dyslexic participants $t1(49) = 4.88$, $p < .001$, ($d = -0.56$); $t2(39) = 5.91$, $p < .001$ showed significantly longer reading times for the ambiguous as compared to the unambiguous sentences. The interaction, in this case, was driven by the longer total reading times for ambiguous sentences compared to unambiguous sentences in participants with dyslexia.

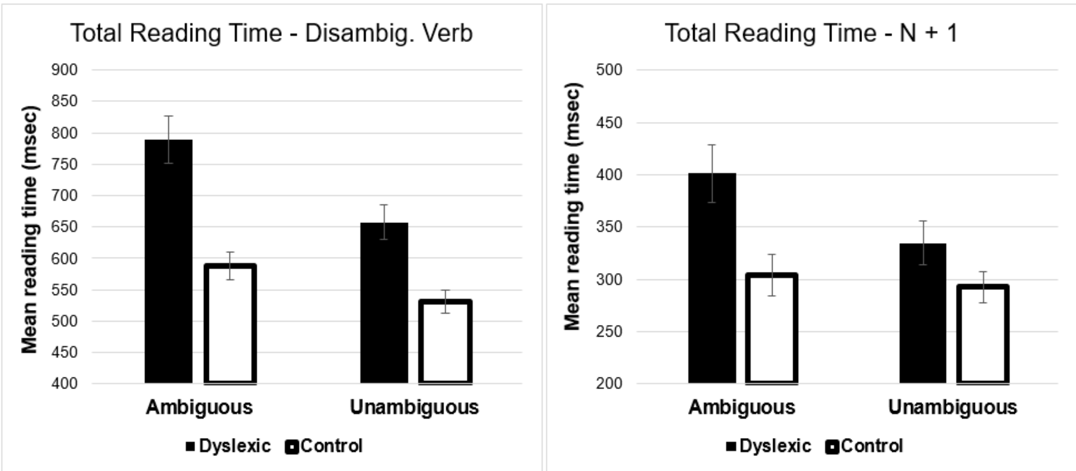

Figure 2. Interactions between sentence structure and group (control vs. dyslexia). Left panel shows the interaction for the disambiguating verb and the right shows the interaction at the spill over region. Error bars show the standard error of the mean.

Regressions out showed a significant main effect of sentence structure $F1(1,98) = 4.89$, $p < .05$, ($\eta^2 = .05$); $F2(1,38) = 6.03$, $p < .05$, as well as a significant by-subjects main effect of verb type $F1(1,98) = 16.11$, $p < .001$, ($\eta^2 = .14$); $F2(1,38) = 1.50$, $p = .23$ (see Table 5). Ambiguous sentences and sentences with reflexive verbs had a higher proportion of trials with a regression. None of the other main effects or interactions were significant. Regression path durations showed a significant main effect of sentence structure $F1(1,98) = 28.06$, $p < .001$, ($\eta^2 = .22$); $F2$ $(1,38) = 22.57$, $p < .001$, with ambiguous sentences showing longer regression paths than unambiguous sentences. There was also a by-subjects main effect of verb type *F1*(1,98) = 13.70, $p < .001$, ($\eta^2 = .12$); *F2*(1,38) = 1.30, $p < .26$, with reflexive verbs showing longer regression path durations than optionally-transitive verbs. None of the other main effects or interactions were significant.

Cognitive Factors. In the above eye movement analysis, we observed three key group differences. They were (1) a main effect of group on first pass reading times, (2) a main effect of group on total reading times, and (3) a significant structure × group interaction on total reading times. The main effect of group on first pass reading times was not significant when working memory was co-varied, but working memory did show a significant main effect (see Table 6). For total reading times, the significant sentence structure × group interaction was marginally significant after working memory was included in the model and the main effect of group was robust with working memory covaried (see Table 6). With respect to processing speed, the main effect of group on first pass times remained significant and co-varying processing speed did not affect the main effect of group on total reading times or the group × sentence structure interaction (see Table 6).

Table 6

Mixed ANCOVA analysis for risk factors at disambiguating verb

First Pass Reading Times	
Working Memory	
Group	$F(1,97) = 1.11, p = .30, \eta^2 = .01$
Working Memory	$F(1,97) = 4.92, p < .05, \eta^2 = .05$
Processing Speed	
Group	$F(1,97) = 4.16, p < .05, \eta^2 = .04$
Processing speed	$F(1,97) = 1.38, p = .24, \eta^2 = .01$
Total Reading Times	
Working Memory	
Structure type	$F(1,97) = 33.24, p < .001, \eta^2 = .26$
Verb type	$F(1,97) = 11.85, p < .01, \eta^2 = .11$
Group	$F(1,97) = 14.05, p < .001, \eta^2 = .13$
Working Memory	$F(1,97) = .063, p = .80, \eta^2 = .001$
Structure type x Group	$F(1,97) = 3.78, p = .055, \eta^2 = .04$
Processing Speed	
Structure type	$F(1,97) = 33.32, p < .001, \eta^2 = .26$
Verb type	$F(1,97) = 11.72, p < .01, \eta^2 = .11$
Group	$F(1,97) = 16.66, p < .001, \eta^2 = .15$
Processing speed	$F(1,97) = .463, p = .50, \eta^2 = .01$
Structure type x Group	$F(1,97) = 5.38, p < .05, \eta^2 = .05$

Summary. For working memory, the group effect on first pass reading times was not significant, which indicates that variance in working memory is related to first pass reading times. However, for both cognitive factors, the group effect remained significant on total reading times, as well as on first pass reading times when processing speed was co-varied. Dyslexic participants showed longer total reading times and a significant sentence structure × group interaction. The form of that interaction was such that the ambiguous sentences had longer total reading times than unambiguous sentences in participants with dyslexia as compared to controls. These group differences were just shy of significance with working memory covaried.

Eye Movements – N + 1

First pass reading times showed a significant main effect of sentence structure $F1(1,98) = 4.27$, $p < .05$, ($\eta^2 = .04$); $F2(1,37) = 4.71$, $p < .05$, in which the unambiguous sentences had longer first pass reading times. None of the other main effects or interactions were significant. Total reading times showed a significant main effect of group $F1(1,98) = 6.37$, $p < .05$, ($\eta^2 = .06$); $F2(1,37) = 30.90$, $p < .001$ and a significant main effect of sentence structure $F1(1,98) = 10.26$, $p < .01$, ($\eta^2 = .10$); $F2(1,37) = 8.47$, $p < .01$. Participants with dyslexia and the ambiguous sentences has longer total reading times. There was also a significant by-subjects sentence structure × group interaction $F1(1,98) = 5.08$, $p < .01$, ($\eta^2 = .05$); $F2(1,37) = 1.94$, $p = .17$ (see Figure 2, right panel, and Table 7 for correlations between variables). Paired comparisons showed significant differences between controls and dyslexics for the ambiguous sentences $t1(88) = 2.87$, $p < .05$, ($d = 0.57$); $t2(38) = -4.36$, $p < .001$ but not for the unambiguous sentences $t1(98) = 1.63$, $p = .11$, ($d = 0.33$); $t2(39) = -2.76$, $p < .01$. The controls showed no difference between the two types of sentence structure $t1(49) = .76$, $p = .45$, ($d = 0.09$); $t2(38) = 1.05$, $p = .30$, but the dyslexic participants did show significantly longer reading times for the ambiguous as compared to the unambiguous sentences $t1(49) = 3.5$, $p < .01$, ($d = 0.38$); $t2(38) = 2.83$, $p < .01$. None of the other main effects or interactions were significant. In general, the form of the sentence structure × group interaction was similar to the one observed at the disambiguating verb.

Table 7

Bivariate correlations between diagnostic group, working memory, processing speed, comprehension, and reading times

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Dyslexia	-	-.54**	-.35**	-.22*	-.17	-.17	-.24*	.28**	.22*	.11	.19	.21*	.17	.18	.11
2. WM Factor		-	.52**	.21*	.16	.17	.34**	-.28**	-.29**	-.17	-.24*	-.08	-.05	-.24*	-.04
3. PS Factor			-	.13	.00	.27**	.27**	-.20*	-.19	-.17	-.21*	-.06	.03	-.11	-.16
4. Comp. Ambig – optional				-	.75**	.42**	.33**	-.16	.03	-.18	-.13	.08	.02	-.07	.04
5. Comp. Ambig – reflexive					-	.36**	.36**	-.15	.11	-.15	-.11	.18	-.01	-.05	.08
6. Comp. Unambig – optional						-	.57**	-.01	.06	.05	.02	.08	.26**	.03	-.09
7. Comp. Unambig – reflexive							-	-.02	.11	.00	-.10	.07	.24*	-.10	.06
8. Total RT Ambig – optional								-	.65**	.63**	.66**	.36**	.37**	.40**	.36**
9. Total RT Ambig – reflexive									-	.54**	.49**	.29**	.43**	.36**	.37**
10. Total RT Unambig – optional										-	.63**	.30**	.33**	.52**	.32**
11. Total RT Unambig – reflexive											-	.27**	.39**	.36**	.38**
12. Reg. Path Ambig – optional												-	.47**	.48**	.54**
13. Reg. Path Ambig – reflexive													-	.43**	.43**
14. Reg. Path Unambig – optional														-	.56**
15. Reg. Path Unambig – reflexive															-

Note. **p* < .05, ***p* < .01. Dyslexia coded 0 = control and 1 = dyslexic, WM = working memory, PS = processing speed, comp. = comprehension accuracy, RT = reading time.

Regressions out showed only a significant main effect of sentence structure $F1(1,98) = 7.54$, $p < .01$, ($\eta^2 = .07$); $F2(1,37) = 8.37$, $p < .01$, in which the ambiguous sentences had more regressions out. None of the other main effects or interactions were significant. The fact that there were no differences between the two groups in regressions out could suggest that dyslexia status does not influence the probability of noticing the error signal. Regression path durations showed a significant main effect of sentence structure $F1(1,99) = 42.37$, $p < .001$, ($\eta^2 = .30$); $F2(1,37) = 26.55$, $p < .001$, as well as a significant main effect of group $F1(1,98) = 4.72$, $p < .05$, ($\eta^2 = .05$); $F2(1,37) = 14.22$, $p < .01$. Participants with dyslexia and the ambiguous sentences had higher regression path durations. None of the other main effects or interactions were significant.

Cognitive Factors. The main effect of group on total reading times and structure × group interaction were no longer significant when working memory was co-varied (see Table 8). For regression paths, the main effect of group was not significant with working memory included, although it remained marginal. For processing speed, the main effect on total reading times was marginally significant, and the sentence structure × group interaction was robust to the inclusion of working memory. Finally, the main effect of group on regression path durations remained significant, when processing speed was included in the model.

Table 8

Mixed ANCOVA analysis for risk factors at N + 1 word

Total Reading Times	
Working Memory	
Structure type	$F(1,97) = 10.26, p < .01, \eta^2 = .10$
Group	$F(1,97) = 1.13, p = .29, \eta^2 = .01$
Working Memory	$F(1,97) = 4.12, p < .05, \eta^2 = .04$
Structure type x Group	$F(1,97) = 1.85, p = .18, \eta^2 = .02$
Processing Speed	
Structure type	$F(1,97) = 10.15, p < .01, \eta^2 = .10$
Group	$F(1,97) = 3.27, p = .07, \eta^2 = .03$
Processing speed	$F(1,97) = 2.60, p = .11, \eta^2 = .03$
Structure type x Group	$F(1,97) = 4.36, p < .05, \eta^2 = .04$
Regression-Path Duration	
Working Memory	
Group	$F(1,97) = 3.27, p = .07, \eta^2 = .03$
Working Memory	$F(1,97) = 0.00, p = .99, \eta^2 = .00$
Processing Speed	
Group	$F(1,97) = 4.00, p < .05, \eta^2 = .04$
Processing speed	$F(1,97) = .004, p = .95, \eta^2 = .00$

Summary. For both cognitive factors, the group effect on total reading times was not significant, which indicates that variance in working memory and processing speed are related to total reading times. However, for processing speed, the group effect on regression path durations remained, which indicates that variance only in working memory is associated with regression path durations. Dyslexic participants showed longer total reading times and a significant structure × group interaction. That interaction was unaffected by working memory and processing speed. The form of that interaction was such that the ambiguous sentences had longer total reading times in participants with dyslexia, similar to the pattern at the disambiguating verb.

Discussion

In this study, we examined how dyslexic as well as non-dyslexic adults comprehend and read sentences that contained a temporary syntactic ambiguity. We were specifically interested in whether individuals with dyslexia have difficulty overcoming the temporary ambiguity (Research Question 1), and we found some evidence that they do. Our findings are consistent with theories (e.g. Verbal Efficiency and Synchronisation), which assume that poor automatic word identification in individuals with dyslexia will lead to comprehension difficulties and slower reading (Bishop & Snowling, 2004; Breznitz, 2006; Perfetti, 2007; Wolf & Bowers, 1999). The underlying assumption is that individuals who fail to automate word identification/lexical access will experience excessive demands on processing resources necessary for comprehension (Verbal Efficiency) and/or experience timing issues resulting in asynchrony in different processes required for comprehension (Synchronisation).

The novelty of the current study is that we specifically investigated how individuals with dyslexia process temporary syntactic ambiguity. We also explored the impact of two key cognitive factors (i.e. working memory and processing speed) and how individual differences in these variables affected both online and offline processing measures (Research Question 2). In the remainder of the discussion, we cover the comprehension results and the eye movements, following that we discuss the relationship between the online and offline processing measures and the cognitive factors. The discussion ends with the limitations and the conclusions.

Comprehension Accuracy

Our results suggest two main conclusions regarding the comprehension of garden-path sentences in individuals with dyslexia. The first was that their comprehension was generally poorer than participants without dyslexia (i.e. there was a main effect of group on comprehension). They were more likely to respond “yes” to comprehension questions, suggesting at first glance that they tended to engage in partial reanalysis, but because it was just a main effect, it suggests that dyslexics also experienced difficulty with unambiguous sentences. With respect to the differences between ambiguous and unambiguous sentences, the correlations (see Table 4) revealed that group (or dyslexia status) was significantly correlated with comprehension in the ambiguous-optional and unambiguous reflexive conditions. (These are the hardest and easiest conditions, respectively). The other two conditions (i.e. ambiguous-reflexive and unambiguous-optional) also produced negative correlations $r = -.17$, $p = .09$. In these conditions, one-sample *t*-tests showed that controls were no different from chance, but in both, dyslexics were significantly more likely to respond “yes” meaning that they retained the temporary misinterpretation in the ambiguous-reflexive condition and made the plausibility-based inference in the unambiguous-optional condition (Ferreira et al., 2001). The tendency to answer “yes” with unambiguous sentences has previously been suggested (i.e. Christianson et al., 2006) as evidence for a semantically-based plausibility inference process based on the Good-Enough Approach to language comprehension (Ferreira & Patson, 2007). This is especially true with optional verbs.

The second conclusion regards how cognitive factors affected comprehension accuracy, and specifically, the group main effect on comprehension. When working memory was included in the model as a covariate, the group main effect was no longer significant, suggesting that individual differences in working memory are related to comprehension accuracy.[3] Our results indicate that variance in working memory is associated with comprehension, and specifically, in determining the thematic roles of the various constituents in the sentence, especially in cases where thematic roles are initially (incorrectly) assigned. Thus, our data suggest that comprehension is dependent on or related to individual differences in working memory. This relationship has been previously identified by psycholinguistic studies (e.g. Caplan & Waters, 1999; DeDe et al., 2004), and is also explicitly predicted by Verbal Efficiency Hypothesis (Perfetti, 2007).

Christianson et al. (2006) argued that readers leave the subordinate clause issue (temporary ambiguity) unresolved until being faced with the comprehension question, and then, they realise that the structure (originally built) needed to be repaired. They speculated that holding the details of the sentence in working memory allowed younger adults and older adults with better working memory ability to more accurately complete the reanalysis operation when confronted with the comprehension question. This explanation applies specifically to ambiguous sentences and should result in longer question answering time. Unfortunately, Christianson et al. (2006) did not report question response times or the correlations between question response time and comprehension accuracy.

The arguments from Christianson et al. (2006) do not align with the current data as we found that correlations between working memory and comprehension were actually greater for controls than for dyslexics (i.e. controls showed positive correlations ranging from .13 - .24, and dyslexics showed mixed positive and negative correlations ranging from -.25 to .11). However, there is one key difference between studies that may underlie the discrepancy. In the current study, participants had an intervening math problem to complete before answering the comprehension

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[3] However, working memory only produced a marginally significant ($p = .08$) main effect when included as a covariate (see Table 3).

question. Thus, answering the comprehension question may be more based on long-term memory rather than working memory. By this explanation, the math problem would clear the contents of working memory and answering the comprehension question would be based on the long-term trace of sentence content. Research has suggested that syntactic structure is not encoded but instead only propositional-level content (see, Lewis et al., 2006). Correlations in our study with working memory may simply reflect people with better (working and long-term) memory abilities. We also think that given the relationships between working memory and online measures (discussed below), that working memory has much more of an effect on online processing than Christianson et al. (2006) and others (e.g. Caplan & Waters, 1999; DeDe et al., 2004) concluded. The fact that individuals with dyslexia have lower working memory compared to non-dyslexics may also suggest that they have less capacity for efficiently monitoring comprehension, which has been similarly highlighted by Linderholm, Cong, and Zhao (2008) and Linderholm and Van den Broek (2002), who examined individual differences in working memory in students.

In summary, dyslexic participants showed significantly lower comprehension accuracy compared to controls. However, those differences did not remain when variance in working memory was removed, and thus, offline comprehension revealed overlapping variance between dyslexia status and working memory.

Eye Movements

Before discussing the results with respect to dyslexia, there are a couple of trends in the data that are worth highlighting. First, at the disambiguating word, we observed relatively long first pass and total reading times, and a relatively low proportion of trials with a regression out and relatively low regression-path durations (see Table 5). At the N + 1 word, we observed relatively low first pass and total reading times, but a relatively high proportion of trials with regression out and relatively high regression path durations. What these patterns suggest are that participants initially slowed down upon encountering the disambiguating word and that the spill over effect on the next word was mainly triggering regressions out and longer re-reading times. The longer total reading times at the disambiguating word and the longer regression path durations are indicative of reanalysis operations. The second trend concerns differences between ambiguous and unambiguous sentences, and the means in Table 5 suggest substantial differences between ambiguous and unambiguous sentences in total reading times at the disambiguating word and in regression path durations, again consistent with eye movement behaviour indicative of reanalysis (Frazier & Rayner, 1982). We return to this issue below.

With respect to group differences, we observed two significant main effects. They were in first pass reading times at the disambiguating verb and regression path durations at N +1. In addition, we also observed a significant sentence structure × group interaction, and a similar pattern was observed at both the disambiguating verb and the N + 1 word. However, the two main effects were not significant once working memory was included in the model. This could suggest that variance in fixation durations (and specifically longer first pass and regression path durations in dyslexics) are related to individual differences in working memory. For the interaction, there was a dissociation between the patterns observed at the disambiguating verb and N + 1. The interaction at the disambiguating verb was robust when working memory was included but the interaction at N + 1 was not robust once working memory was co-varied. Thus, there was only one eye movement result that seemed to be specifically related to dyslexia status (beyond that explained by lower working memory), and that was an interaction in total reading times at the disambiguating verb. That interaction was driven by the fact that participants with dyslexia spent more time reading the disambiguating verb in ambiguous sentences compared to controls and compared to reading times with unambiguous sentences (see Figure 2). Dyslexic participants appeared to be inefficient in first pass reading due to working memory difficulties (Perfetti, 2007) or possibility due to word identification issues.[4] However, working memory did not account for dyslexics longer total reading times at the disambiguating verb. At present, we cannot determine conclusively the cause of increased total reading times in individuals with dyslexia, but one suggestion is that involves integration (i.e. integrating the disambiguating verb with the prior sentence context) (Simmons & Singleton, 2000).

The dissociation between interactions at the disambiguating verb and N +1 is a bit perplexing: How could essentially the same interaction have different underlying factors? A couple of points are worth mentioning before we present our interpretation of this finding. First, the total reading times at the N + 1 region are

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[4] The current study did not assess word reading measures, and so, we are not in a position to exclude or confirm how word reading affects first pass reading times.

essentially half of those at the disambiguating word. Second, at the disambiguating word dyslexics showed substantially elevated reading times on the unambiguous sentences, which means that the form of the interaction is in fact quite different between the two different regions of interest. In order to further understand this interaction, we turned to the correlations presented in Tables 4 and 7. In Table 4, it can be seen that the effect of dyslexia status on total reading times at the disambiguating word were quite substantial (i.e. correlations collapsed across verb were ambiguous sentences = .39** and unambiguous sentences = .32**). The correlations with working memory, again collapsed across verb, were lower -.22* and -.20*, respectively. In contrast, at N + 1, the pattern was reversed (i.e. the correlations with working memory (ambiguous = -.28** and unambiguous = -.20*) were generally larger than for dyslexia status (ambiguous = .25* and unambiguous = .15)). Therefore, it is evident that there is additional variance at the disambiguating word (possibly driven by the much higher reading times) that is distinctly due to dyslexia status and not accounted for by working memory. At N + 1, however, the variance accounted for by working memory is larger. Thus, there is no effect distinctly due to dyslexia status after variance in working memory has been removed (the latter of which is predicted by Verbal Efficiency). To summarise, readers with dyslexia spend more time on the disambiguating verb in sentences containing a temporary ambiguity, and that effect is independent of individual differences in working memory.

Relationship between Online and Offline Measures

There is one more finding from the current study that deserves mention, and from a theoretical (psycholinguistic and dyslexia) standpoint very important. We found that first pass reading times at the disambiguating word were significantly correlated with comprehension accuracy in three out of the four within subject conditions, ranging from -.15 to -.26 (see Table 4). However, the negative relationships are opposite of what would be expected by elevated reading times being associated with reanalysis operations (e.g. Frazier & Rayner, 1982). In contrast, total reading times at both the disambiguating word and N +1, and regression path durations at N + 1 were not significantly correlated with comprehension accuracy (see Tables 4 and 7). The correlations ranged from -.16 to .11. Again, most psycholinguistic researchers would expect more time spent reading and re-reading should be linked to <u>higher</u> comprehension accuracy, but the opposite pattern would be expected by the Verbal Efficiency and Synchronization Hypotheses. What our results seem to show is that if readers detect a problem or encounter a syntactic ambiguity, then they slow down on the first pass (see Table 5 and discussion pg. 27-28). However, the amount of time spent reading and re-reading does not increase the likelihood of triggering full reanalysis (for similar findings, see Qian et al., 2018). Thus, the extra time spent by participants (and in particular dyslexics) with ambiguous sentences must be dedicated to confirming the partial interpretation, or at least, an unresolved persistence of the confusion generated by the ambiguity. Again, just to reiterate, the pattern of means (see Table 5) is wholly consistent with previous studies concerning the effects of syntactic ambiguity and reading times, but what was novel and quite unexpected is the nearly complete dissociation between reading times and comprehension accuracy. Qian et al. (2018) and Christianson et al. (2017) reported highly similar findings, and in fact, even noted some patterns in the opposite direction (e.g. P600 amplitude), similar to what we observed in first pass reading times at the disambiguating verb.[5] As one final point to mention, we also think that individuals with dyslexia have a greater tendency to re-read compared to non-dyslexics, and that this likely a learned strategy to in some ways compensate for their difficulties with automatic word identification/lexical access (Breznitz, 2006; Perfetti, 2007).

Cognitive Factors

We found that working memory was significantly related to first pass reading times at the disambiguating verb, and first pass and total reading times at the N + 1 word (see Tables 6 and 8). Individuals with higher working memory had lower reading times. However, in all of the analyses, working memory only produced a main effect, it did not interact with any of the other variables (i.e. group, sentence structure, or verb type). Thus, individual differences in working memory seems to have a very general effect on eye movement measures (and on comprehension). Our findings on working memory also support the findings of Wiseheart et al. (2009) with respect to the impact of poor working memory on failures in sentence

[5] There was one trend in the data that supports our conclusions: We observed consistently positive correlations (.12 - .23) between eye movement measures (total reading times, regressions out, regression paths) and comprehension accuracy in the unambiguous-reflexive condition. The same pattern held for both controls and dyslexics. This is the one condition in which participants rarely obtain the misinterpretation (i.e. accuracy ~80% correct). In the other three conditions, participants are equally likely to get the partial vs. full interpretation, or more likely to get the partial interpretation.

comprehension. However, a relationship between online processing and working memory has been much debated in the psycholinguistic literature (see DeDe et al., 2004).

For processing speed, we observed several instances in which sentence structure interacted with processing speed. It occurred in comprehension accuracy, regression paths at the disambiguating word, and proportion of trials with regression out at N+1. Here the pattern of results suggests that faster processors have (1) better comprehension accuracy, (2) a higher number of trials with a regression, and (3) longer regression path durations, and they do so, specifically with unambiguous sentences. Thus, in cases where the ambiguity is not as strong or does not exist, faster individuals have better comprehension and show key differences in late eye movement measures, which is consistent with efficiency assumptions, i.e., the Verbal Efficiency Hypothesis (Perfetti, 2007). Specifically, faster processors are more likely to re-read and that re-reading improved comprehension.

Limitations

There are several limitations to this study. The first is that we tested university students and many people with dyslexia do not succeed academically to go on to further education. Thus, a sample of community-recruited dyslexics may show even greater differences than those we reported here. Furthermore, our sample might be considered small for the examination of individual differences, and thus, we would recommend future replications with a larger sample. A second limitation is that there were several instances in which the item analyses for verb type missed significance. We attribute this to the fact that the item analyses treated verb type as a between-subjects variable, and thus, had much lower power compared to the by-subjects analysis. Consistent with this conclusion, we examined individual items for outliers and/or unusual patterns, however there were none. The third limitation is that we did not include a standardised reading assessment, which could provide additional confirmation of the dyslexic group's reading difficulties. Finally, we did not include assessments of general intelligence or verbal intelligence (i.e. vocabulary), and recent research has indicated that verbal intelligence is a strong predictor in the success of garden-path sentence comprehension (e.g. Engelhardt et al., 2017; Van Dyke et al., 2014).

Conclusion

This study aimed to investigate processing and comprehension of sentences with temporary syntactic ambiguity in individuals with dyslexia. Our work builds on theories of comprehension (Breznitz, 2006; Perfetti, 2007), which suggest that deficits in word identification/lexical access, due to automaticity failures, have a direct impact on language comprehension. What is novel in our study is that we specifically examined how individuals deal with syntactic ambiguity. We also examined working memory and processing speed, which have been identified as potential cognitive factors for comprehension deficits in dyslexia. Our results showed that dyslexic readers made more comprehension errors compared to controls, and specifically, in ambiguous sentences with optionally-transitive verbs and unambiguous sentences with reflexive verbs. However, the group main effect was not robust when working memory was covaried. With respect to eye movements, the main effects of group were also not significant when working memory was included in the model. There was however, a significant interaction between sentence structure and group at the disambiguating verb in which individuals with dyslexia showed significantly higher total reading times with ambiguous sentences, and this effect was robust to the inclusion of working memory in the model. Across the entire dataset, we observed that working memory had more shared variance with dyslexia status as compared to processing speed, and thus, the current study confirms that working memory is indeed a key cognitive factor in dyslexia with respect to both comprehension and eye movements in reading, consistent with the predictions of Verbal Efficiency (Perfetti, 2007).

As for practical implications from this study, we think that assessments of language comprehension should pay attention to individual differences in working memory. This should be particularly the case for assessments for dyslexia. It remains to be determined whether working memory training may help individuals with dyslexia in terms of reading comprehension (Holmes, Gathercole, & Dunning, 2009; Melby-Lervåg & Hulme, 2013; Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2013), as prior research has shown working memory training often does not apply to other types of task. At the same time, the assumptions of Verbal Efficiency also suggest word reading and fluency training may be beneficial insofar as improvements would free up working memory resources for enhanced comprehension. Second, our findings with respect to the unambiguous sentences shows that comprehension deficits at the sentence level are not restricted to instances of syntactic ambiguity, and thus, there is clear scope for future comprehension interventions that focus on sentence-level comprehension. This would serve to bridge the word-level and text-level interventions that are commonly used in individuals with dyslexia (Edmonds et al., 2009; Wanzek & Vaughn, 2007; Wanzek, Wexler, Vaughn, & Ciullo, 2010). Another issue arising with interventions is that extra time is often offered to dyslexics (for example, in exams), but our data suggests that extra time spent in re-reading does not improve comprehension. And so, another avenue for interventions may be comprehension strategies focused on (more accurate) re-reading. In summary, the current study has provided a better understanding of how individuals with dyslexia process and comprehend sentences with temporary syntactic ambiguities and the cognitive factors associated with comprehension deficits in dyslexia.

Chapter 3

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Comprehension and eye movements in the processing of subject and object relative clauses: Evidence from dyslexia and individual differences

Abstract

In this study, we examined eye movements and comprehension in sentences containing a relative clause. To date, few studies have focused on syntactic processing in dyslexia and so one goal of the study was to contribute to this gap in the experimental literature. A second goal was to contribute to theoretical psycholinguistic debate concerning the cause and the location of the processing difficulty associated with object relatives. We compared dyslexic readers (*N* = 50) to a group of typically-developing controls (*N* = 50). We also assessed two key individual differences variables (working memory and verbal intelligence) which have been theorised to impact reading times and comprehension of subject and object relative clauses. The results showed that dyslexics and controls had similar comprehension accuracy. However, reading times showed participants with dyslexia spent significantly longer reading the sentences compared to controls. With respect to individual differences and the theoretical debate, we found that processing difficulty between the subject and object relatives was no longer significant when individual differences in working memory were controlled. Thus, our findings support theories, which assume that working memory demands are responsible for the processing difficulty incurred by object relative clauses as compared to subject relative clauses.

Introduction

The purpose of the current study was to investigate the processing of subject- and object-extracted relative clauses, henceforth referred to as subject and object relatives. Past research has identified that object relatives are consistently more difficult than subject relatives (e.g. Gordon, Hendrick, & Johnson, 2001; King & Just, 1991; Traxler, Morris, & Seely, 2002). We were interested in examining how individuals with dyslexia process these kinds of sentences because research into sentence processing in dyslexia is extremely limited, and thus, the first goal of the study was to determine whether individuals with dyslexia have difficulties with this particular type of syntactic construction.

The complexity of syntax in sentences with relative clauses, especially object relative clauses, is expected to have an additive effect on the speed of processing for dyslexic readers. According to Bishop & Snowling (2004), difficulties with sentence comprehension and processing are only a secondary symptom of dyslexia, however, there is still only a few studies that have examined these difficulties further. In our previous study (presented in Chapter 2), we found that dyslexic adults had poorer comprehension and showed more difficulties in processing garden path sentences. Therefore, in this study we aimed to investigate whether the secondary difficulties in sentence processing are also present in sentences with relative clauses (Wiseheart et al., 2009). This will help us understand better whether complexity in syntax and/or semantics is associated with difficulties in sentence comprehension and processing in dyslexia and whether the bottleneck in working memory storage and processing capacity remains regardless of the type of sentence examined.

Additionally, the results from this study on dyslexia have the potential to further inform the frameworks and debates around dyslexia and reading. Our predictions that dyslexics would show difficulties in processing and comprehension could further highlight the fact that the factors and skills underlying dyslexic performance are different from the ones that underlie non-dyslexics' reading performance. More specifically, the dyslexics' working memory bottleneck could result in difficulties in distinguishing the thematic roles of the components of sentences with relative clauses, especially object relative clauses, due to the position of the key thematic roles within the sentence (Gathercole et al., 2006; Staub, 2010). Their phonological processing difficulties would also result in slower processing, which will further impact on the working memory demands and the participants' comprehension. Controls should have intact phonological processing skills which will result in faster processing and lower the demands on their working memory storage and processing.

The second goal of the study was to contribute to the theoretical debate concerning the source of processing difficulty between subject and object relatives. Theoretical debates have identified two key issues: The first is violation of predictive expectations, which have been computationally assessed via Surprisal (Hale, 2001; Levy, 2008), and is very closely related to linguistic prediction (for reviews see Ferreira & Lowder, 2016; Kuperberg & Jaeger, 2016). The second source of difficulty is working memory. With object relatives, the object noun phrase must be held in memory until the reader encounters the relative clause verb, with which it is associated (Gennari & MacDonald, 2008; Gibson, 1998; Gordon et al., 2001;

Grodner & Gibson, 2005; Just & Carpenter, 1992; Lewis & Vasishth, 2005; Traxler et al., 2002; Waters & Caplan, 1996). Thus, resolving the long-distance dependency is expected to incur substantial demand on cognitive resources, especially in terms of working memory.

Dyslexia presents a very interesting test of these theoretical debates because dyslexia has been previously associated with deficits in both working memory (Chiappe et al., 2000; Jeffries & Everatt, 2004) and linguistic prediction (Huettig & Brouwer, 2015). Thus, there is good reason to suspect that individuals with dyslexia will show both online processing and offline comprehension deficits with object relative sentence.

In the remainder of the Introduction, we first cover the literature on dyslexia with a particular focus on sentence comprehension in dyslexia and what is known about the eye movement behaviour of individuals with dyslexia when they read. We then turn our attention to the theoretical psycholinguistics literature, and the two broad classes of processing models (memory-based and expectation-based) that make predictions about the processing difficulty associated with these particular kinds of sentences. Finally, we present the rationale and hypotheses of the current study.

Psycholinguistic Theories – Relative Clauses

As mentioned previously, individuals with dyslexia show deficits in several areas, which are assumed to be linked to their problems with reading. In the current study, we focused on two key individual differences variables, which were assessed along with sentence comprehension and eye movements. The first was working memory (Chiappe et al., 2000) and the second was verbal intelligence (Engelhardt et al., 2017; Van Dyke, Johns, & Kukona, 2014; Vellutino, 1977). We assumed that these two individual differences variable would play a role in the processing and comprehension of sentences with object relative clauses. In order to read and understand a sentence, people need to be able to store and process information at the same time, as it requires them to combine prior information provided in the sentence to make inferences and resolve long-distance dependencies (Oakhill & Cain, 2012). Working memory has been suggested as a key factor in the successful comprehension of object relative clauses (e.g. Gibson, 1998), and individuals with dyslexia often have deficits in short-term and working memory (Chiappe et al., 2000; Jeffries & Everatt, 2004).

With respect to verbal intelligence, reading requires a broad vocabulary in order to quickly extract the correct meaning of words, and in turn, the meaning of sentences. According to Perfetti (2007), low-quality lexical representations lead to comprehension difficulty because the lack of automatic and/or precise associations, either at the junction of orthography-phonology or phonology-semantics, which causes information necessary for integrating a word into its sentential context to be unavailable at the time when it is needed. Van Dyke et al. (2014) reported that offline comprehension of subject and object relatives was much more related to verbal intelligence than to working memory (see also Engelhardt et al., 2017). The same may also be true for individuals with dyslexia, who are often reported to have lower verbal intelligence (Stanovich, 1991; Vellutino, 1977). In summary, we expected individuals with dyslexia to show differences both in terms of comprehension and eye movements, and thus, our first goal of the study was to test whether this prediction holds for subject and object relatives.

Several studies have established that sentences containing object relatives are more difficult to comprehend than sentences containing subject relatives (Gordon et al., 2001; Staub, 2010; Traxler et al., 2002). The difficulty can be manipulated by several factors, such as animacy and semantic similarity of the noun phrases occurring in the sentence (Gennari & MacDonald, 2008, 2009; Gordon et al., 2001; Gordon, Hendrick, & Johnson, 2004; Traxler, Williams, Blozis, & Morris, 2005), as well as by the fact that object relative as much less common than subject relatives (Roland et al., 2007). According to Gibson's (1998) Syntactic Prediction Locality Theory (SPLT), which emphasises memory processes, it is predicted that while processing a sentence with a relative clause, more difficulty should arise at the relative clause **verb** (e.g. *passed* in a sentence like *The fisherman that the hiker passed carried the heavy gear*) (Grodner & Gibson, 2005; Levy, 2008). On the other hand, a probabilistic expectation-based account (e.g. Hale, 2001), which focuses on experience- and frequency-based expectations, predicts earlier difficulty at the relative clause **noun** (e.g. *hiker* in the previous example). These differential predictions are important for two reasons. The first is that the source of the processing difficulty is distinct. One class of theory assumes working memory demands are the key factor, while the other assumes that difficulty arises from a violation of predictive expectation. The second reason is that the theories make different predictions about where processing difficulty should be incurred.

Eye movement studies on object and subject relatives have reported an increased number of regressions and longer reading times for object relatives compared to subject relatives (Gordon, Hendrick, Johnson, & Lee, 2006; Traxler et al., 2002, 2005). Expanding on previous eye-tracking studies, Staub (2010) reported, in a study that more closely resembled normal reading, that sentences with object relatives took longer to read than sentences with subject relatives. In particular, he showed elevated reading times at the relative verb and increased regressions from the relative noun. Based on this pattern, Staub concluded that both “classes” of theories were partially correct (i.e. difficulty at the noun was in the form of increased regression, consistent with violation of expectation, and difficulty at the verb was in the form of elevated reading times, consistent with memory retrieval once the verb was encountered).

Current Study

As mentioned in the opening paragraph, the main goals of the current study were (1) to investigate whether individuals with dyslexia have difficulty processing and comprehending subject and object relatives, and (2) to contribute to theoretical debates concerning both the source of processing difficulty associated with object relatives and also the location of that expected processing difficulty. In order to investigate the second goal of the study, we did two things. The first was that we monitored eye movements as participants read the sentence, which was not done in the Wiseheart et al. (2009) study. The second was that we administered several additional tasks in order to determine how individual differences in working memory (Chiappe et al., 2000) and verbal intelligence (Hulme & Snowling, 1992; Vellutino, 1977) were related to both online and offline processing measures.

Table 1

Example stimuli showing object and subject relative clauses, and comprehension questions

Object Relative
The fisherman that the | **hiker** | **passed** | carried heavy gear.
Comprehension Questions
Did the hiker pass the fisherman? (correct answer = Yes)
Did the fisherman pass the hiker? (correct answer = No)
Subject Relative
The fisherman that | **passed** | the | **hiker** | carried heavy gear.
Comprehension Questions
Did the fisherman pass the hiker? (correct answer = Yes)
Did the hiker pass the fisherman? (correct answer = No)

Note. Bolded words show key regions of interest (hiker = relative noun, passed = relative verb). Words were not bolded in the experiment.

The current study included a sentence-processing task that assessed comprehension of subject and object relatives (see Table 1). We also administered a battery of cognitive measures, which assessed both verbal intelligence and working memory. Analyses focused on whether there were differences in the eye movement measures between participants with dyslexia and controls, and whether there were effects of verbal intelligence and working memory on comprehension and reading times. We expected participants with dyslexia to show poorer comprehension compared to controls, as well as to show differential eye movement patterns. More specifically, we expected to see longer reading times, more regressions, and longer regression path durations in dyslexic participants in the key regions of the relative clause. Regarding the theoretical psycholinguistic debate, Gibson's (1998) SPLT predicts difficulty at the verb in an object relative, as there is a ''storage cost" that slows processing while the long-distance dependency is unresolved. In contrast, expectation-based theories (e.g. Hale, 2001 and Gennari & MacDonald, 2008) predict difficulty at the relative noun. Thus, we focused our eye movement analyses on the relative verb and relative noun in the relative clause (Traxler et al., 2002). If we find more processing difficulty at either the noun or the verb, then this would provide support for the theory that predicts difficulty at each location. Moreover, because we assessed individual differences in verbal intelligence and working memory, we were in a position to provide additional confirmatory evidence to support the underlying factors responsible for the processing difficulty associated with object relatives.

Method

Participants

Fifty adults with self-reported dyslexia were recruited via advertisements and 50 undergraduate psychology students were tested as typically-developing control participants.[6] Both groups were recruited from the campus of the University of East Anglia. All participants with dyslexia verified that they had diagnostic assessments for dyslexia in the past. All were native speakers of British English with normal or corrected-to-normal vision. Dyslexics were reimbursed with £16 for their time, and controls were compensated with participation pool credits. Demographic information about the two groups is provided in Table 2, as are the means for the individual differences variables. Table 3 shows the correlations between the demographic variables, the individual differences variables, and comprehension accuracy for subject and object relatives.

Standardised Measures

Rapid automatised naming. All participants completed both a letter and a number RAN test (Denckla & Rudel, 1976) using the Comprehensive Test Of Phonological Processing (CTOPP 2). The RAN task requires participants to name a series of letters or numbers sequentially out loud as quickly and accurately as possible. The time taken to complete an array was recorded with a stopwatch. Participants completed one letter array for practice, and two served as the critical trials (i.e. one letter array and one number array). The score for each task was the total time that was needed to complete the task, with higher scores indicating worse performance. Each array consisted of four rows of nine items. Letters and numbers

[6] Dyslexic and control participants were also screened for ADHD symptoms. Self-reported ADHD symptoms (for both controls and dyslexics) were assessed with the Conners Adult ADHD Rating Scale (CAARS) (Barkley & Murphy, 1998; Conners, Erhardt, & Sparrow, 1999).

were presented in Arial font, and all items appeared on the same side of a white sheet of A4 paper. The standardised procedures of administration for this task were followed as described in the test manual. Independent samples *t*–tests revealed significantly longer naming times for the dyslexic group on both the letter and number array (see Table 2). The reliability of the CTOPP-2 subtests have been demonstrated by average internal consistency that exceeds .80 (R. K. Wagner et al., 2013).

Table 2

Means and standard deviations for demographic variables, the Rapid Automatised Naming task, and the individual differences variables.

Variable	Controls (N = 50) Mean (SD)	Dyslexia (N = 50) Mean (SD)	*t-value*
Age (years)	20.31 (1.22)	21.7 (2.67)	$t(98) = 3.34$***
Gender (% male)	8.0	34.0	$t(98) = 3.33$***
Handedness (% left)	12.0	10.0	$t(98) = -.317$
RAN Letters (seconds)	12.46 (2.59)	16.50 (6.20)	$t(98) = 4.25$***
RAN Numbers (seconds)	11.44 (2.43)	15.26 (5.29)	$t(98) = 4.64$***
Similarities	93.5(8.65)	98.8(11.76)	$t(98) = -2.57$*
Vocabulary	99.9(9.18)	101.3(9.02)	$t(98) = -.77$
Comprehension	93.5(10.70)	94.3(9.31)	$t(98) = -.40$
Verbal Skills (latent)	-.152(.98)	.152(1.00)	$t(98) = -1.53$
Rotation Span	17.7(7.23)	16.9(8.04)	$t(98) = .51$

Note. *$p < .05$, **$p < .01$, ***$p < .001$

Table 3

Correlations between demographics, individual difference variables, and comprehension

Variable	1	2	3	4	5	6	7	8	9
1. Age	-	.35**	.32**	-.18	-.17	.16	.04	.10	.13
2. Gender		-	.32**	-.24*	-.19	.13	.30**	.11	.10
3. Dyslexia Status			-	.42**	.40**	-.05	.15	.05	-.07
4. RAN Numbers				-	.92**	-.40**	-.05	-.18	-.11
5. RAN Letters					-	-.31**	-.07	-.16	-.05
6. Rotation Span						-	-.04	.17	.18
7. Verbal Intelligence							-	.30**	.04
8. Object Relative								-	.20*
9. Subject Relative									-

Note. **p* < .05, ***p* < .01. Gender coded 0 = female and 1 = male. Dyslexia coded 1 = dyslexic and 0 = control

Working memory. A rotation span task was used as a measure of working memory, as it has been shown to assess both processing and storage functions (Daneman & Carpenter, 1980; Unsworth, Heitz, Schrock, & Engle, 2005). Participants were required to look at a rotated letter and then verify whether or not the letter is facing in the correct direction or not (mirrored). After each letter, participants were presented with an isolated arrow which was either long or short and could be facing eight different directions (0° – 360°). The position and length of the arrows presented needed to be recalled at the end of the set. The task consisted of 15 trials (six each of list length 2 and three each of list lengths 3-5) and in total 48 arrow-storage pairs (Unsworth et al., 2005). The rotation span task was developed by Engle's Working Memory Laboratory, and reported reliability ranging between .67 and .77 for the rotation span (Conway et al., 2005).

The working memory task for this study was different from the tasks used in the study presented in Chapter 2, due to the fact that we wanted to ensure that dyslexic participants' phonological processing deficit was not affecting their performance in the working memory tasks. So we selected to use the rotation span instead of the reading span and the tasks from the WAIS-IV, as it does not include any reading or word identification components.

Verbal Intelligence. Verbal intelligence was measured by the following subtests of the fourth edition of the Wechsler Adult Intelligence Scale (WAIS-IV) (Wechsler, 2014): vocabulary, comprehension, and similarities. In the comprehension task, participants were required to respond to questions about general concepts (e.g. reasons to protect endangered species). Vocabulary requires participants to provide the definitions of words and measures the degree to which one has learned and is able to express meanings verbally. Similarities requires participants to describe how two words are similar, with the more difficult items typically describing the opposite ends of a "unifying continuum". The similarities subtest measures abstract verbal reasoning (Engelhardt et al., 2017). For all subtests, higher values correspond to higher verbal intelligence and the score for each of these tasks was the total number of items that the participants could identify accurately. The standardised procedures of administration for these subtests were followed as described in the test manual. With respect to the reliability of the WAIS-IV, the manual reports average internal reliability coefficients for subtests that range from .78 to .94 (Benson et al., 2010).

Sentence Processing

To investigate subject and object relatives, we used 20 sentences based on the items in Traxler et al. (2002). Each participant read 10 sentences containing object relative clauses and 10 containing subject relative clauses. Items were rotated in a Latin Square Design. All 20 critical items were rotated across two counterbalance lists, with object relatives changing to subject relatives and vice versa (see Table 1). Ten sentences with relative clauses required a "yes" response and 10 required a "no" response. All questions for sentences with relative clauses rotated across four counterbalance lists, with changing accordingly to require a "yes" or "no" response and vice versa for each version of every item.

Participants also read 120 filler sentences. All filler sentences were grammatically correct. They consisted of five sets of 16 sentences. The first set were subordinate-main structures in which the subordinate clause was transitive. The second set were main-subordinate sentences. The third set were transitive sentences containing a relative clause at the end of the sentence. The fourth set were transitive sentences that contained an embedded relative clause that modified the subject noun phrase. The fifth set were coordination structures, in which two transitive sentences were conjoined with *and*. Half of these had a comma between *and* and the preceding word and half did not. In addition, there were also 20 active and passive sentences. Half of these were implausible and half were plausible. There were also 20 sentences containing a subject or object relative clause following the main clause. Therefore, each participant read 140 sentences in total. Fifty-eight filler questions required a "yes" response and 62 required a "no" response.

Apparatus

Eye movements were recorded with an SR Research Ltd. EyeLink 1000 eye-tracker which records the position of the reader's eye every millisecond. Head movements were minimised with a chin rest. Eye movements were recorded from the right eye. The sentences were presented in 12 pt. Arial black font on a white background.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 (Type × Group) mixed design, in which "type" was within subjects, and "group" was between subjects. Participants completed three practice trials, 20 experimental trials, and 120 fillers. Trials were presented in a random order for each participant.

Participants were provided with a set of instructions that detailed the experimental procedure. They were then seated at the eye tracker and asked to respond to on-screen instructions using the keyboard. At the beginning of each trial, a message appeared asking the participant to press a button when they were ready to continue. After the participant pressed the button, they were required to fixate a drift-correction dot. The experimenter then initiated the trial. The sentence appeared after 500 ms, and the initial letter of each sentence was in the same position, in terms of x and y coordinates, as the drift correction dot (i.e. on the left edge of the monitor and centred vertically).

The entire sentence was presented on a single line on the screen. The participant read the sentence silently and then pressed the spacebar on the keyboard. Following a delay of 500 ms, an arithmetic problem (either addition or subtraction) appeared on the screen (e.g. 45 + 67 = 112). The problem was presented for 3000 ms and was followed by a screen prompting the participant to press the green button on the keyboard if the solution was correct, or the red button if it was incorrect. After participants read the sentence, they were asked a comprehension question, such as *"Did hiker pass the fisherman?"*. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were ten items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was α = .34.

The rationale for including the additional arithmetic problem was the fact that we wanted to assess the representation that comprehenders generated of the sentences, without allowing them to have direct access to the sentence. We expected that the presence of the mathematical problem would clear the immediate contents of working memory, therefore resulting in the participants responding to the comprehension questions on the basis of a more long-term representation/trace of the sentence.

The testing session for each participant lasted approximately 2 hours, with several breaks included between tasks to avoid fatigue. The tests were delivered in the following order for each participant: vocabulary, rotation span, comprehension, sentence processing, RAN digits, RAN letters and similarities.

Data Screening and Analysis

In order to keep the analyses as straightforward as possible we submitted the verbal intelligence subtests to a factor analysis in which we saved the retained factor as variable. The factor analysis produced only a single factor, and thus, we used this composite (or latent) variable in our analyses examining "individual differences".

We analysed the comprehension and eye movement data using standard ANOVAs with subjects (*F*1) and items (*F*2) as random effects. *First pass reading time* is the sum of all fixations on a word from when a reader first enters a region to when they leave that region either forward or backward. *Total reading time* is the sum of all fixations on a word. *Regressions* out of an interest area are the sum of all right-to-left eye movements to previously read word. *Regression path duration* is the sum of all fixations from the time the eyes first enter a region until they move beyond that region in a forward direction. We analysed data from two main regions of interest, which included the relative clause verb and the relative noun (see Table

1). We first report the comprehension results, and second, the eye movements. To assess verbal intelligence and working memory, we conducted two additional ANCOVAs in which each variable was co-varied separately.

Results

Comprehension Accuracy

The mean comprehension accuracies are presented in Figure 1, and the results of the inferential analyses are presented in Table 4. Results showed a main effect of type, in which the subject relatives had higher comprehension than did object relatives. When verbal intelligence was included in the model, it produced a main effect and interacted with type. The form of the interaction is shown in Figure 2. As can be seen, verbal intelligence was positively related to comprehension of object relatives, such that, individuals with lower verbal intelligence showed many more incorrect responses for object relatives. In contrast, with subject relatives there was not much of an effect of verbal intelligence. When working memory was included in the model, it produced a significant main effect and the main effect of type was no longer significant. This pattern of results suggests overlapping variance between individual differences in working memory and comprehension. That is, when variance in working memory was removed, then the difference in comprehension between subject and object relatives is no longer significant. To ensure the direction and the strength of the relationship between working memory and comprehension, we ran the correlations between working memory and subject relatives, and between working memory and object relatives. In both cases, the relationship was positive, and for the subject relatives, the correlation was significant ($r = .20$, $p < .05$). For object relatives, the correlation was similar ($r = .17$, $p = .098$) but not significant. In the comprehension, there was no effect of group (i.e. control vs. dyslexia), which suggests that the individuals with dyslexia are not worse at comprehending these particular types of sentences (cf. Wiseheart et al., 2009).

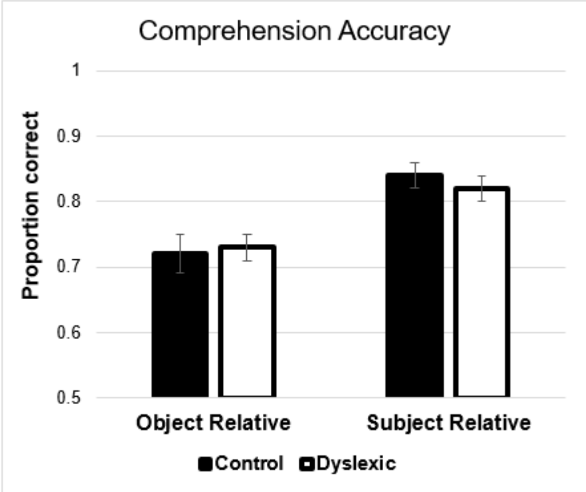

Figure 1. Mean comprehension accuracy. Error bars show the standard error of the mean.

Table 4

Inferential results for comprehension accuracy

2 x 2 (Type x Group)	
Type	$F(1,98) = 29.69, p < .001, \eta_p^2 = .23$
Group	$F(1,98) = .01, p = .97$
Type x Group	$F(1,98) = .78, p = .38$
ANCOVA – with Verbal IQ	
Type	$F(1,97) = 31.16, p < .001, \eta_p^2 = .24$
Group	$F(1,97) = .18, p = .67$
Verbal IQ	$F(1,97) = 6.23, p < .05, \eta_p^2 = .06$
Type x Group	$F(1,97) = .28, p = .60$
Type x Verbal IQ	$F(1,97) = 5.84, p < .05, \eta_p^2 = .06$
ANCOVA – with WM	
Type	$F(1,97) = 6.18, p < .05, \eta_p^2 = .06$
Group	$F(1,97) = .01, p = .94$
Working Memory	$F(1,97) = 4.98, p < .05, \eta_p^2 = .05$
Type x Group	$F(1,97) = .80, p = .37$
Type x Working Memory	$F(1,97) = .12, p = .73$

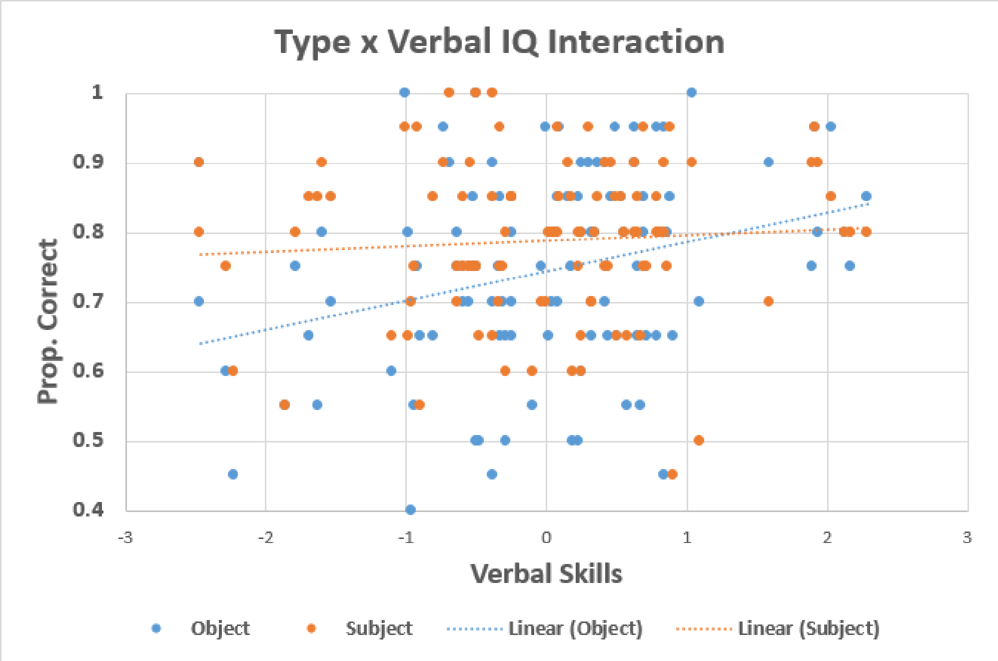

Figure 2. Sentence “Type” by verbal intelligence interaction.

Eye Movements – Relative Verb

Reading Times. The means for the eye movement measures are presented in Table 5, and the results of the inferential analyses are presented in Table 6. Results showed a largely consistent pattern for both first pass reading times and total reading times. There were main effects of type and group, in which object relatives had higher reading times than did subject relatives, and likewise, individuals with dyslexia had higher reading times than did controls. The mean difference between subject and object relatives was 38 msec on first pass and 141 msec on total reading time. For group, the mean difference between controls and dyslexics was 44 msec on first pass reading times and 291 msec on total reading times. When verbal intelligence was included, the same pattern of results emerged, and verbal intelligence was not significant and did not interact with sentence type. When working memory was included in the model, the main effect of type remained significant only for the total reading times and the main effect of group remained unchanged in both measures. What this pattern tells us, similar to comprehension accuracy, is that when variance in working memory is removed, the processing difficulty between subject and object relatives disappeared for first pass reading times (i.e. there is overlapping variance between reading times and individual differences in working memory).

Table 5

Mean reading times clause by group and experimental condition – relative verb.

	First Pass RT		Total RT		Reg. Out		Reg. Path	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*S*
Relative Verb								
Controls								
OR centre	320.5	73.5	867.2	299.1	.24	.18	597.9	310.3
SR centre	291.9	61.1	703.8	262.9	.26	.16	504.4	195.5
Dyslexics								
OR centre	374.6	110.1	1134.9	492.5	.28	.14	762.5	340.2
SR centre	326.5	95.3	1015.6	465.9	.32	.16	696.8	311.0
Relative Noun								
Controls								
OR centre	257.2	49.4	655.5	281.6	.23	.16	474.1	182.6
SR centre	280.9	75.5	524.2	165.1	.17	.17	445.8	221.7
Dyslexics								
OR centre	255.0	67.3	820.6	460.6	.28	.17	668.2	361.7
SR centre	300.1	82.3	760.9	341.6	.21	.13	593.6	307.7

Regressions. For regressions out of the relative verb, there were no significant effects. Across all trials, we observed that there were approximately one-in-four to one-in-three trials with a regression. For regression path durations, results showed that both the main effect of type and group were significant and remained significant with the inclusion of both covariates. Object relatives had approximately 79 msec longer regression paths than did subject relatives, and dyslexics had approximately 179 msec longer regression paths than did controls.

We also observed a main effect of verbal intelligence, and the pattern was such that individuals with higher verbal intelligence had shorter regression path durations. The correlation between object relatives and verbal intelligence was marginally significant (r = -.19, p = .06) and for subject relatives it was not significant (r = -.11, p = .26).

Table 6

Mixed ANCOVA analysis for eye movement measures for the relative verb

	First Pass RT	Total RT	Reg. Out	Reg. Path
2 x 2 (Type x Group)				
Type	$F(1,98) = 15.10, p < .001, (.13)$[a]	$F(1,98) = 19.18, p < .001, (.16)$[a]	$F(1,98) = 2.16, p = .15$	$F(1,98) = 7.45, p < .01, (.07)$[a]
Group	$F(1,98) = 9.56, p < .01, (.09)$[a]	$F(1,98) = 16.33, p < .001, (.14)$[a]	$F(1,98) = 3.26, p = .07$	$F(1,98) = 12.16, p < .01, (.11)$[a]
Type x Group	$F(1,98) = .97, p = .33$	$F(1,98) = .47, p = .50$	$F(1,98) = .61, p = .44$	$F(1,98) = .23, p = .64$
ANCOVA – with Verbal IQ				
Type	$F(1,97) = 15.08, p < .001, (.14)$[a]	$F(1,97) = 18.98, p < .001, (.16)$[a]	$F(1,97) = 2.15, p = .15$	$F(1,97) = 7.45, p < .01, (.07)$[a]
Group	$F(1,97) = 9.98, p < .01, (.09)$[a]	$F(1,97) = 16.03, p < .001, (.14)$[a]	$F(1,97) = 3.49, p = .07$	$F(1,97) = 15.28, p < .001, (.14)$[a]
Verbal IQ	$F(1,97) = .53, p = .47$	$F(1,97) = .04, p = .85$	$F(1,97) = .34, p = .56$	$F(1,97) = 6.04, p < .05, (.06)$
Type x Group	$F(1,97) = .69, p = .41$	$F(1,97) = .42, p = .52$	$F(1,97) = .39, p = .54$	$F(1,97) = 1.00, p = .76$
Type x Verbal IQ	$F(1,97) = .89, p = .35$	$F(1,97) = .02, p = .88$	$F(1,97) = .92, p = .34$	$F(1,97) = 1.07, p = .31$
ANCOVA – with WM				
Type	$F(1,97) = 3.08, p = .08$	$F(1,97) = 6.01, p < .05, (.06)$[a]	$F(1,97) = .07, p = .79$	$F(1,97) = 8.07, p < .01, (.08)$
Group	$F(1,97) = 9.20, p < .01, (.09)$	$F(1,97) = 16.04, p < .001, (.14)$[a]	$F(1,97) = 3.23, p = .07$	$F(1,97) = 11.76, p < .01, (.11)$
Working Memory	$F(1,97) = 1.42, p = .24$	$F(1,97) = .06, p = .81$	$F(1,97) = .00, p = .97$	$F(1,97) = 1.28, p = .26$
Type x Group	$F(1,97) = .94, p = .34$	$F(1,97) = .52, p = .47$	$F(1,97) = .68, p = .41$	$F(1,97) = .34, p = .56$
Type x Working Memory	$F(1,97) = .05, p = .82$	$F(1,97) = .59, p = .45$	$F(1,97) = .88, p = .35$	$F(1,97) = 3.58, p = .06$

Note. Effect sizes η_p^2 are reported in parentheses. [a] indicates significant in F2 item analysis (see Appendix Table A).

Table 7

Mixed ANCOVA analysis for eye movement measures for the relative noun.

	First Pass RT	Total RT	Reg. Out	Reg. Path
2 x 2 (Type x Group)				
Type	$F(1,98) = 24.57, p < .001$, (.20)[a]	$F(1,98) = 13.30, p < .001$, (.12)[a]	$F(1,98) = 9.81, p < .01$, (.09)[a]	$F(1,98) = 4.08, p < .05$, (.04)
Group	$F(1,98) = .50, p = .48$	$F(1,98) = 10.70, p < .01$, (.10)[a]	$F(1,98) = 2.59, p = .11$	$F(1,98) = 12.03, p < .01$, (.11)[a]
Type x Group	$F(1,98) = 2.38, p = .13$	$F(1,98) = 1.87, p = .18$	$F(1,98) = .02, p = .90$	$F(1,98) = .83, p = .37$
ANCOVA – with Verbal IQ				
Type	$F(1,97) = 24.53, p < .001$, (.20)[a]	$F(1,97) = 13.24, p < .001$, (.12)[a]	$F(1,98) = 9.81, p < .01$, (.09)[a]	$F(1,97) = 4.05, p < .05$, (.04)
Group	$F(1,97) = .55, p = .46$	$F(1,97) = 10.45, p < .01$, (.10)	$F(1,97) = 2.67, p = .11$	$F(1,97) = 13.74, p < .001$, (.12)[a]
Verbal IQ	$F(1,97) = .09, p = .77$	$F(1,97) = .01, p = .91$	$F(1,97) = .12, p = .74$	$F(1,97) = 2.67, p = .11$
Type x Group	$F(1,97) = 1.91, p = .17$	$F(1,97) = 1.52, p = .22$	$F(1,97) = .00, p = .99$	$F(1,97) = .65, p = .42$
Type x Verbal IQ	$F(1,97) = .87, p = .35$	$F(1,97) = .58, p = .46$	$F(1,97) = .95, p = .33$	$F(1,97) = .35, p = .55$
ANCOVA – with WM				
Type	$F(1,97) = 7.18, p < .01$, (.07)[a]	$F(1,97) = 4.37, p < .05$, (.04)[a]	$F(1,97) = 6.41, p < .05$, (.06)	$F(1,97) = 4.04, p < .05$, (.04)
Group	$F(1,97) = .42, p = .52$	$F(1,97) = 10.42, p < .01$, (.10)[a]	$F(1,97) = 2.43, p = .12$	$F(1,97) = 11.64, p < .01$, (.11)
Working Memory	$F(1,97) = 1.14, p = .29$	$F(1,97) = .25, p = .62$	$F(1,97) = .87, p = .35$	$F(1,97) = 3.42, p = .07$
Type x Group	$F(1,97) = 2.25, p = .14$	$F(1,97) = 1.95, p = .17$	$F(1,97) = .00, p = .95$	$F(1,97) = .71, p = .40$
Type x Working Memory	$F(1,97) = .58, p = .45$	$F(1,97) = .48, p = .49$	$F(1,97) = 1.93, p = .17$	$F(1,97) = 1.71, p = .19$

Note. Effect sizes η_p^2 are reported in parentheses. [a] indicates significant in F2 item analysis (see Appendix Table B).

Table 8

Bivariate correlations between individual differences variables, comprehension, and eye movement measures.

	Object Relative				Subject Relative			
	First Pass	Total RT	Reg. Out	Reg. Path	First Pass	Total RT	Reg. Out	Reg. Path
Relative Verb								
Dyslexia Status	.28**	.32**	.11	.25*	.21*	.38**	.19	.35**
Verbal Intelligence	.04	.03	-.09	-.19	-.09	.05	.04	-.11
Working Memory	-.11	-.07	-.06	-.18	-.10	-.01	.05	-.02
Comp. Object	.14	.09	.02	.01				
Comp. Subject					-.07	.23*	.11	.01
Relative Noun								
Dyslexia Status	-.02	.21*	.13	.32**	.12	.40**	.13	.27**
Verbal Intelligence	-.09	.00	.05	-.06	.04	.08	-.07	-.13
Working Memory	-.06	-.07	-.16	-.22*	-.12	-.04	.01	-.12
Comp. Object	-.05	.06	-.13	-.16				
Comp. Subject					.07	.16	.14	.11

Note. *$p < .05$, **$p < .01$.

Eye Movements – Relative Noun

Reading Times. The means for the eye movement measures are presented in Table 5 and the results of the inferential analyses are presented in Table 7. Results showed some similarities to the patterns that were observed at the relative verb, this is especially true of the total reading times, which were identical. In contrast, in first pass reading time, there was no significant effect of group, but there was a consistent group effect on total reading times. Participants with dyslexia had approximately 200 msec longer total reading times than did controls, and this effect remained significant with the inclusion of both verbal intelligence and working memory. Similar to results at the relative verb, the main effect of type was not significant when working memory was included in the model. Again, suggesting some overlapping variance between individual differences in working memory and the difficulty incurred in processing object relatives compared to subject relatives.

Regressions. For regressions out of the relative noun, there was only a significant effect of type, regressions were more frequent from object relatives compared to subject relatives. This effect held when verbal intelligence was included in the model but not working memory. Across all trials, we observed slightly fewer regressions from the relative noun. In this case, there were approximately one-in-five to one-in-four trials with a regression. The pattern of results in regression path durations was similar to total reading times at the relative noun and first pass and total reading times at the relative verb. There were significant main effects of type and group. Group was robust to the inclusion of both covariates and the same was the case for the main effect of type.

Finally, the correlations between the eye movement measures and several of the individual differences measures and comprehension (see Table 8), revealed only one significant correlation between eye movements and comprehension. The total reading time on the relative verb (in subject relative sentences) correlated with comprehension accuracy. For object relatives there were no significant correlations, and in fact, there were two that were in the opposite direction of what would be expected by more processing effect resulting in better comprehension. Those two negative correlations occurred at the relative noun for regressions out (-.13) and regression path duration (-.16).

Discussion

In this study, we examined how dyslexic and non-dyslexic adults comprehend and process sentences with complex syntax, and specifically, sentences that contain subject and object relative clauses. We were interested in whether individuals with dyslexia show deficits in comprehension and how their eye movement behaviour differed from control participants. We also explored the impact of two individual differences variables (i.e. working memory and verbal intelligence) as potential key individual difference variables in the processing of subject and object relative clauses. A second goal of the study was to contribute to theoretical debates on both the location of processing difficulty and the cause of processing difficulty, associated with object relatives. Here the choice of dyslexia was key, as individuals with dyslexia often have lower working memory, and in one recent study, were reported to have deficits in linguistic prediction (Huettig & Brouwer, 2015). Thus, individuals with dyslexia are assumed to have deficits in the two "sources" of processing difficulty proposed by the competing psycholinguistic theories (e.g. Gibson, 1998 vs. Hale, 2001). In this case, the goal was to use a clinical population to inform theoretical debate.

To summarise our main findings with respect to dyslexia, we found that individuals with dyslexia had similar comprehension accuracy to controls, which is inconsistent with another study that investigated these types of sentences in dyslexia (i.e. Wiseheart et al., 2009). Despite the fact that dyslexics showed similar comprehension to controls, they spent significantly longer reading the sentences. More specifically, our results with respect to eye movements showed that the dyslexics showed longer first pass reading times, longer total reading times, and longer regression path durations. These findings occurred for both regions of interest, except that the group difference in first pass reading times was not significant at the relative noun.

In addition, there were no significant group effects in terms of regressions out of the regions of interest, and group did not interact with any of the other variables (i.e. type, verbal intelligence, or working memory). Thus, individuals with dyslexia spent longer reading than did controls, and ultimately, achieved very similar performance in terms of comprehension accuracy. Finally, in this study, neither of the individual difference variables were related to the group effect (i.e. dyslexia appeared to have an independent effect on the time spent reading independent of individual differences in verbal intelligence and working memory).

Processing Relative Clauses in Dyslexia

In the field of psycholinguistics, the vast majority of research on the processing of subject and object relative clauses has been conducted on typically-developing samples (e.g. Andrews, Birney, & Halford, 2006; Gennari & MacDonald, 2008, 2009). In the Introduction, we reviewed the results from the only other paper to examine the comprehension of subject and object relatives in dyslexia (i.e. Wiseheart et al., 2009). Our results were largely inconsistent with that study, as we did not find differences in terms of comprehension.

There are several differences between the two studies that may account for the differences in comprehension. The most important difference is the experimental paradigm, as Wiseheart et al. (2009) used a picture-sentence verification task in which two pictures were available on the screen with the sentence. Wiseheart et al. (2009) found worse comprehension in individuals with dyslexia, but generally higher accuracy than what we reported. In short, in Wiseheart et al. (2009), the comprehension decision was made when the sentence was still visible. In contrast, in our paradigm there was an intervening maths problem and participants were answering very specific comprehension questions, regarding thematic roles and the association of specific nouns with specific verbs.

This difference in the two paradigms could potentially explain some of the disparity in the findings of the two studies. The generally higher accuracy in Wiseheart et al. (2009) than the one we reported could be explained by the fact that participants in Wiseheart et al.'s (2009) study selected the comprehension response while the sentence was visible which could allow for further revision of the sentence before choosing a comprehension response. The second difference concerns the sample, in our study participants were all university students, and in Wiseheart et al. (2009), participants were younger and that sample also showed differences in working memory. The age discrepancy is important because our participants may have more exposure to complex syntax given their enrolment in higher education.

Due to the multiple differences in the method and paradigms used in the two studies, apart from the type of sentences examined, it is very difficult to make meaningful comparisons that could help us reach a definitive conclusion about the processing of relative clauses in dyslexia. Future work is essential in order to address the differences between what we have reported and those reported by Wiseheart et al. (2009). Careful consideration of the participant sample and the experimental paradigm will be critically important.

In this study, the performance of the non-dyslexic participants was very much in line with Staub's (2010) study, as well as Gibson's (1998) SLP theory. They showed more difficulties in comprehending object relatives compared to subject relatives and these difficulties mainly arose at the relative verb. This highlights the association of our findings with the importance of working memory processes during reading of sentences with relative clauses in general. It is also important to mention that controls showed longer reading times compared to the reading times in other studies on sentences with relative clauses (i.e. Traxler et al., 2002; Wiseheart et al., 2009), which could be a result of the additional difficulty of the sentences we examined. All relative clauses within the sentences were centre-embedded and previous studies have suggested that compared to right-branching relative clauses, centre-embedded ones tend to require further revision (Staub, 2010; Traxler et al., 2002).

As we mentioned in our results summary, individuals with dyslexia are assumed to have deficits in the two "sources" of processing difficulty proposed by the competing psycholinguistic theories (e.g. Gibson, 1998 vs. Hale, 2001). In this case, the goal was to use a clinical population to inform theoretical debate. Overall our eye movement and individual differences analysis supports theories of processing difficulty that assume difficulty is linked with memory-based processing (e.g. Gibson, 1998), rather than surprisal (Hale, 2001; Levy, 2008). More specifically, our findings about the fact that both dyslexics and non-dyslexics have more difficulty comprehending object relatives are more associated with Gibson's (1998) SPL theory. This focuses on the working memory procedures that are key in processing sentences with object relative clauses and in our study all participants showed elevated reading times at the relative clause verb, which is in line with Gibson's (1998) theory.

In general, individuals with dyslexia showed even longer reading times compared to controls, and those differences were not accounted for by individual differences in working memory or verbal intelligence. Thus, on the basis of our findings, we believe that much more of the processing difficulty incurred with object relatives is due to memory-based processes, and in particular holding the extracted constituent in memory rather than retrieving the constituent at the moment the relative verb in encountered.

Our data from Chapter 2 highlighted the differences in working memory between the two groups, as well as the importance of working memory as a cognitive factor in the comprehension and processing of garden path sentences. However, in Chapter 3, the dyslexic group did not appear to be impaired on working memory compared to the control group. Despite the similarities in working memory and comprehension between the two groups in this study, the significantly longer reading times for dyslexics, especially in object relatives, could be associated with the bottleneck in working memory processes and could be further linked to our findings presented in Chapter 2. More specifically, the fact that the processing difficulty in object relatives is particularly due to the delay in retrieving the extracted constituent when the relative verb is encountered could be resulting in the dyslexics needing to spend more time reading these sentences. Our dyslexic group spent more time reading the sentences with object relative clauses due to their bottleneck in working memory, but the longer reading times allowed them to respond accurately to the comprehension questions.

Eye Movements in Relative Clause Region

Recall that Staub (2010) reported a dissociation in the eye movements occurring in the relative noun and relative verb. More specifically, he found an increase in the number of regressive eye movements but no increase in first pass reading times at the noun, and elevated first pass reading times but not an increase in the number of regressive eye movements at the verb (Lewis & Vasishth, 2005; Staub, 2010). On the basis of this dissociation, Staub concluded that both theoretical accounts (i.e. memory-based vs. expectation-based) were partially correct and both contribute to the processing of relative clauses (e.g. Gennari & MacDonald, 2008; Gordon et al., 2001; Just & Carpenter, 1992; MacDonald & Christiansen, 2002;

Reali & Christiansen, 2007; Waters & Caplan, 1996). Moreover, Staub speculated that the dissociation in eye movement patterns may reflect different underlying processing effects. An increase in fixation durations reflects processing difficulty that eventually succeeds, and an increase in regressions reflects processing difficulty that has failed (Gordon et al., 2006; Traxler et al., 2002, 2005).

Comparing Staub's findings to ours, reveals some striking similarities, but also some differences. At the relative verb, we found effects of type on all three fixation "duration" measures (i.e. first pass reading time, total reading time, and regression path duration). The key finding of our study concerning processing difficulty at the relative noun, which is particularly difficult to reconcile with Staub's study is that in our data, processing difficulty at the noun seemed to be clearly linked to individual differences in working memory. It is also worth mentioning that we found that dyslexics in this study, were slightly higher for both regressions and first pass reading times at the relative noun in subject relatives, which is in line with Staub's findings. Therefore, we did not observe nearly as high a rate of regressions from the relative noun, despite the difference being statistically significant.

Limitations and Future Directions

One of the main strengths of this study is the fact that we assessed the performance of a large number of participants on a variety of different tasks. However, because our sample of dyslexics was recruited through a university, they were quite high functioning. This is potentially problematic because often individuals with dyslexia do not go on to higher education. It remains to future work to determine if a sample of community-recruited dyslexics achieves similar performance in terms of comprehension accuracy and individual differences. Furthermore, our sample of dyslexics was potentially atypical, so far as they had similar working memory and verbal intelligence as the controls To assess working memory, we used a rotation span task, which did not include any literacy or reading components in order to avoid any additional difficulties for participants with dyslexia. However, we only had a single measure. In future, we would recommend using multiple measures of working memory, and also, including some that have linguistic component (e.g. reading span). Future work should also investigate the processing of subject and object relatives using some of the manipulations that have been investigated in the psycholinguistic literature (e.g. animate and inanimate nouns), which would allow future studies to examine how semantic issues affect dyslexic readers' comprehension of relative clause sentences (Gennari & MacDonald, 2009). We would also recommend for future research to include standardised reading, spelling or phonological awareness assessments as additional measures of participants' dyslexia diagnosis. Moreover, we suggest that dyslexia should be examined across the lifespan, which calls for further research on children and adolescents in order to investigate the processing of sentences prior to adulthood, as well as during the critical period of reading acquisition.

Conclusion

This study aimed first to investigate processing and comprehension of sentences that contain relative clauses in individuals with dyslexia. We found three main findings with respect to this aim, individuals with dyslexia (1) achieved similar performance in terms of comprehension accuracy, (2) showed significantly longer reading times, and (3) the effect of dyslexia was robust even when individual differences in verbal intelligence and working memory were controlled. The second main aim of the study was to contribute to the psycholinguistic debate concerning where and why processing difficulty occurs in object relatives as compared to subject relatives, and this aim focused exclusively on the eye movement results. Here our data was very clearly linked to individual differences in working memory, such that when variance in working memory was removed the differences between subject and object relatives was no longer significant. Moreover, working memory also accounted for the subject-object difference even at the relative noun, which refutes prior claims about processing difficulty at this word being linked to violations of expectations. Thus, overall our eye movement and individual differences analysis supports theories of processing difficulty that assume difficulty is linked with memory-based processing (e.g. Gibson, 1998), rather than surprisal (Hale, 2001; Levy, 2008).

Appendix

Table A

Mixed ANCOVA item analysis for eye movement measures for the relative verb

	First Pass RT	Total RT	Regressions Out	Regression Path
2 x 2 (Type x Group)				
Type	$F(1,19) = 13.67, p < .01$	$F(1,19) = 12.82, p < .01$	N.S.	$F(1,19) = 5.24, p < .05$
Group	$F(1,19) = 16.52, p < .01$	$F(1,19) = 48.97, p < .001$	$F(1,19) = 7.81, p < .05$	$F(1,19) = 50.03, p < .001$
Type x Group	N.S.	N.S.	N.S.	N.S.
ANCOVA – with Verbal IQ				
Type	$F(1,18) = 14.68, p < .01$	$F(1,18) = 25.96, p < .001$	N.S.	$F(1,18) = 7.36, p < .05$
Group	$F(1,18) = 11.90, p < .01$	$F(1,18) = 37.22, p < .001$	$F(1,18) = 6.05, p < .05$	$F(1,18) = 39.02, p < .001$
Verbal IQ	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Verbal IQ	N.S.	$F(1,18) = 8.91, p < .01$	N.S.	N.S.
ANCOVA – with WM				
Type	N.S.	$F(1,18) = 5.17, p < .05$	N.S.	N.S.
Group	N.S.	$F(1,18) = 6.49, p < .05$	N.S.	N.S.
Working Memory	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Working Memory	N.S.	N.S.	N.S.	N.S.

Table B

Mixed ANCOVA item analysis for eye movement measures for the relative noun

	First Pass RT	Total RT	Regressions Out	Regression Path
2 x 2 (Type x Group)				
Type	$F(1,19) = 21.44, p < .001$	$F(1,19) = 17.31, p < .01$	$F(1,19) = 9.16, p < .01$	N.S.
Group	N.S.	$F(1,19) = 39.50, p < .001$	$F(1,19) = 5.37, p < .05$	$F(1,19) = 27.28, p < .001$
Type x Group	N.S.	N.S.	N.S.	N.S.
ANCOVA – with Verbal IQ				
Type	$F(1,18) = 19.22, p < .001$	$F(1,18) = 18.02, p < .001$	$F(1,18) = 5.39, p < .05$	N.S.
Group	N.S.	$F(1,18) = 33.11, p < .001$	N.S.	$F(1,18) = 19.56, p < .001$
Verbal IQ	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Verbal IQ	N.S.	N.S.	N.S.	N.S.
ANCOVA – with WM				
Type	$F(1,18) = 5.21, p < .05$	$F(1,18) = 7.23, p < .05$	N.S.	N.S.
Group	N.S.	$F(1,18) = 8.03, p < .05$	N.S.	N.S.
Working Memory	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Working Memory	N.S.	N.S.	N.S.	N.S.

Chapter 4

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Use of parsing heuristics in the comprehension of passive sentences: Evidence from dyslexia

Abstract

This study examined the comprehension of passive sentences in order to investigate whether individuals with dyslexia rely on parsing heuristics in language comprehension to a greater extent than non-dyslexic readers. One hundred adults (50 dyslexics and 50 controls) read active and passive sentences, and we also, manipulated semantic plausibility. Eye movements were monitored while participants read each sentence, and afterwards, participants answered a comprehension question. We also assessed verbal intelligence and working memory. Results showed that comprehension errors were more frequent with passive sentences and with implausible sentences. Dyslexic participants had worse comprehension than controls. With respect to verbal intelligence and working memory, we found that individuals with lower verbal intelligence were significantly more likely to misinterpret implausible sentences, and individuals with lower working memory showed particularly difficulties with passive sentences that were implausible. These findings suggest that (1) individuals with dyslexia do not necessarily rely on heuristics to a greater extent than do non-dyslexic individuals, despite their poorer performance and (2) individual differences variables (e.g. verbal intelligence and working memory) **are** related to the use of parsing heuristics.

Introduction

Research into the comprehension of passive sentences has a long history in psycholinguistics (Clark, 1965; Gough, 1966; Herriot, 1969; Olson & Filby, 1972; Slobin, 1968), and has also been looked at developmentally (i.e. de Villiers & de Villiers, 1973; Hayhurst, 1967; Precious & Conti-Ramsden, 1988; Sinclair, Sinclair, & De Marcelus, 1971) and in clinical populations (e.g. aphasia). Passive sentences are interesting because they are syntactically more complex than actives, and violate the canonical subject-verb-object word order in English. With passive sentences the object comes first and the subject follows the verb, and relatedly, the thematic roles are also reversed (i.e. patient/theme sentence initial and agent sentence final).

These sentences have been most extensively used in the assessment of different types of aphasia. Individuals with Broca's aphasia tend to use different strategies to comprehend sentences compared to individuals with Wernicke's aphasia, due to the differential deficits associated with each type of aphasia (Friederici & Graetz, 1987). More specifically, patients with Wernicke's aphasia use general strategies for interpretation by assigning syntactic roles according to the sequential ordering of words. In contrast, Broca's aphasics tend to base their interpretation on specific structural elements in a sentence (Friederici & Graetz, 1987). These findings have also been extended to differences in the neural correlates of processing passive sentences (Mack, Meltzer-Asscher, Barbieri, & Thompson, 2013; Yokoyama et al., 2007).

Good Enough Comprehension

One prominent theory that has been offered to account for the fact that listeners often develop inaccurate representations in language comprehension is called "Good Enough" processing (Ferreira, Bailey, & Ferraro, 2002; Ferreira & Patson, 2007; Sanford & Sturt, 2002). According to this theory, listeners may generate an interpretation of an ambiguous or a temporarily ambiguous utterance that is not consistent with the actual input. Instead, the comprehension system has a tendency to generate shallow or superficial representations, and much of the time misinterpretations are consistent with the plausibility of events in the real world (Christianson et al., 2001; Ferreira et al., 2001). One of the main aims of the current study was to investigate whether readers with dyslexia rely on parsing heuristics (good-enough processing) to a greater extent than typically-developing individuals, and how they comprehend passive sentences more generally.

The vast majority of research on the comprehension of passive sentences has looked at whether listeners can correctly identify the thematic roles in the sentence. In one prominent study, Ferreira (2003) conducted three experiments in which participants listened to sentences in active and passive voice, and were either semantically plausible or semantically implausible. Participants were asked to identify one of the thematic roles in the sentence (e.g. *Who was the agent in the sentence?*). Ferreira's results showed that passive sentences were misinterpreted more frequently than active sentences, and the differences were greater for passive-implausible sentences (e.g. *The dog was bitten by the man.*). Ferreira referred to these kinds of (passive-implausible) sentences as "biased-reversible", because real-world semantic knowledge "biases" people to assume that the dog was the agent of the action (i.e. in the real world it is much more likely for dogs to bite men than vice versa). "Reversible" refers to the fact that both nouns in the sentence are animate, and thus, capable of performing the action described by the verb.

Based on the results from her study of passives, Ferreira (2003) postulated that two parsing strategies (or heuristics) underlie participants' tendency to engage in good-enough processing. The first is a syntactically-based strategy, and referred to as the "noun-verb-noun" (NVN) strategy. This strategy assumes that comprehenders tend to assign the subject role to the first noun in the sentence (i.e. the subject is the agent of the action) and assign the object role to the final noun in the sentence (i.e. that the object is the patient or theme). This follows the highly dominant frequency bias in English for sentences to follow subject-verb-object word order. Several corpus studies report that active sentences occur approximately 99% of the time in spoken language and 95% of the time in written language (for an overview see, Dick & Elman, 2001; Engelhardt & Ferreira, 2010). The second strategy postulated by Ferreira (2003) was referred to as the "semantic-plausibility" (SP) strategy. This strategy has participants consult their knowledge about states of affairs in the real world, and in cases where there is a conflict between sentence content and real-world knowledge, comprehenders choose the interpretation that is more likely to have occurred in the real world.

In summary, the use of strategies during reading sentences in which the actual meaning of a sentence is incompatible with the readers' interpretation of that sentence. The use of strategies in language comprehension is assumed to be an adaptable function based on fast and frugal heuristics (Gigerenzer, 2008; Gigerenzer & Selten, 2001) and the basic idea is that they permit (cognitive) shortcuts that override the more time consuming and cognitively demanding algorithmic parsing governed by the full set of grammatical knowledge held by a competent speaker. Ferreira (2003) referred to these as pseudo parsing and algorithmic parsing, respectively.

One question that naturally arises is how often readers adopt a good enough interpretation based on fast-and-frugal processing strategies rather than the full algorithmic parse. Results from the Ferreira (2003) study showed that participants were equally good (and in fact near perfect) for both active-plausible and active-implausible sentences (see Table 1). However, for passive sentences, listeners made errors in approximately one out of every five sentences, and there was a clear difference between plausible and implausible passives. The results of Experiment 2 (Ferreira, 2003) are shown in the upper-left panel of Figure 1, and based on this pattern, Ferreira concluded that the noun-verb-noun strategy is employed more often than the semantic-plausibility strategy. In the other panels of Figure 1, we have shown the other possibilities comparing the two different processing strategies with one another. However, in order to be clear, we think it is important to work through these different predictions systematically. With active-plausible sentences (the easiest of the four conditions), no strategies are assumed to be employed. With active-implausible sentences, participants have the potential for misinterpretations if they go with what was more likely to have happened in the real world (semantic-plausibility). With passive-plausible sentences, participants have the potential for misinterpretations if they assign the subject role to the sentence initial noun phrase and object role to the sentence final noun phrase (noun-verb-noun). Finally, with passive-implausible sentences, the potential for misinterpretation is the highest because both strategies could be employed (i.e. this is the most difficult condition).

Table 1

Example sentences and comprehension questions.

Actives	Comprehension Question
1. The dog bit the man. (Plausible)	Did the man bite the dog?
2. The man bit the dog. (Implausible)	Did dog bite the man?
Passives	
3. The man was bitten by the dog. (Plausible)	Did the man bite the dog?
4. The dog was bitten by the man. (Implausible)	Did the dog bite the man?

Returning to the issue of how often comprehenders engage each type of strategy, Ferreira (2003) concluded that noun-verb-noun was stronger than semantic plausibility. In Figure 1 below, we have included the potential results of the various potential role of each strategy on comprehension. First of all, if both strategies affect comprehension equally, then we should observe a pattern like the one shown in the upper-right panel of Figure 1, where there are main effects of type and plausibility. If semantic plausibility is employed more frequently, then the pattern should be like the one shown in bottom-left panel, with only a main effect of plausibility. Finally, if the two strategies interact with one another, then we should observe the pattern shown in the bottom-right, which would be an interaction between type and plausibility.

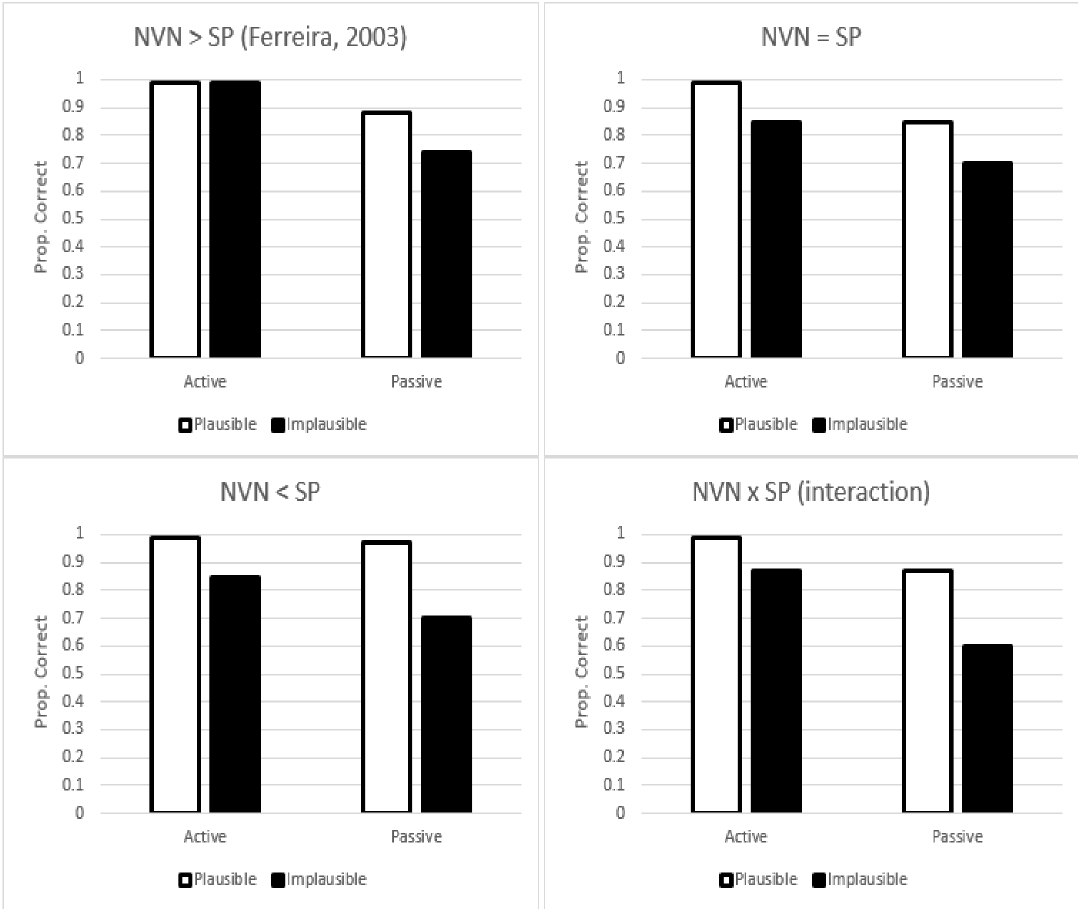

Figure 1. Predicted comprehension results based on the impact of noun-verb-noun (NVN) and semantic plausibility (SP) heuristics.

Comprehension in Dyslexia

Studies on dyslexia have described syntactic processing deficits in both oral and written language across the lifespan (Bishop & Snowling, 2004; Leikin & Assayag-Bouskila, 2004). Impairments in the comprehension of syntactically complex sentences may arise from several factors: (1) a secondary symptom of phonological processing difficulties (Bishop & Snowling, 2004), (2) deficits in cognitive abilities that underlie language comprehension, like working memory and/or processing speed (de Jong, 1998; Kibby, Marks, Morgan, & Long, 2004; Tunmer & Hoover, 1992), or (3) a secondary consequence of reduced reading experience (Bishop & Snowling, 2004; Stanovich, 1986). However, there have been few systematic studies investigating whether individuals with dyslexia have deficits in sentence comprehension (cf. De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hyönä & Olson, 1995). This is important because many of the existing dyslexia studies have focused on single word decoding, but there are considerable differences between reading single words and comprehending sentences. Comprehending sentences requires the ability to combine words together into meaningful phrases and extract compositional meaning (Fodor, 2001), and is therefore, considerably different and more complex than single word reading.

To date, there has been only one study on the comprehension of passive sentences in individuals with dyslexia. Wiseheart et al. (2009) examined sentence comprehension in adults with and without dyslexia while reading active and passive sentences. In their study, they used non-biased reversible sentences (e.g. *The queen kissed the king.* vs. *The king was kissed by the queen*), which means that there was no bias between the potential doer of the action and patient of the action. Participants were shown two images side-by-side on the computer screen under the sentence and they had to choose which picture corresponded to the sentence. Wiseheart et al. (2009) showed that dyslexic readers were marginally slower in their response times and had poorer comprehension accuracy on passive sentences compared to the control group. Controls were 98% accurate on actives and 95% accurate on passives. In contrast, participants with dyslexia were 98% accurate on actives and 83% accurate on passives. In their conclusions, Wiseheart et al. (2009) argued for a frequency-based (or exposure-based) explanation. In general, people encounter passives much less frequently that actives, and given dyslexics difficulties with reading and their inherent aversion to reading, the differential frequency for people with dyslexia would be even greater (Dick & Elman, 2001).

We think this explanation is untenable for a couple of reasons, but most importantly, Dabrowska and Street (2006) showed that non-native English speakers actually perform better on the comprehension of passive sentences than native English speakers. Non-native speakers, obviously, have less exposure compared to native speakers. In the current study, we pursued an alternate explanation for difficulties showed by individuals with dyslexia in the comprehension of passive sentences. Namely, that individuals with dyslexia may be more likely than typically-developing readers to engage in good enough processing, and thus, more likely to apply comprehension strategies (i.e. noun-verb-noun or semantic plausibility). We also note that multiple studies on dyslexia have shown that individuals with dyslexia, and particularly children, use context to compensate for poor word decoding skills (i.e. Conners & Olson, 1990; Nation, 2005; Nation & Snowling, 1998). It is also possible that individuals with dyslexia utilise their real-world knowledge to a greater extent, to again compensate for difficulties with decoding.

Current Study

The main aim of the current study was to investigate the comprehension of passive sentences in individuals with dyslexia. We hypothesised that individuals with dyslexia are more likely to rely on good enough processing, and thus, are more likely to employ processing strategies in comprehension. We used the “biased-reversible” sentences (see Table 1) from Ferreira (2003) because these sentences have the potential to create conflict between sentence content and real-world knowledge (i.e. these sentences are specifically the ones that tap into the semantic-plausibility strategy) (Ferreira et al., 2002). Thus, the materials used in the current study were expected to show some effect of both the syntactic (noun-verb-noun) strategy and the semantic-plausibility strategy. We also monitored eye movements in order to assess how long participants read each sentence. According to the Good Enough theory, the application of parsing strategies occurs because comprehenders seek to generate interpretations, while at the same time keeping the demand on cognitive resources as low as possible (Ferreira et al., 2002; Ferreira, Engelhardt, & Jones, 2009). Thus, if good enough processing is engaged, then we might expect reading times to be shorter for trials in which the participant makes a comprehension error. That is, the relationship between reading times and comprehension should be positive.

Passive sentences have the characteristic that they are syntactically challenging but essentially unambiguous sentences and the way that they are processed requires thematic roles to be assigned in an atypical order (Ferreira, 2003). The potential use of semantic heuristics would impose a more demanding load on working memory processes and capacity in order for the structure and meaning of the sentence to be maintained. As we have already explored ambiguous sentences in Chapter 2 and syntactically and semantically complex sentences in Chapter 3, in this study we focused on passive and implausible sentences, as we aimed to investigate whether dyslexic readers would use heuristics more than non-dyslexics and whether they would rely more on a particular strategy. This will allow us to further explore the potential sentence processing difficulties arising as a secondary symptom of dyslexia (Bishop & Snowling, 2004). Furthemore, the use of working memory as part of parsing heuristics in passive sentences could be associated with the bottleneck in working memory that dyslexics experience, which is another reason for expecting dyslexic readers to use heuristics more than non-dyslexics.

In the current study, we had two broad research objectives. The first, mentioned previously, focused on whether individuals with dyslexia rely on parsing heuristics to a greater extent than individuals without dyslexia. In general, given what is known about dyslexia, we expected individuals with dyslexia to show lower comprehension and higher reading times (e.g. Wiseheart et al., 2009). However, by manipulating both structure type (active vs. passive) and plausibility (plausible vs. implausible) in biased-reversible sentences, we were also interested in assessing the strength of the noun-verb-noun strategy and semantic-plausibility strategy, and whether the two groups of participants (dyslexics and controls) show the same pattern. More specifically, whether they show the same pattern of predicted results as outlined in Figure 1.

The second broad research objective focused on individual differences in verbal intelligence and working memory. Previous studies have shown that individuals with dyslexia have lower working memory and reduced processing speed (Denckla & Rudel, 1976; Gathercole et al., 2006; Jeffries & Everatt, 2004; Jones et al., 2009; Wolf, Bowers, & Biddle, 2000). However, in a recent study, we found that the comprehension of garden-path sentences was much more related to individual differences in working memory than individual differences in processing speed (Engelhardt et al., 2008; Stella & Engelhardt, 2019). Likewise, several recent individual differences studies have shown that the best predictor of the comprehension of syntactically complex sentences is verbal intelligence (Engelhardt, Nigg, & Ferreira, 2017; Van Dyke et al., 2014). Our specific research question for this objective was how do individual differences verbal intelligence and working memory affect both comprehension accuracy and reading times? To assess individual differences (i.e. working memory and verbal intelligence), we conducted an additional ANCOVA in which both verbal intelligence and working memory were co-varied.

There is one further point worth mentioning with regards to the memory demand of the task we used. We included a maths problem in between the sentence and the comprehension question, and participants had to determine whether the maths problem was correct or not. (Participants received feedback on their response to the maths problem.) The rationale for including this additional task is that we wanted to assess the representation that comprehenders generated of the sentence without allowing them to have direct access to the sentence. We assumed that the presence of the maths problem would clear the immediate contents of working memory, and thus, participants would be answering comprehension questions on the basis of a more long-term representation/trace of the sentence. Due to the slower phonological decoding increasing the working memory demands for dyslexics, we wanted to ensure that the participants' responses to the comprehension question would be affected as little as possible by the bottleneck in working memory processes.

Method

Participants

Fifty adults with self-reported dyslexia were recruited via advertisements and 50 undergraduate psychology students were tested as typically-developing control participants (see Table 2). Both groups were recruited from the campus of the University of East Anglia. All participants with dyslexia verified that they had diagnostic assessments for dyslexia in the past. All were native speakers of British English with normal or corrected-to-normal vision. Dyslexics were reimbursed £16 for their time, and controls were compensated with participation credits. Participants in the two groups were well matched in regard to verbal intelligence and working memory scores.

Standardised Measures

Rapid Automatised Naming. All participants completed both a letter and a number RAN test using the second edition of the Comprehensive Test of Phonological Processing (CTOPP 2) (Wagner, Torgensen, Rashotte, & Pearson, 2013). The RAN task requires participants to name a series of letters or numbers sequentially out loud as quickly and accurately as possible. The time taken to complete an array was recorded with a stopwatch. Participants completed one letter and one number array for practice, and two served as the critical trials (i.e. one letter array and one number array). The score for each task was the total time that was needed to complete the task, higher scores indicate worse performance. Each array consisted of four rows of nine items. Letters and numbers were presented in Arial font, and all items appeared on the same side of white A4 paper. The standardised procedures of administration for this task were followed as described in the test manual. Independent samples *t*-tests revealed significantly longer naming times for the dyslexic group compared to controls on both versions of the task (see Table 2), which is consistent with prior studies (e.g. Wolf & Bowers, 1999). The reliability of the CTOPP-2 subtests have been demonstrated by average internal consistency that exceeds .80 (Wagner et al., 2013).

Table 2

Means and standard deviations for demographic variables, Rapid Automatised Naming, verbal intelligence, and working memory for the two diagnostic groups.

	Controls (*N* = 50)	Dyslexia (*N* = 50)	*t-value*	Cohen's d
Variable	Mean (SD)	Mean (SD)		
Age (years)	20.31 (1.22)	21.7 (2.67)	*t*(98) = 3.34***	*d* = .67
Gender (% male)	8.0	34.0	*t*(98) = 3.33***	*d* = .67
Handedness (% left)	12.0	10.0	*t*(98) = -.317	*d* = .06
RAN Letters (seconds)	12.46 (2.59)	16.50 (6.20)	*t*(98) = 4.25***	*d* = .85
RAN Numbers (seconds)	11.44 (2.43)	15.26 (5.29)	*t*(98) = 4.64***	*d* = .93
Similarities	93.5(8.65)	98.8(11.76)	*t*(98) = -2.57*	*d* = .51
Vocabulary	99.9(9.18)	101.3(9.02)	*t*(98) = -.77	*d* = .15
Comprehension	93.5(10.70)	94.3(9.31)	*t*(98) = -.40	*d* = .08
Verbal Skills (latent)	-.152(.98)	.152(1.00)	*t*(98) = -1.53	*d* = .31
Rotation Span	17.7(7.23)	16.9(8.04)	*t*(98) = .51	*d* = .10

*Note. *p < .05, **p < .01, ***p < .001*. RAN = rapid automatised naming. Reported scores for RAN tasks and Rotation span are raw scores. Standard scores are reported for all other tasks.

Working Memory. For working memory, a rotation span was used as a measure of working memory, as it has been shown to assess both processing and storage functions (Daneman & Carpenter, 1980; Unsworth et al., 2005). Participants were required to look at a rotated letter and then verify whether or not the letter is facing in the correct direction or mirrored. After each letter, participants were presented with an isolated arrow which was either long or short and could be facing eight different directions (0° – 360°). The position and length of the arrows presented needed to be recalled at the end of the set. The task consisted of 15 trials (six each of list length 2 and three each of list lengths 3-5) and in total 48 arrow-storage pairs (Unsworth et al., 2005). The rotation span task was developed by Engle's Working Memory Laboratory, and reported reliability ranging between .67 and .77 for the rotation span (Conway et al., 2005).

Verbal Intelligence. Verbal intelligence was measured by the following subtests of the fourth edition of the Wechsler Adult Intelligence Scale (WAIS-IV) (Wechsler, 2014): comprehension, vocabulary and similarities. In the comprehension task, participants were required to respond to questions about general concepts (e.g. reasons to protect endangered species). Vocabulary requires participants to provide the definitions of words and measures the degree to which one has learned and is able to express meanings verbally. Similarities requires participants to describe how two words are similar, with the more difficult items typically describing the opposite ends of a "unifying continuum". The similarities subtest measures abstract verbal reasoning. For all subtests, higher values correspond to higher verbal intelligence and the score for each of these tasks was the total number of items that the participants could identify accurately. The standardised procedures of administration for these subtests were followed as described in the test manual. With respect to the reliability of the WAIS-IV, the manual reports average internal reliability coefficients for subtests that range from .78 to .94 (Benson et al., 2010).

Sentence Processing

We used 20 sentences, half of which were active and half were passive. Furthermore, in each category half of the sentences were plausible and half were implausible (see Table 1). Participants also read 80 filler sentences. All filler sentences were grammatically correct and consisted of five sets of 16 sentences. The first set were subordinate-main structures in which the subordinate clause was transitive. The second set were main-subordinate sentences. The third set were transitive sentences containing a relative clause at the end of the sentence. The fourth set were transitive sentences that contained an embedded relative clause that modified the subject noun phrase. The fifth set were coordination structures, in which two transitive sentences were conjoined with *and*. Half had a comma between *and* and the preceding word and half did not. In addition, there were also 40 sentences with relative clauses, half of which were object relative and half were subject relative. Therefore, each participant read 140 sentences in total. All 20 interest items (active and passive sentences) were rotated across two counterbalance lists, with plausible sentences changing to implausible and vice versa (see Table 1). The comprehension questions were also rotated to match the corresponding types of sentences.

Apparatus

Eye movements were recorded with an SR Research Ltd. EyeLink 1000 eye-tracker which records the position of the reader's eye every millisecond. Head movements were minimised with a chin rest. Eye movements were recorded from the right eye. The sentences were presented in 12 pt. Arial black font on a white background.

Design and Procedure

For the sentence processing task, the design was 2 × 2 × 2 (Sentence Type × Plausibility × Group) mixed design, in which sentence type and plausibility were within subjects and group was between subjects. Participants completed three practice trials, 20 experimental trials and 120 fillers. Participants were provided with a set of instructions that detailed the experimental procedure. They were then seated at the eye tracker and asked to respond to on-screen instructions using the keyboard. At the beginning of each trial, a message appeared asking the participant to press a button when they were ready to continue. After the participant pressed the button, they were required to fixate a drift-correction dot. The experimenter then initiated the trial. The sentence appeared after 500 ms, and the initial letter of each sentence was in the same position, in terms of *x* and *y* coordinates, as the drift correction dot (i.e. on the left edge of the monitor and centred vertically).

The entire sentence was presented on a single line on the screen. The participant read the sentence silently and then pressed the spacebar on the keyboard. Following a delay of 500 ms, an arithmetic problem (either addition or subtraction) appeared on the screen (e.g. 45 + 67 = 112). The problem was presented for 3000 ms and was followed by a screen prompting the participant to press the green button on the keyboard if the solution was correct, or the red button if it was incorrect. After participants responded, they were asked a comprehension question (see Table 1, for examples). For all active and passive sentences, the correct response to the comprehension questions was "no". Sixty-eight filler questions required a "yes" response and 52 required a "no" response. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were ten items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was $\alpha = .68$.

The rationale for including the additional arithmetic problem was the fact that we wanted to assess the representation that comprehenders generated of the sentences, without allowing them to have direct access to the sentence. We expected that the presence of the mathematical problem would clear the immediate contents of working memory, therefore resulting in the participants responding to the comprehension questions on the basis of a more long-term representation/trace of the sentence.

The testing session for each participant lasted approximately 2 hours, with several breaks between tasks to avoid fatigue. The tests were delivered in the following order: vocabulary, rotation span, comprehension, sentence processing, RAN digits, RAN letters and similarities.

Data Screening and Analysis

In order to keep the analyses as straightforward as possible, we submitted the verbal intelligence subtests to a factor analysis in which we saved the retained factor as variable. For verbal intelligence, the factor analysis produced only a single factor, and thus, we used this composite (or latent) variable in our analyses examining "individual differences". Working memory was only measured by the rotation span, and thus, that variable was used in analyses of working memory. We analysed the comprehension and reading time data using standard mixed ANOVAs with subjects ($F1$) and items ($F2$) as random effects. For eye movement, we examined the reading times of the entire sentence. We first report the comprehension results, and second the reading times. For the reading times, we report *total reading time*, which is the sum of all fixations on the whole sentence.

Results

Comprehension Accuracy

For comprehension accuracy, there were significant main effects of sentence type *F1*(1,99) = 25.85, $p < .001$, $\eta^2 = .21$; *F2*(1,18) = 5.15, $p < .05$, plausibility *F1*(1,99) = 23.65, $p < .001$, $\eta^2 = .19$; *F2*(1,19) = 13.76, $p < .01$, and group *F1*(1,98) = 6.13, $p < .05$, $\eta^2 = .06$; *F2*(1,19) = 12.71, $p < .01$ (see Figure 2). Active sentences had higher comprehension accuracy than passives, plausible sentences had higher comprehension accuracy than implausible sentences, and controls had higher comprehension accuracy than participants with dyslexia. None of the interactions were significant.[7]

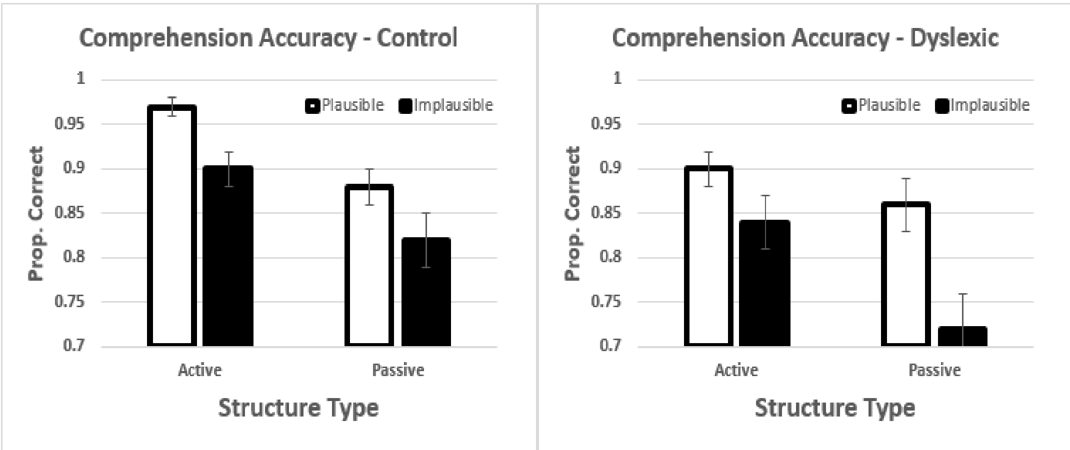

Figure 2. Mean comprehension accuracy. Error bars show the standard error of the mean.

Individual Differences. The bi-variate correlations between demographic variables, individual differences variables, and comprehension accuracy are presented in Table 3. Rotation span significantly correlated with comprehension in active-plausible and passive-implausible sentences, and verbal intelligence correlated with active-implausible sentences.

When verbal intelligence and working memory were included as covariates, we observed the same significant main effects as in the previous analysis: sentence type *F1*(1,96) = 16.22, $p < .001$, $\eta^2 = .15$; *F2*(1,19) = 4.87, $p < .05$, plausibility

[7] Results of paired comparisons (control vs. dyslexic) showed significant differences in the active-plausible $t(98) = 3.04$, $p < .01$ and the passive-implausible conditions $t(98) = 1.98$, $p < .05$. There were marginally significant differences in the active-implausible condition $t(98) = 1.81$, $p = .073$.

F1(1,96) = 18.57, $p < .001$, $\eta^2 = .16$; *F2*(1,19) = 2.07, $p = .17$, and group *F1*(1,96) = 8.15, $p < .01$, $\eta^2 = .08$; *F2*(1,19) = 1.83, $p = .19$.[8] The main effects of verbal intelligence and working memory were also significant: verbal intelligence $F(1,96) = 6.52$, $p < .05$, $\eta^2 = .06$ and working memory $F(1,96) = 3.79$, $p = .05$, $\eta^2 = .02$. The correlations in Table 3 suggest that in both cases the relationships are positive (i.e. individuals with higher verbal intelligence and higher working memory have higher comprehension accuracy).

Table 3

Bivariate correlations between demographics, working memory, verbal skills and comprehension.

Variable	1	2	3	4	5	6	7	8	9
1. Age	-	.35**	.32**	.16	.04	.19#	-.06	.06	.02
2. Gender		-	.32**	.13	.30**	.00	.05	.00	.11
3. Dyslexia Status			-	-.05	.15	-.29**	-.18#	-.07	-.20#
4. Rotation Span				-	-.04	.26**	.10	.00	.20*
5. Verbal Skills					-	.03	.27**	.10	.13
6. Active-plausible						-	.37**	.33**	.45**
7. Active-implausible							-	.26**	.34**
8. Passive-plausible								-	.39**
9. Passive-implausible									-

Note. #$p < .08$, *$p < .05$, **$p < .01$. Gender: 0=female, 1=male; Dyslexia: 1=dyslexic, 0=control

In addition, there were three significant interactions. First, verbal intelligence interacted with plausibility $F(1,96) = 9.74$, $p < .01$, $\eta^2 = .05$. As can be seen in Figure 3, this interaction is due to performance in implausible sentences. Individuals with lower verbal intelligence have lower comprehension accuracy, specifically in implausible sentences. In contrast, verbal intelligence has little effect on performance with plausible sentences. Second, there was a significant structure type × plausibility interaction $F(1,96) = 5.92$, $p < .05$, $\eta^2 = .05$, and this interaction only emerged when working memory is included in the model. We did not investigate this interaction further because the final interaction was a significant three-way interaction between structure type, plausibility, and working memory $F(1,96) = 4.78$, $p < .05$, $\eta^2 = .04$. In

[8] The plausibility and group main effects were not significant in the by-items analysis, but those by-item analyses are substantially less powerful than the by-subjects analyses because they are treated as between subject. Thus, some reduction in statistical significance is expected.

order to decompose this 3-way interaction, we divided the sample into high-spans and low-spans. The means for each group are presented in Figure 4. As can be seen in Figure 4, the difference between high- and low-spans is quite striking. Results for the high-span participants show a clear double main effect: structure type $F(1,49) = 14.53$, $p < .001$ and plausibility $F(1,49) = 8.97$, $p < .01$. In contrast, for low-span participants, there was a significant interaction $F(1,49) = 3.94$, $p = .05$. Paired comparisons for low spans showed significant differences between active-implausible and passive-implausible $t(49) = 3.56$, $p < .01$, and between passive-plausible and passive-implausible $t(49) = -3.49$, $p < .01$. The difference between active-plausible and active-implausible was also significant $t(49) = -2.08$, $p < .05$. What these results show is that participants with lower working memory capacity show particular difficulties with the passive-implausible sentences.

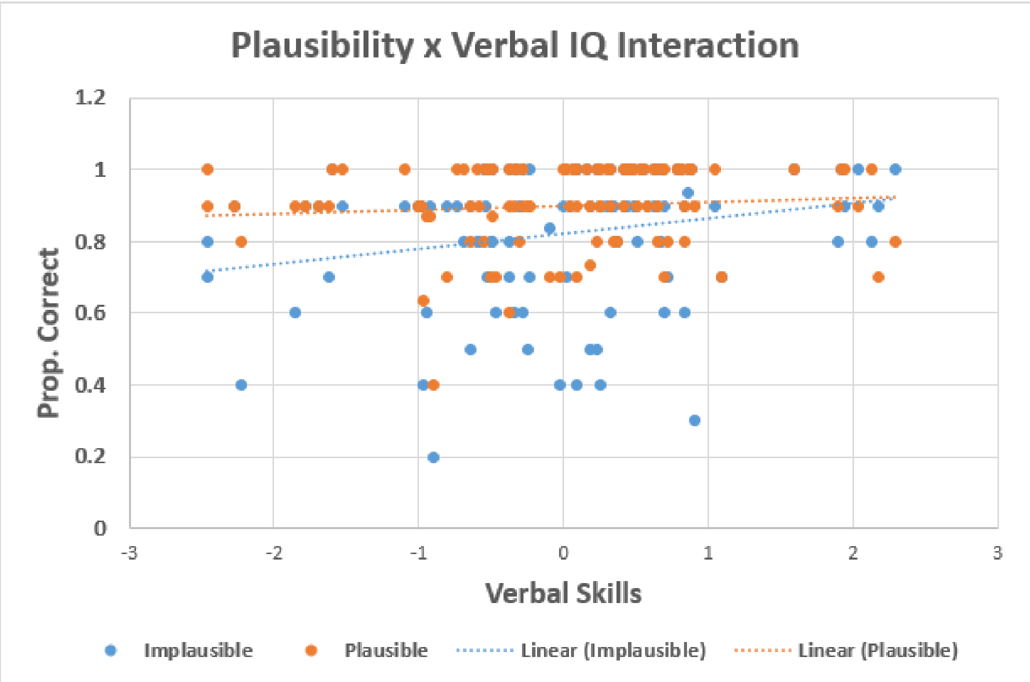

Figure 3. Scatter plot showing the plausibility × verbal intelligence interaction.

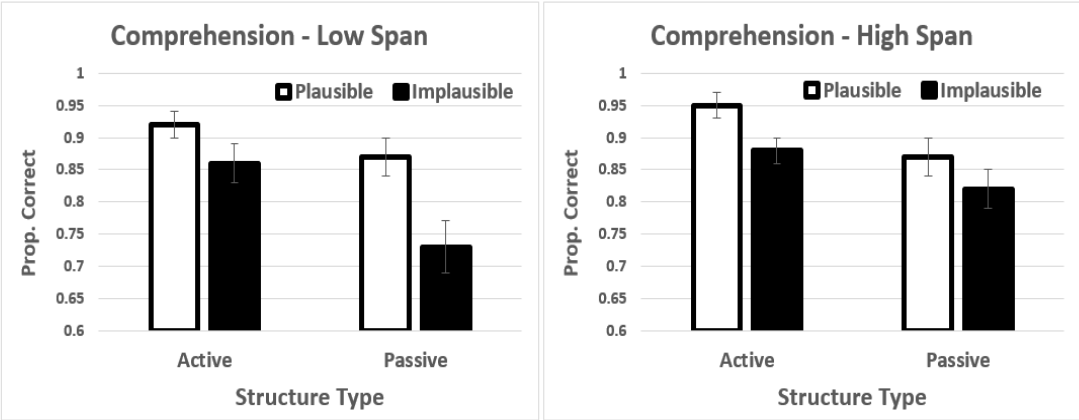

Figure 4. Mean comprehension accuracy broken down by high- and low-span participants. Error bars show the standard error of the mean.

Reading Times

In the below analysis, we report the total sentence reading time, and we used the same analysis procedures as we did for comprehension. There is one caveat to bear in mind for these analyses, and that is the passive sentences have two more words than do the actives. Thus, any main effects of structure type or interactions with structure type need to be qualified by the fact that these sentences are slightly longer, and thus, could show longer reading times (i.e. length and complexity are confounded). The issue of length is one previously considered by other studies on active and passive sentences, but it has also been highlighted that the differences in length, as was the case in this study, are not enough on their own to significantly affect the participants' reading times (Ferreira, 2003).

Total Reading Times. Results showed significant main effects of structure type $F1(1,98) = 10.54$, $p < .01$, $\eta^2 = .10$; $F2(1,18) = 4.50$, $p < .05$, plausibility $F1(1,98) = 22.40$, $p < .001$, $\eta^2 = .19$; $F2(1,19) = 16.84$, $p < .01$, and group $F1(1,98) = 12.66$, $p < .01$, $\eta^2 = .11$; $F2(1,19) = 278.41$, $p < .001$ (see Figure 5). Passive sentences, implausible sentences, and dyslexic participants all showed longer total reading times. None of the interactions were significant.

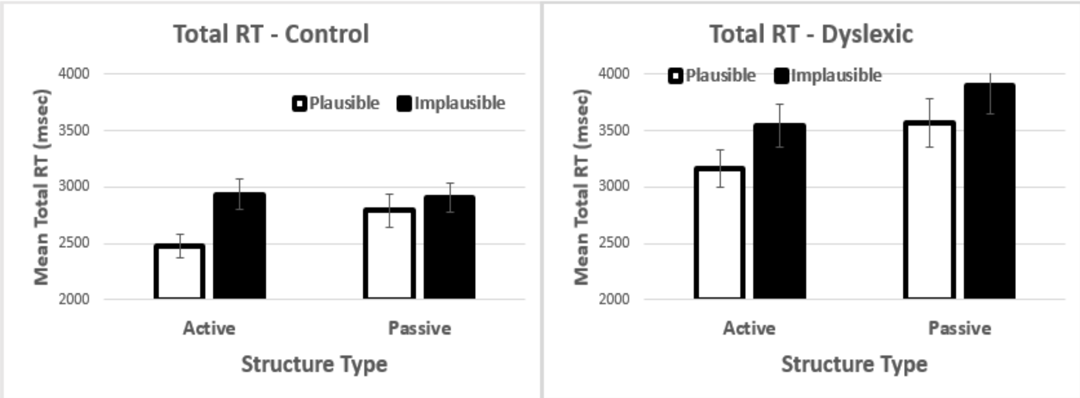

Figure 5. Mean total reading times. Error bars show the standard error of the mean.

Individual Differences. The bi-variate correlations between demographic variables, individual differences variables, and reading times are presented in Table 4. Rotation span significantly correlated with reading times in active-plausible and active-implausible sentences, and here, both were negative (i.e. higher span participants had lower reading times). In contrast, verbal intelligence did not correlate with reading times.

Table 4

Bivariate correlations between demographics, working memory, verbal skills, and total reading time.

Variable	1	2	3	4	5	6	7	8	9
1. Age	-	.35**	.32**	.16	.04	-.07	-.07	-.01	-.07
2. Gender		-	.32**	.13	.30**	.11	.05	.17	.18#
3. Dyslexia Status			-	-.05	.15	.33**	.27*	.29**	.33**
4. Rotation Span				-	-.04	-.33**	-.27**	-.12	-.15
5. Verbal Skills					-	-.08	-.12	.01	.08
6. Active-plausible						-	.72**	.72**	.73**
7. Active-implausible							-	.65**	.69**
8. Passive-plausible								-	.76**
9. Passive-implausible									-

Note. #*p* < *.08,* **p* < .05, ***p* < .01. Gender: 0=female, 1=male; Dyslexia: 1=dyslexic, 0=control

When working memory and verbal intelligence were included in the model, we observed significant main effects of plausibility $F1(1,96) = 4.38$, $p < .05$, η^2 =

.13; *F2*(1,16) = 6.38, $p < .05$ and group *F1*(1,96) = 12.92, $p < .01$, $\eta^2 = .12$; *F2*(1,16) = 42.40, $p < .001$, in which implausible sentences and participants with dyslexia showed longer total reading times. With respect to covariates, we observed a significant main effect of working memory *F*(1,96) = 5.45, $p < .05$, $\eta^2 = .02$, in which individuals with higher working memory showed lower reading times. There was also an interaction between structure type × verbal intelligence *F*(1,96) = 4.45, $p < .05$, $\eta^2 = .05$, in which individuals with lower verbal intelligence had higher reading times and individuals with higher verbal intelligence has lower reading times. The effect was greater for the actives than the passives (see Figure 6). Again, it is important to note that passive sentences are longer, and thus, should have longer reading times. The correlations in Table 4 further highlight that the relationships are negative (i.e. individuals with higher working memory and higher verbal intelligence have lower reading times).

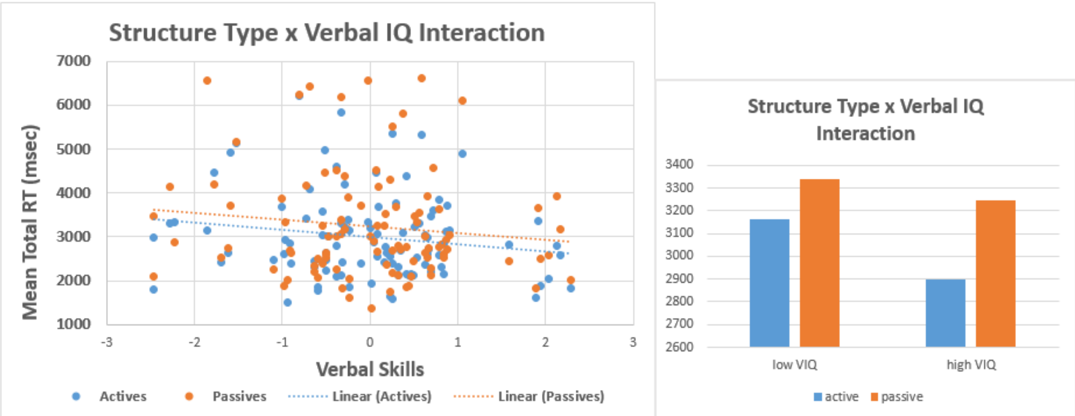

Figure 6. Interaction between structure type and verbal intelligence. The left panel shows the scatterplot, and the right shows the means.

Discussion

In this study, we examined how dyslexic and non-dyslexic adults comprehend and process passive sentences, and we also manipulated the semantic plausibility of both active and passive sentences. Our main research objective was to investigate whether individuals with dyslexia rely more on parsing heuristics compared to non-dyslexic readers. In the Introduction, we identified several reasons why the parsing heuristics assumed by the good-enough approach to language comprehension would be employed more frequently in individuals with reading difficulties (Ferreira & Patson, 2007; Ferreira, 2003; Wiseheart et al., 2009). Our second research objective focused on the role of individual differences in two key variables (i.e. working memory and verbal intelligence). We found clear evidence that these variables affected both comprehension accuracy and reading times. However, when working memory and verbal intelligence were included in the model, the main effect of group (dyslexic vs. control) remained significant, which suggests that the individual differences account for unique variance in comprehension and reading time over and above that accounted for by dyslexia status. In the remainder of the discussion, we cover the comprehension results and reading times, as well as the implications our results have for the good enough approach, and specifically, the use of parsing strategies.

Comprehension Accuracy

In terms of comprehension, we found a pattern of results that is consistent with both noun-verb-noun and semantic plausibility heuristics impacting comprehension, and that those two heuristics do not interact. Thus, our results are largely consistent with the predicted pattern shown in the upper-right panel of Figure 1 (cf. Ferreira, 2003). With respect to dyslexia, we found that individuals with dyslexia showed across-the-board lower comprehension (i.e. there was a main effect of group). These results show similarities with Wiseheart et al.'s study (2009), as they also found the same difference in comprehension between the two groups, with dyslexics showing poorer comprehension than non-dyslexics, especially in passive sentences. However, there was a trend in our data in which individuals with dyslexia showed an interaction between structure type and plausibility, which is consistent with an interaction between noun-verb-noun and semantic plausibility. However, because the main effects were significant and the interaction was not ($p = .09$), we conclude that even in individuals with dyslexia the two parsing heuristics do not interact.

Recall that our main research aim was to determine whether individuals with dyslexia rely on parsing heuristics to a greater extent than do controls. At this point, we are reluctant to make that conclusion even though participants with dyslexia showed worse comprehension, and we think there are several reasons why caution is warranted. The first is that participants with dyslexia showed poorer comprehension with active-plausible sentences and these sentences are not hypothesised to be affected by parsing heuristics. The second is that in the entire study, dyslexia status did not interact with any of the other within subject or individual differences variables, which suggests that the problems associated with dyslexia seem to account for unique variance in comprehension performance. The final reason, covered in more detail below, is that our strongest evidence for the use of parsing heuristics was individual differences in verbal intelligence and working memory. Our controls and dyslexics were surprisingly well matched on both variables, despite what is commonly reported in dyslexia (see Table 2).

With respect to individual differences, we found that verbal intelligence predicted comprehension of implausible sentences. Individuals with lower verbal intelligence showed particularly poor comprehension of implausible sentences. Thus, in offline comprehension, verbal intelligence seems to be linked to semantic processing abilities. Working memory interacted with both the structure type and plausibility variables. The pattern of results for low-span individuals was clearly consistent with a noun-verb-noun and semantic plausibility interaction (i.e. the passive-implausible condition showed significantly lower accuracy). This finding is intriguing because it suggests that individuals with less ability to hold information in memory have a greater tendency to consult real-world knowledge, and hence make a greater number of comprehension errors in sentences that are semantically implausible.

Reading Times

The main finding with regard to reading times was that participants showed longer reading times for passive sentences compared to actives and for implausible compared to plausible sentences. Dyslexics also showed longer reading times than the controls. When the individual differences variables were entered into the model, the main effect of structure type was not significant and the main effect of working memory was significant.

Parsing Heuristics and Good Enough Comprehension

The Good Enough theory postulates the application of parsing heuristics in situations where depth of processing is not required or in cases where comprehenders seek to curtail processing effort. The latter assumption suggests positive relationships between comprehension accuracy and reading times (i.e. higher reading times would be associated with more algorithmic parsing, and lower reading times associated with strategy use). In the Appendix (Tables A-F), we have provided several sets of correlations which show the relationships between reading times and comprehension accuracy. It is also important to bear in mind that only three of the four within subject conditions were expected to show evidence of strategy use (i.e.

active-implausible, passive-plausible, and passive-implausible). We conducted several logistic regressions looking at whether reading time or even regressions predicted comprehension accuracy, and the results showed that clearly not to be the case.[9] Ultimately, there is no objective way to ascertain whether participants responses were based on heuristics (what Ferreira referred to as a pseudo-parse) or some kind of failure or error associated with the outcome of the full algorithmic parse. We have to assume that some number of the comprehension errors were due to both possibilities. But clearly, our data indicates that reading times (and regressions) cannot be used to differentiate these two possible sources of comprehension errors.

Interestingly, we did find that individual difference variables were significantly related to comprehension accuracy, and specifically, verbal intelligence interacted with plausibility – individuals with low verbal ability showed a much higher number of comprehension errors with implausible sentences. Working memory, in contrast, interacted with both within subject variables and the pattern suggested that low-span individuals were much more likely to misinterpret passive-implausible sentences, which invites the inference that in cases where the participant has limited working memory capacity, they will tend to rely on the plausibility of events in the real-world to guide their decision making. We think that these individual differences findings open the door for a large range of new and exciting research questions concerning the use of parsing heuristics, and how and when people engage good enough comprehension. We suspect that some of the effect with low-span participants was made evident by the inclusion of the additional maths problem between the sentence and the comprehension question. It remains to future work to determine whether the effect of working memory on the comprehension of passive-implausible sentences is replicated without the intervening maths problem, or whether the question itself may produce some bias in participant responses. To address this second issue, a comprehension task utilising paraphrasing may be informative (Patson, Darowski, Moon, & Ferreira, 2009)

There is one further point about our data that deserves mention, and it involves the relationships between the reading times and the comprehension. We

[9] The only condition to show significant correlations between reading time and comprehension accuracy was the active-plausible condition (i.e. the one assumed not to involve parsing strategies).

have already noted that reading time does not predict comprehension accuracy; however, the patterns between controls and dyslexics were quite distinct. Controls showed an interaction between structure and plausibility in reading times, but only main effects in comprehension. In contrast, individuals with dyslexia showed main effects of structure type and plausibility in reading times, but a trend towards an interaction in comprehension, which again suggests some dissociation between online and offline processing measures.

Strengths and Limitations

We think the main strength of this study is the large nature of the sample and the test battery. The use of a variety of cognitive assessments, as well as the fact that we tracked the eye movements of 100 participants, makes this study a rare case of a large-scale individual differences dataset from a clinical population. There were also some limitations. The first is that our sample consisted mainly of university students, and the fact that many individuals with dyslexia do not continue into higher education means that a community-recruited dyslexia sample may show even greater differences than the ones reported here. The second is in regards to the assessment of working memory. We used only a single measure (rotation span), but this particular task does not include any reading or lexical components (Unsworth et al., 2005), which avoids any difficulties that dyslexic participants might have with lexical processing. In future, we would recommend using both verbal and non-verbal working memory tasks, and it is always better to have multiple measures to avoid task impurity issues. We also utilized “yes or no” (forced-choice) comprehension questions which potentially introduced a non-canonical structure and implausibility (e.g. “Did the man bite the dog?”). This could have had an effect on comprehension accuracy and the participants’ interpretation of the sentences. In future research, we would suggest the use of a paraphrasing task where participants would be required to paraphrase the sentences they have read, which could potentially provide new information regarding the processing of non-canonical sentences (Patson et al., 2009).

Conclusion

This study aimed to investigate the processing and comprehension of passive sentences and the use of parsing heuristics in individuals with dyslexia. We also examined the individual differences in verbal intelligence and working memory, their role in parsing heuristics and their links to comprehension and reading times. Our results showed that dyslexic readers made more comprehension errors compared to controls, and specifically, with passive sentences and implausible sentences. With respect to the use of parsing heuristics, our findings indicate that despite their lower comprehension, individuals with dyslexia do not necessarily use parsing heuristics more than individuals without dyslexia. Furthermore, we found that individual differences in verbal intelligence and working memory affected both comprehension accuracy and reading times, and they seemed to be more related to the use of parsing heuristics. Verbal intelligence was specifically linked to semantic processing abilities, while working memory interacted with both structure type and plausibility, which highlighted that participants with lower working memory made more comprehension errors in passive-implausible sentences. Finally, our data showed that individuals with dyslexia showed longer reading times than non-dyslexics. The current study has provided a better understanding of how dyslexic readers process and comprehend passive sentences, as well as evidence for the relationship between individual differences and the use of parsing strategies to interpret noncanonical sentences.

Appendix

In the tables below, we present the correlations between eye movement measures and comprehension accuracy. Table A presents correlations between total sentence reading time and comprehension, and Table B presents correlations between regressions and comprehension. Results are provided for the full sample and also broken down by the two groups (control and dyslexics). In addition, in Table C we have also provided the means for correct and incorrect responses separately for controls and dyslexics.

Table A

Bivariate correlations between comprehension accuracy and reading time.

	Full Sample	Controls	Dyslexics
Active-plausible	-.33**	-.21	-.28*
Active-implausible	-.10	.04	-.10
Passive-plausible	.14	.10	.20
Passive-implausible	-.03	-.09	.08

Note. $^{\#}p < .08$, $^{*}p < .05$, $^{**}p < .01$.

Table B

Bivariate correlations between comprehension accuracy and regressions.

	Full Sample	Controls	Dyslexics
Active-plausible	-.12	.00	-.07
Active-implausible	.10	.17	.16
Passive-plausible	.04	.12	-.04
Passive-implausible	-.11	.02	-.15

Note. $^{\#}p < .08$, $^{*}p < .05$, $^{**}p < .01$.

Table C

Mean reading times (msec) and regressions for correct and incorrect responses by group and experimental condition.

	Incorrect Reading times	Incorrect Regressions	Correct Reading times	Correct Regressions
Controls				
Active-implausible	2739.46	1.41	2963.94	1.45
Active-plausible	2608.00	1.36	2466.95	1.28
Passive-implausible	2695.30	1.52	2952.61	1.69
Passive-plausible	2799.63	1.43	2789.16	1.65
Dyslexics				
Active-implausible	3659.05	1.49	3522.51	1.69
Active-plausible	3540.82	1.58	3105.88	1.60
Passive-implausible	3553.96	1.93	4032	1.98
Passive-plausible	3705.11	1.75	3544.82	1.83

Chapter 5

-

Adolescents' processing of sentences with complex syntax and an examination of a Keith Rayner hypothesis

Abstract

In this study, we examined eye movements and comprehension of dyslexic and non-dyslexic adolescents, while they read several different types of sentences with complex syntax. To date, very few studies have focused on sentence-level comprehension in adolescents with dyslexia. We compared a sample of dyslexic adolescents ($N = 13$) to a control group of typically-developing adolescents, who were gender and age matched ($N = 13$). We had two main research aims. The first was to contribute to the gap in the literature concerning sentence processing in adolescents with dyslexia, and the second was to compare results of adolescents with the adults in our previous studies. Results showed, across the different types of sentences, that dyslexic adolescents had worse comprehension and longer first pass and longer total reading times compared to typically-developing adolescents. The comprehension differences were not robust to individual differences in working memory, processing speed, or verbal intelligence. Thus, in adolescence, the key differences between dyslexic and non-dyslexic individuals primarily involves longer reading times. Comparing the results of adolescents and adults showed little differences between typically-developing adolescents and typically-developing adults, suggesting little difference in this particular developmental time period. However, the comparison of dyslexic adolescents and dyslexic adults did show differences. Specifically, the adults showed higher comprehension and lower first pass and lower total reading times. In one of the key review papers in the literature, Rayner (1998) made two claims regarding the eye movements of dyslexic readers. These claims suggested that adult dyslexics would show eye movement patterns similar to typically-developing adolescents. However, these claims were not supported by our data.

Introduction

In this study, we focused on investigating further our findings from Chapters 2, 3 and 4, by exploring the development of sentence processing and comprehension from adolescence to adulthood. According to Bishop & Snowling (2004), the potential sentence processing difficulties that dyslexic readers show is a secondary result of phonological processing impairments. In the previous chapters, we found that in two out of the three types of sentences that were examined, the dyslexic participants showed poorer comprehension accuracy and also showed longer reading times in all types of sentences compared to the control group. Therefore, in this exploratory study, we wanted to investigate whether there is a discrepancy between the performance of adults and adolescents with dyslexia. We expected that any potential differences between the two age groups could be reflecting the co-development of adequate cognitive and reading skills, as well as exposure to a range of types of print and grammatical structures.

Very little psycholinguistic research has focused on adolescents. Many studies use undergraduate students as samples, given the ease of recruitment and availability. Developmentally, a lot of research has focused on young children, and the mechanisms of word learning and early syntactic learning (e.g. Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). Some researchers have even gone so far as to call adolescence the developmental "*the missing link*". However, important changes occur developmentally in middle childhood, which are currently poorly understood (Snedeker & Trueswell, 2004). A second aim of this study was to follow up on an eye movement claim originally made by Rayner (1998) regarding dyslexia. Rayner (1998) argued that the eye movements of adults with dyslexia are in some ways similar to the eye movements of adolescents. He claimed that if you present children (or adolescents) with texts that are too advanced for their age, then their eye movements become similar to adults with dyslexia. In the current study, we assessed sentence comprehension in adolescents (between 13 and 17 years of age) in order to (1) shed light on sentence processing abilities in this age range, and (2) to determine whether the claim made by Rayner is correct.

Dyslexia in Children and Adolescents

Dyslexia is a heritable language disorder (Pennington & Olson, 2005), and multiple studies have followed the developmental progression of children with genetic risk of dyslexia from the pre-school years (i.e. prior to official diagnosis of dyslexia). In the UK, children can be diagnosed with dyslexia, from the age of 5 or 6 during the period they begin developing reading and spelling skills (Reid, 2016). However, indications of dyslexia can be identified before the age of 5. Research has suggested that speech and language difficulties in early childhood are associated with later literacy difficulties. Therefore, pre-school children, who show speech difficulties, difficulties remembering letters and confuse words that sound familiar could be showing early language deficits that are consistent with dyslexia. Scarborough (1990) further reported that at 2 years of age, children who were later diagnosed with dyslexia, showed deficits in mean length of utterance and difficulties in pronunciation accuracy, and at 3 years of age, they showed deficits in receptive vocabulary and object-naming.

Family studies have also noted that the behavioural profile of children with dyslexia changes with age, from the previously reported pattern of delayed language development in the pre-school years to a more specific profile of phonological difficulties in the school years (Scarborough, 1990; Snowling, Muter, & Carroll, 2007). Children in school (from 6 years old and upwards) show impairments in phonological awareness (Swan & Goswami, 1997), phonological processing (Snowling, 1995), verbal short-term and working memory (Bruck, 1990), non-word repetition (Snowling, 1987), and verbal naming (Bowers & Wolf, 1993; Swan & Goswami, 1997). Despite the fact that only a few studies have focused on dyslexia in adolescence, Snowling et al. (2007) conducted a longitudinal study on children at family risk of dyslexia. When the participants were assessed in early adolescence for literacy and language skills, as well as print exposure, a significant proportion of the 'at-risk' group showed reading and spelling impairments. Regarding print exposure, they found that adolescents in the 'at-risk' group read less than controls, and generally showed more reading difficulties at school than did typically-developing adolescents.

As mentioned previously, prior research on sentence comprehension and eye movements during reading in adolescents has been limited, and the majority of adolescent studies have combined children and adolescents together, which makes it difficult to understand the unique features of dyslexia in adolescence. Therefore, in the remainder of Introduction, we review studies that tested groups with a broad range of ages.

Children's and Adolescents' Sentence Processing and Comprehension

Previous studies on children's processing of garden path sentences has been limited. In one study, Engelhardt (2014) examined the processing and comprehension of sentences (e.g. *"While the storm blew the boat sat in the shed."*) in children and adolescents between 9 and 16 years old. Participants were presented with a sentence and were asked to read it silently. They were then asked a yes/no comprehension question (e.g. *Did the storm blow the boat?*). Engelhardt (2014) found that adolescents showed better comprehension than children, which was linked to an increased number of regressions from the disambiguating verb. This suggests that older participants spent more time re-reading the sentence in order to revise the temporary ambiguity and extract the correct meaning.

In a similar study, Traxler (2002) investigated syntactic ambiguity and semantic plausibility in children, between the ages of 8 and 12 years old. This experiment used a self-paced reading task, in which participants pressed a button to reveal one word at a time. The participant was then asked a yes/no comprehension question. Traxler (2002) found that children did not use plausibility to avoid garden paths in sentences, such as *When Sue tripped the table fell over and the vase was broken*. In this case, the fact that it is not possible to trip an inanimate object creates the implausibility. Furthermore, children's reading times in the temporarily ambiguous region indicated that they generally misanalysed sentences with a temporary ambiguity (i.e. they did not show elevated reading times at the disambiguating region).

Joseph et al. (2008) examined 7 year olds, 12 year olds, and adults processing of sentences that contained plausible thematic relations (*"Beatrice used a password to open the important programme on the computer."*), implausible thematic relations (*"Beatrice used a key to open the important programme on the computer."*), and anomalous thematic relations (*"Beatrice used a towel to dry the important programme on the computer."*). After reading the sentence, participants were asked a comprehension question. Results showed that while adults exhibited longer gaze durations on target words in implausible sentences, children showed delays in those effects. Thus, while children and adults shared similarities in thematic assignment during reading, children were delayed (or less efficient) in their ability to utilise real-world knowledge to resolve the semantic anomalies.

To summarise across the relevant studies, it is clear that there are developmental changes in both syntactic and semantic processing abilities from childhood to adulthood. In some cases, these changes can be linked to specific processing mechanisms associated with better comprehension, and in other cases, the causal mechanisms remain un-elucidated. More specifically, these developmental changes seem to primarily involve individuals' activation of mental representations (Gernsbacher, 1990), decoding skills (Moll et al., 2014), reasoning and executive function (Shaywitz & Shaywitz, 2005). As part of protocol in the current study, we also assessed several individual difference variables, in order to determine whether these variables can be linked to eye movement differences or comprehension differences between dyslexic and non-dyslexic participants.

Individual Differences Variables

Working Memory. Longitudinal studies of short-term and working memory have shown a steady increase in capacity from preschool children to adolescence (Gathercole, Pickering, Ambridge, & Wearing, 2004). As children grow older, the rate of rehearsal increases, and enables a child to maintain increasing amounts of material in working memory (Hulme, Thomson, Muir, & Lawrence, 1984). However, before approximately the age of 7, spontaneous rehearsal does not reliably occur (Gathercole & Hitch, 1993). The capacity of all working memory components increases linearly from the age of 4 to early adolescence (Gathercole et al., 2004).

Individual differences in working memory have also been shown to be associated with sentence comprehension (Adams & Gathercole, 2000; King & Just, 1991; MacDonald, Just & Carpenter, 1992). More specifically, Caplan and Waters (1999) suggested that language comprehension and cognitive abilities, like working memory, are separate systems and DeDe, Caplan, Kemtes and Waters (2004) also concluded that offline sentence comprehension is affected by working memory capacity, but not online sentence processing. The double function of processing and storage capacity of working memory indicates that it plays an important role in reading comprehension (Daneman & Carpenter, 1980). Readers need to store and process text information while reading a sentence, as they are required to combine their pre-existing knowledge about the world and information provided by the sentence in order to make inferences and interpret its meaning (Oakhill & Cain, 2012; Perfetti, Landi, & Oakhill, 2008). More specifically, both syntactic and semantic information needs to be stored and processed, and some of that information can be maintained in working memory.

Processing Speed. Ridderinkhof and Van Der Molen (1997) compared the development of processing speed from childhood to adulthood to the clock speed of a microcomputer. While children grow, the speed of processing in all cognitive processes increases until the expected adult level is reached. Children are generally assumed to show an increase in the available amount of processing resources or capacity over the course of development (Kail & Bisanz, 1982). Bjorklund (1987) suggested that processes, like memory retrieval, become more automatic with age and as these processes become automatised, they require less processing capacity and can be completed in less time. These age-related changes in processing speed could be a result of age-related changes in general intellectual functions or in physiological changes (e.g. increased myelination) (Kail, 1991; Vernon & Kantor, 1986).

Kail and Salthouse (1994) argued that processing speed is finite, it increases during development and then decreases during senescence. They further reported that for an individual with higher processing speed, all cognitive processing takes place at a faster rate than for individuals with lower processing speed. Regarding the development of speed of processing in children, they highlighted that all age-related changes in processing speed are globally connected to all cognitive processes in the same proportional degree. However, more recent studies have shown that some aspects of processing speed might develop at different rates from global processing speed. Kail and Miller (2006) for example, argued that the developmental change in processing speed in children at 9 and 14 years of age was greater on non-verbal tasks than on language tasks, while processing speed was faster on language tasks than on non-language tasks for 9-year-olds, but that was not the case at the age of 14.

Verbal intelligence. Van Dyke et al. (2014) investigated the role of verbal intelligence and working memory in comprehension of syntactically complex sentences. They found that receptive vocabulary knowledge was the largest predictor of comprehension performance and reading times of sentences with relative clauses. Their conclusions focused on the role of high quality lexical representations and verbal intelligence as key determinants of efficient reading and successful comprehension (Van Dyke et al., 2014). Other studies have also reported the importance of vocabulary and verbal intelligence as key measures in assessing individual differences in linguistic performance and as a fundamental component of an a structural account of comprehension difficulty (Braze, Tabor, Shankweiler, & Mencl, 2007; Traxler & Tooley, 2007; Tunmer & Chapman, 2012). Furthermore, previous research with poor readers has shown that they are less able to inhibit the context-irrelevant meanings of ambiguous words in sentence comprehension compared to skilled readers (Gernsbacher & Faust, 1995; Gernsbacher & Robertson, 1995).

Current Study

The first aim of this research was to contribute to the gap in current research on sentence comprehension and eye movements, specifically with respect to adolescents. This gap is potentially due to the diverse abilities in this age range and difficulties with recruitment. We also included adolescents from a clinical population in order to examine the manifestation of dyslexia in adolescence and the differences between dyslexic and non-dyslexic adolescents. Furthermore, while verbal intelligence and executive function continue to develop during adolescence, language skills remain more or less developmentally stable (Shaw et al., 2006). The second aim of this research was to investigate Rayner's (1998; 1986) claim that the eye movements of typically-developing adolescents while reading a text that is too difficult for them is similar to the eye movements of dyslexic adult readers. Therefore, in this study, our second aim was to examine more closely adolescents in order to compare their results to our earlier studies on both dyslexic and non-dyslexic adults. The results of our studies on dyslexic and non-dyslexic adults showed that dyslexic adults had poorer comprehension of garden path and implausible sentences compared to non-dyslexics and longer reading times in garden-path sentences, sentences that contain relative clauses, and implausible sentences.

The current study monitored eye movements during a sentence comprehension task, which included three different types of sentences: garden-path sentences, sentences that contain relative clauses, and implausible sentences (see Table 1). Furthermore, as part of this study, a battery of cognitive measures was administered, which included tasks on working memory, processing speed, and verbal intelligence. Analyses focused on the relationship between these individual difference variables and reading comprehension and reading times, as well as whether there were differences in comprehension and reading times between dyslexic participants and controls. The project has the following main research questions: (1) What are the differences in sentence comprehension and eye movements between dyslexic and non-dyslexic adolescents? (2) Do working memory, processing speed and/or verbal intelligence affect processing (comprehension and reading times) of sentences with complex syntax? (3) How do the results from the adolescents in the current study compare with our prior studies on adults? The final question is one that we take up in detail in the General Discussion.

Table 1

Example stimuli and comprehension questions

Experiment 1 – Garden Paths
Reflexive verbs
While Anna dressed the baby that was small and cute played on the bed. (Ambiguous)
While Anna dressed, the baby that was small and cute played on the bed. (Unambiguous)
Comprehension question
Did Anna dressed the baby?

Optionally-transitive verbs
While Susan wrote the letter that was long and eloquent fell off the table. (Ambiguous)
While Susan wrote, the letter that was long and eloquent fell off the table. (Unambiguous)
Comprehension question
Did Susan write the letter?

Experiment 2 – Relative Clauses
The fisherman that the hiker passed carried heavy gear. (Object relative)
The fisherman that passed the hiker carried heavy gear. (Subject relative)
Comprehension question
Did the hiker pass the fisherman?
Did the fisherman pass the hiker?

Experiment 3 - Implausible
The man bit the dog. (Active)
The dog was bitten by the man. (Passive)
Comprehension question
Did the dog bite the man?

In the sentence processing task, we were expecting participants with dyslexia to show eye movements characteristic of dyslexia (Hawelka et al., 2010; Heiman & Ross, 1974). This includes longer reading times and more regressions. Furthermore, we expected dyslexic adolescents to show differences in comprehension compared to non-dyslexic adolescents. For ease of exposition, we present results as three experiments, but note that the same participants took part in all three experiments.

Experiment 1

Previous research on sentences with temporary syntactic ambiguities have primarily focused on typically-developing adults (Engelhardt, 2014; Traxler, 2002; Trueswell, Sekerina, Hill & Logrip, 1999). For example, Christianson et al. (2001)

showed that readers often maintain the initial interpretation of a garden-path sentence, and at the same time, they correctly analyse the main clause of the sentence, leading them to only partially reanalyse the garden-path. In these cases, the syntactic roles that were initially and incorrectly assigned continued to linger in the final interpretation of the sentence. In other cases, participants would fully reanalyse the sentence and correct their initial misinterpretations, which results in a final interpretation which has a syntactic structure that is fully consistent with the input string (Christianson et al., 2001).

With regard to predictions for this experiment, we hypothesised that our adolescent participants, both controls and dyslexics, would be less likely to engage in full reanalysis than the adults in Chapter 2. This is due to the adolescents' lack of print exposure and experience with more complex grammatical and syntactical structures. As adolescents gain experience in reading more complex prints and texts through maturation and time, it was expected that this lack of experiences would affect their abilities to efficiently revise garden path sentences. Additionally, for dyslexic adolescents, their phonological processing deficit would result in further difficulties in reading complex sentences, like garden path sentences (Bishop & Snowling, 2004). Furthermore, the bottleneck in working memory will also result in more misinterpretations of ambiguous sentences (Gathercole et al., 2006).

Moreover, we expected higher rates of full reanalysis to be associated with regressions from the disambiguating region and elevated total reading times, which would be consistent with the differences observed between children and adolescents (Engelhardt, 2014). We also expected dyslexic adolescents to show longer reading times in the disambiguating region of the sentence, and for them to be even more likely than control adolescents to engage in partial reanalysis. Regarding individual differences, we expected that working memory and verbal intelligence to be more highly associated with comprehension accuracy than would processing speed, due to the significance of those two cognitive factors in sentence comprehension in our adult sample.

Method

Participants

Thirteen adolescents with self-reported dyslexia and 13 adolescents without dyslexia were recruited from local secondary schools and colleges. All participants with dyslexia and their parents verified that they had diagnostic assessments for dyslexia in the past. All participants were native speakers of British English with normal or corrected-to-normal vision and they were between 13 and 17 years old. All participants were reimbursed with an £8 voucher. Demographic information about the sample is provided in Table 2.

Table 2

Means and standard deviations for demographic variables and the Rapid Automatised Naming, working memory, processing speed and verbal skills for the two diagnostic groups.

	Controls (N = 13)	Dyslexics (N = 13)	*t-value*
Variable	Mean (SD)	Mean (SD)	
Age (years)	15.0 (1.4)	15.0 (1.4)	$t(24) = .04$
Gender (% male)	.54	.54	$t(24) < .001$
RAN Letters (seconds)	13.3 (2.6)	18.9 (6.5)	$t(15.6) = -2.9$*
RAN Numbers (seconds)	11.7 (1.9)	16.1 (4.1)	$t(24) = -3.5$**
Working memory			
Digit span backward	99.6 (17.5)	89.6 (10.5)	$t(24) = -1.77$
Processing speed			
Symbol search	92.3 (9.0)	81.9 (13.3)	$t(24) = -2.33$*
Verbal skills			
Vocabulary	96.5 (11.6)	81.9 (14.2)	$t(24) = -2.87$**

Note. *$p < .05$, **$p < .01$. RAN = rapid automatised naming.

Standardised Measures

Rapid Automatised Naming. All participants completed both a letter and a number RAN test (Denckla & Rudel, 1976) using the Comprehensive Test Of Phonological Processing (CTOPP 2). The RAN task requires participants to name a series of letters or numbers sequentially aloud as quickly and accurately as possible. The time taken to complete an array was recorded with a stopwatch. Participants completed one letter array for practice, and two served as the critical trials (i.e. one letter array and one number array). The score for each task was the total time that was needed to complete the task, higher scores indicate worse performance. Each array consisted of four rows of nine items. Letters and numbers were presented in Arial font, and all items appeared on the same side of a white sheet of A4 paper. The standardised procedures of administration for this task were followed as described in the test manual. Independent samples *t*–tests revealed significantly longer naming times for the dyslexic group on the letter array (see Table 2). The reliability of the CTOPP-2 subtests have been demonstrated by average internal consistency that exceeds .80 (Wagner et al., 2013).

Working memory. Working memory was measured using a digit backward span task from the 5th Edition of the Wechsler Intelligence Scale for Children (WISC-V). In this task, participants were given increasing sequences of numbers and they were asked to repeat them back in reverse order. The score for this task was the total number of items that the participants could recall accurately. The standardised procedures of administration for this task were followed as described in the test manual.

Processing speed. Processing speed was measured using the speeded subtest of symbol search from the WISC-V. In this task, participants were required to identify whether one of the two given target symbols for every item could be found in an array of five symbols in a set amount of time. The score for this task was the total number of items that the participants could identify accurately. The standardised procedures of administration for this task were followed as described in the test manual.

Verbal Intelligence. Verbal intelligence was measured using the vocabulary subtest of WISC-V. This test requires participants to provide the definitions of words, and assesses the degree to which one has learned and is able to express meanings verbally. More specifically, participants were presented with 29 single words, one at a time, and they were asked to provide a definition for each presented word. The score for this task was the total number of items for which the participants could provide an accurate definition. The standardised procedures of administration for this task were followed as described in the test manual. With respect to the reliability of the WISC-V, the internal consistency reliability for composite, subtest, and process scores ranges from r = .80 to r = .96 (Na & Burns, 2016).

Sentence Processing

To investigate syntactic processing, we used 28 garden path sentences with two different types of verbs (i.e. reflexives and optionally transitive). The sentences were based on the long-plausible items from Christianson et al. (2001). Each participant saw 14 ambiguous and 14 unambiguous sentences. All 28 interest items (ambiguous and unambiguous sentences) were rotated across two counterbalance lists, with ambiguous sentences changing to unambiguous and vice versa (see Table 1). All items were rotated in a Latin Square Design.

Apparatus

Eye movements were recorded with an SR Research Ltd. EyeLink 1000 eye-tracker which records the position of the reader's eye every millisecond. Head movements were minimised with a chin rest. Eye movements were recorded from the right eye. The sentences were presented in 12 pt. Arial black font on a white background.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 × 2 (Sentence Structure × Verb Type × Group) mixed model, in which sentence structure and verb type were within subjects and group was between subjects. Participants completed three practice trials and 28 experimental trials. Trials were presented in a random order for each participant.

Participants were provided with a set of instructions that detailed the experimental procedure. They were then seated at the eye tracker and asked to respond to on-screen instructions using the keyboard. At the beginning of each trial, a message appeared asking the participant to press a button when they were ready to continue. After the participant pressed the button, they were required to fixate a drift-correction dot. The experimenter then initiated the trial. The sentence appeared after 500 ms, and the initial letter of each sentence was in the same position, in terms of x and y coordinates, as the drift correction dot (i.e. on the left edge of the monitor and centred vertically).

The entire sentence was presented on a single line on the screen. The participant read the sentence silently and then pressed the spacebar on the keyboard. Following a delay of 500 ms, an arithmetic problem (either addition or subtraction) appeared on the screen (e.g. 45 + 67 = 112). The problem was presented for 3000 ms and was followed by a screen prompting the participant to press the green button on the keyboard if the solution was correct, or the red button if it was incorrect. Feedback on the accuracy of the response to the math problem was given. After the feedback, participants were asked a comprehension question, which could be answered by 'Yes' or 'No' by pressing the green or red button accordingly. For all sentences, the correct response to the comprehension questions was "no". For the ambiguous sentences, accurate "no" responses indicate the extent to which participants fully revise the temporary syntactic ambiguity. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were 14 items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was $\alpha = .77$.

The rationale for including the additional arithmetic problem was the fact that we wanted to assess the representation that comprehenders generated of the sentences, without allowing them to have direct access to the sentence. We expected that the presence of the mathematical problem would clear the immediate contents of working memory, therefore resulting in the participants responding to the comprehension questions on the basis of a more long-term representation/trace of the sentence.

The testing session for each participant lasted approximately 1 hour, with several breaks between tasks to avoid fatigue. The tests were delivered in the following order for each participant: vocabulary, digits backward span, sentence processing, symbol search, RAN digits, RAN letters.

Data Screening and Analysis

We analysed the comprehension and reading time data using standard mixed ANOVAs with subjects ($F1$) and items ($F2$) as random effects. For reading times in garden path sentences, we examined the critical disambiguating word (i.e. main clause verb), and to assess whether the experimental manipulations might have a spill-over effect, we also examined the eye movements on the word that followed (i.e. N+1 word).

We first report the comprehension results, and second the eye movements. For eye movements, we report four dependent measures: first pass reading time, total reading time, proportion of trials with regression out of a word, and regression-path durations. *First pass reading time* is the sum of all fixations on a word from when a reader first enters a region to when they leave that region either forward or backward. *Total reading time* is the sum of all fixations on a word. *Regressions out* are the sum of all right-to-left eye movements from a word. *Regression path duration* is the sum of all fixations from the first time the eyes enter a region until they move beyond that region.

To assess the effects of working memory, processing speed and verbal intelligence (i.e. the individual differences), we conducted ANCOVAs in which each risk factor was co-varied separately. We were specifically interested in whether any group effects (dyslexic vs. control) changed with the inclusion of the covariate, and we were particularly interested in instances in which a group effect went from significant to non-significant with the inclusion of a covariate, suggesting shared variance.

Results

Comprehension Accuracy

The correlations between the demographic variables, the individual differences variables, and comprehension accuracy are provided in the Appendix. For comprehension accuracy, there were significant main effects of sentence structure $F1(1,25) = 14.83$, $p < .01$; $F2(1,27) = 29.08$, $p < .001$, verb type $F1(1,25) = 12.82$, $p < .01$; $F2(1,26) = 3.98$, $p = .05$ and group $F1(1,24) = 5.68$, $p < .05$; $F2(1,27) = 73.49$, $p < .001$ (see Figure 1). The unambiguous sentences had higher accuracy than ambiguous sentences (.58 vs .38), and sentences with reflexive verbs had higher accuracy than sentences with optionally-transitive verbs (.54 vs .43). Dyslexic participants had poorer comprehension accuracy than the controls (.37 vs .60). There was also a significant sentence structure × verb type interaction $F1(1,24) = 13.42$, $p < .01$; $F2(1,26) = 9.23$, $p < .01$. This interaction was driven by performance in the unambiguous-reflexive condition which was substantially higher than both unambiguous-optionally transitive $t1(25) = 4.43$, $p < .001$; $t2(19.33) = 3.07$, $p < .05$ and ambiguous-reflexive conditions $t1(25) = 5.81$, $p < .001$; $t2(13) = 7.48$, $p < .001$. None of the other interactions were significant.

As a follow up, we conducted one-sample *t*-tests to assess whether performance was significantly different from chance (i.e. 50/50). Control participants were significantly above chance in the unambiguous-reflexive condition $t(12) = 6.97$, $p < .001$. In contrast, dyslexic participants were less accurate than chance in three conditions: ambiguous-optional $t(12) = -2.63$, $p < .05$, ambiguous-reflexive $t(12) = -2.82$, $p < .05$, and unambiguous-optional $t(12) = -2.99$, $p < .05$.[10]

Individual Differences. When working memory and processing speed were included as a covariate in a 2 × 2 × 2 (Sentence Structure × Verb Type × Group) ANCOVA, the main effect of group remained significant (working memory: $F(1,23)$

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[10] Conditions that were significantly different from chance are indicated with an asterisk in Figure 1.

= 4.60, $p < .05$, and processing speed: $F(1,23) = 6.61$, $p < .05$). In contrast, when the verbal intelligence was co-varied, the main effect of group was no longer significant $F(1,23) = 2.15$, $p = .16$.

Summary. Results indicated that dyslexic participants had lower comprehension compared to controls, but this effect was not robust to the inclusion of verbal intelligence, which suggests that group differences are, at least in part, linked to differences in verbal intelligence (see Table 2).

Eye Movements – Disambiguating Verb

Fixation Durations. First pass reading times showed only a significant main effect of group $F1(1,24) = 15.27$, $p < .01$; $F2(1,27) = 94.73$, $p < .001$, in which dyslexic participants had longer first pass reading times compared to controls (see Table 3). None of the other main effects or interactions were significant. Total reading times showed only a significant main effect of sentence structure $F1(1,25) = 5.97$, $p < .05$; $F2(1,27) = 7.96$, $p < .01$, where the ambiguous sentences had longer reading times than the unambiguous. None of the other main effects or interactions were significant.

Regressions. Regressions out of the disambiguating verb showed only a significant main effect of verb type $F1(1,25) = 5.98$, $p < .05$; $F2(1,26) = 1.12$, $p = .30$, in which sentences with reflexive verbs had a higher proportion of trials with a regression than did the optional verbs.[11] None of the other main effects or interactions were significant. Regression path durations showed significant main effects of sentence structure $F1(1,25) = 5.56$, $p < .05$; $F2(1,27) = 8.41$, $p < .01$ and verb type $F1(1,25) = 7.20$, $p < .05$; $F2(1,26) = 3.06$, $p = .09$. Ambiguous sentences and sentences with reflexive verbs showed longer regression paths than unambiguous sentences and sentences with optional verbs, respectively. None of the other main effects or interactions were significant.

[11] Verb type was marginally significant in two of the item analyses, and this is likely due to the fact that the item analyses treat “verb type” as a between subjects variable, which means it has less power than the by subjects analysis.

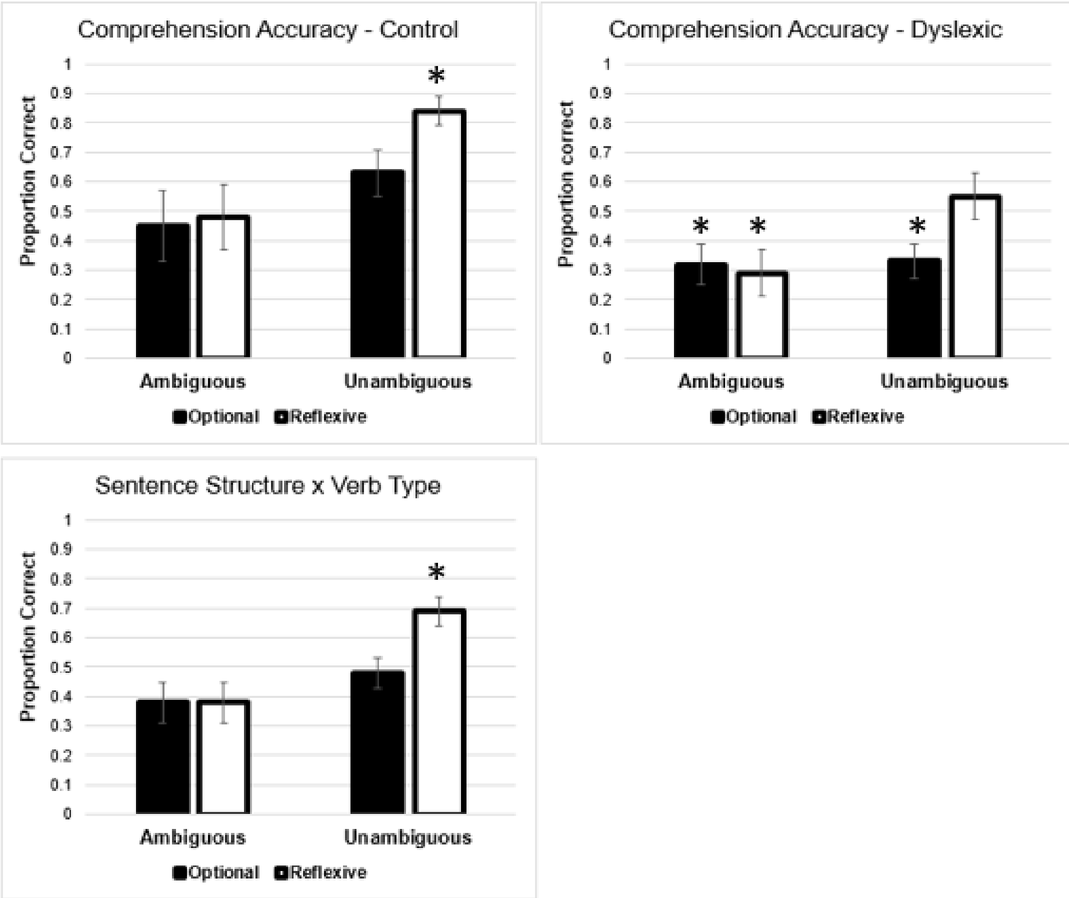

Figure 1. Mean comprehension accuracy. Upper left shows results for controls, upper right shows results for dyslexics, and lower left shows the structure by verb type interaction. Error bars show the standard error of mean.

Individual Differences. The only significant group effect was first pass reading times. For first pass reading times, the main effect of group was robust to all three individual differences variables (working memory: $F(1,23) = 11.00$, $p < .01$, verbal intelligence: $F(1,23) = 12.04$, $p < .01$, and processing speed $F(1,23) = 8.83$, $p < .01$).

Summary. Dyslexic participants showed longer first pass reading times than the controls. When working memory, processing speed and verbal intelligence were co-varied, the main effect of group remained significant.

Eye Movements - N+1

Fixation Durations. First pass reading times showed only a significant main effect of group $F1(1,24) = 7.09$, $p < .05$; $F2(1,27) = 25.12$, $p < .001$, in which dyslexic participants showed longer reading times than the controls (see Table 3) .

None of the other main effects or interactions were significant. Total reading times showed only a significant main effect of group $F1(1,24) = 5.04$, $p < .05$; $F2(1,27) = 15.28$, $p < .01$, with dyslexic participants showing longer total reading times. None of the other main effects or interactions were significant.

Regressions. None of the main effects or interactions were significant for either regressions out or regression path durations.

Individual differences. For first pass reading times, when working memory was co-varied, the main effect of group remained significant $F(1,23) = 4.55$, $p < .05$, and when processing speed was covaried, the main effect of group was marginal $F(1,23) = 3.83$, $p = .06$. However, when verbal intelligence was included in the model, the main effect of group was no longer significant $F(1,23) = 1.40$, $p = .25$. For total reading times, when individual differences were included in the model the main effect of group was no longer significant with processing speed $F(1,23) = 1.74$, $p = .20$ and verbal intelligence $F(1,23) = 2.25$, $p = .15$. However, when working memory was included the main effect of group was marginal $F(1,23) = 3.31$, $p = .08$.

Summary. When verbal intelligence and processing speed were included, the group effect on first pass and total reading times were not significant, which indicates that variance in verbal intelligence and processing speed can account for differences in fixation durations. For working memory, the main effect of group was not significant on total reading times, but remained significant on first pass reading times, which suggests that variance in working memory can account for differences in total reading times but not first pass reading times [12] .

[12] Marginally significant results for both regions are presented in the Appendix.

Table 3

Mean reading times for disambiguating verb and N + 1 by group and experimental condition.

	First Run		Total Reading		Regressions		Regression path		
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
Controls									Disambiguating verb
GP opt	284.1	108.7	630.5	250.2	.36	.26	1091.4	672.1	
GP ref	327.1	109.1	613.7	193.0	.42	.31	1576.9	1430.8	
NGP opt	292.1	71.8	509.7	169.5	.24	.21	690.7	531.9	
NGP ref	284.8	52.5	497.9	178.2	.31	.16	788.7	477.3	
Mean	297.0	71.8	563.0	166.9	.33	.18	1036.9	600.8	
Dyslexics									
GP opt	476.7	150.2	871.5	573.7	.23	.19	762.6	387.7	
GP ref	450.2	150.5	863.1	515.3	.26	.18	1031.5	798.6	
NGP opt	400.9	107.6	644.0	298.6	.17	.19	664.5	420.1	
NGP ref	440.1	165.1	764.1	329.3	.28	.20	1045.7	652.9	
Mean	441.8	112.9	785.7	372.8	.24	.14	876.1	409.8	
Controls									N + 1 word
GP opt	283.6	132.8	325.5	194.8	.58	.31	1869.8	1246.9	
GP ref	247.9	120.3	336.6	185.1	.55	.24	1577.4	1116.2	
NGP opt	287.0	162.4	339.6	237.9	.45	.19	1376.5	821.1	
NGP ref	285.4	93.4	285.1	153.1	.60	.22	1743.6	728.0	
Mean	276.0	110.3	321.7	157.4	.55	.18	1641.8	713.6	
Dyslexics									
GP opt	403.1	128.9	527.8	365.2	.42	.25	1627.0	1142.3	
GP ref	412.4	190.3	460.5	187.2	.56	.20	2067.9	2285.6	
NGP opt	429.2	181.8	532.9	294.4	.47	.30	1592.0	1057.1	
NGP ref	321.5	126.3	392.9	210.0	.57	.27	1554.2	1361.4	
Mean	391.5	110.8	478.5	196.8	.50	.16	1710.3	984.5	

Discussion

Experiment 1 showed that individuals with dyslexia had worse comprehension than controls, but the difference was not robust to the inclusion of verbal intelligence. The relationship between successful full reanalysis and verbal intelligence is something that we had expected given previous findings (e.g. Van Dyke et al., 2014). A few more comments are in order about the comprehension data. The first is that individuals with dyslexia were more likely to obtain the garden-path misinterpretation (partial reanalysis) in three out of four conditions (both ambiguous conditions and the un-ambiguous optional condition) and in one condition were essentially at chance performance (unambiguous-reflexive). Controls in contrast, were essentially at chance in three conditions (both ambiguous conditions and the un-ambiguous optional condition), and in one condition were successfully obtaining the correct interpretation. This pattern of results suggests that individuals with dyslexia do not revise the misinterpretation, despite the fact that they spend more time reading the sentences.

Regarding the comparisons of adolescents to adults, a couple of key findings stand out from the results of this experiment and those presented in Chapter 2. The first is that control adolescents performed better than control adults with sentences containing optionally-transitive verbs, which suggests that they do make inferences as much as adult readers. The second is that dyslexic adolescents performed worse than adult dyslexics with sentences containing reflexive verbs, which suggests that they do not have the ability to shift to the reflexive reading of the intransitive verb. This suggests a deficit in semantic processing, which is consistent with the findings of Traxler (2002), who tested typically-developing children. However, it is important to note that these differences are descriptive and not statistically different, as the two data sets were not entered in the same model for comparison.

In terms of fixation durations, we found that dyslexics had elevated first pass reading times at the disambiguating verb, which was robust to the inclusion of individual differences. At the N + 1 word, we also observed elevated first pass reading times in dyslexics, but this difference was not robust to individual differences in verbal intelligence. One key prediction that was based on prior research (i.e. Engelhardt, 2014) was that increased comprehension may be linked with an increased likelihood of regressions from the disambiguating word. However, the correlations between comprehension and the eye movement measures (see

Appendix) only revealed only one marginal positive correlation and it was in the ambiguous-optional condition. Participants with a higher proportion of trials with regression in this condition were more likely to get the comprehension question correct. Regarding the comparisons of adolescents to adults (Chapter 2), we observed a several key differences in first pass and total reading times between controls and dyslexics. Specifically, control adolescents performed similarly in terms of the time spent reading, whereas dyslexic adolescents showed elevated readings over adult dyslexics, in every case, more than 100 ms longer, which could be a secondary result of slower phonological processing (Bishop & Snowling, 2004; Breznitz, 2002).

Experiment 2

Research on adult readers has established that object relative clauses are more difficult to comprehend than subject relative clauses (e.g. Gordon et al., 2001; Staub, 2010; Traxler et al., 2002). With respect to eye movements, studies have reported an increased number of regressions and longer reading times for object relatives compared to subject relatives (Gordon, Hendrick, Johnson, & Lee, 2006; Staub, 2010; Traxler et al., 2002, Traxler et al., 2005). In a recent study, Staub (2010) reported that adult readers showed increased reading times at the relative verb and an increased number of regressions from the relative noun. This pattern of results was interpreted as evidence that both expectation-based processes (Hale, 2001; Levy, 2008) and memory-based processes (Gibson, 1998) contribute to the difficulty of object relatives as compared to subject relatives. The contrast, between expectation- and memory-based processes relates to the debate about the underlying causal factors associated with object relatives compared to subject relatives, and also, about where that difficulty should occur.

Regarding children's comprehension of relative clauses, de Villiers, Flusberg, Hakuta and Cohen (1979) focused on the difficulties that children (3 – 7 years old) showed in the comprehension relative clauses. Their results showed a clear developmental trend in which older children comprehended relative clauses better than younger children. Thus, in the current study, we expected to observe in all participants a difference between subject and object relatives, that is, object relatives would show lower comprehension accuracy and eye movement signatures of increased processing difficulty. In adults, we did not observe differences between dyslexic and non-dyslexics in comprehension, but we did observe that dyslexics spent longer reading the sentences (i.e. longer total reading times and longer regression path durations). Moreover, much more of the difference between subject and object relatives was accounted for by individual differences in working memory.

Therefore, in the current study, we predicted equal comprehension accuracy between controls and dyslexic adolescents, but that adolescents would show lower comprehension than adults in our earlier study. This is due to the fact that comprehension accuracy in sentences with relative clauses is associated more with processing of semantics, which is not impaired in individuals with dyslexia. In terms of eye movements, we expected that both controls and dyslexic adolescents would spend significantly longer reading the sentences, rather than an increased number of regressions (cf. Staub, 2010). Our prediction here is based on the adolescents lack of exposure and experience with more complex syntactically structures and texts, which will require additional processing and revision of the components of each sentence. Finally, we expected that group differences would likely be accounted for by individual differences in working memory, which would be consistent with the assumption that object relative difficulty is driven by memory-based processes (Gibson, 1998).

Method

Participants

Same as Experiment 1.

Standardised Measures

Same as Experiment 1.

Apparatus

Same as Experiment 1.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 (Type × Group) mixed model, in which sentence structure was within subjects and group was between subjects. We used 14 sentences with two different types of relative clause, seven with object-relatives and seven with subject relatives (see Table 1). These sentences were based on the items used in Traxler et al. (2002). Trials were presented in a random order for each participant. All 14 experimental items were rotated across two counterbalance lists, with object relative clauses changing to subject relative clauses and vice versa. Seven sentences with relative clauses required a “yes” response and 7 required a “no” response. The procedure was the same as in Experiment 1. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were 14 items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was α = .89.

Data Screening and Analysis

We analysed the comprehension and reading time data using standard mixed ANOVAs with subjects (*F*1) and items (*F*2) as random effects. For eye movement regions of interest, we examined the relative verb and the relative noun separately. We first report the comprehension results, and second the eye movements. For both interest areas, we report four dependent measures: first pass reading time, total reading time, proportion of trials with regression, and regression-path durations. The same analysis procedures were followed as in Experiment 1.

Results

Comprehension Accuracy

The correlations between the demographic variables, the individual differences variables, and comprehension accuracy are presented in the Appendix. For comprehension accuracy, the main effect of type was marginally significant $F(1,23) = 3.52$, $p = .07$ (see Figure 2). The subject relatives had higher comprehension accuracy than object relatives (.75 vs .65). Participants with dyslexia showed poorer comprehension compared to controls (.61 vs .78), but the difference was not significant ($p > .10$). The interaction was also not significant ($p > .90$).[13]

[13] All four conditions (see Figure 2) were significantly (all *p's* < .01) above chance (i.e. > 50%).

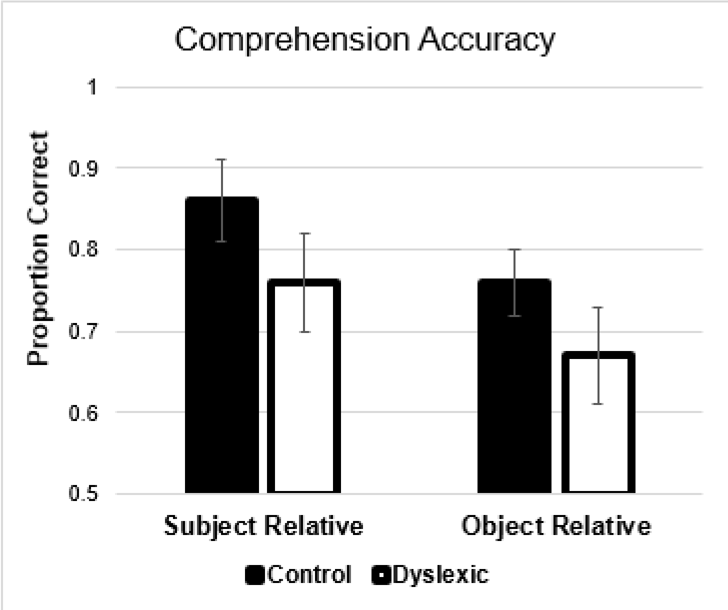

Figure 2. Mean comprehension accuracy. Error bars show the standard error of the mean.

Eye Movements - Relative Noun

Fixation Durations. The means for the eye movement measures are presented in Table 4, and the results of the inferential analyses are presented in Table 5. Results showed a main effect of type on total reading times, with object relatives showing longer reading times, but this effect was not robust to the inclusion of individual differences variables. When verbal intelligence was included in the model, the main effect of type on first pass reading times was significant. There was also a significant interaction between verbal intelligence and type (see Appendix). None of the other main effects or interactions were significant.

Regressions. There were no significant effects on either regressions or regression path durations.

Eye Movements – Relative Verb

Fixation Durations. The means for the eye movement measures are presented in Table 4, and the results of the inferential analyses are presented in Table 6. Results showed a significant main effect of group on first pass reading times, in which dyslexic participants showed longer first pass reading times compared to controls (314 ms vs. 477 ms). When verbal intelligence was included in the model, the main effect of group remained unchanged and a significant main effect of type and a significant interaction between type and verbal intelligence emerged (see Appendix). When working memory and processing speed were covaried, the main effect of group remained significant. For total reading times, results showed only significant main effect of type when verbal intelligence was covaried. There was also a significant main effect of verbal intelligence and the same interaction between type and verbal intelligence that was observed for first pass reading times. There were two marginal effects. The first was a marginal interaction between type and group, and the second was a marginal main effect of processing speed. The interaction was driven by the differences between subject and object relatives in controls. The dyslexics, in contrast, had higher reading times and there was no difference between subject and object relatives.

Regressions. For regression and regression path durations, results showed only two significant effects. The first was an interaction between type and working memory on regressions, and the second was a main effect of type on regression path durations, in which object relatives showed longer regression path durations compared to subject relatives. However, this main effect was not robust when individual differences variables were included in the model. With respect to the interaction, results showed that it was the subject relatives that were significantly correlated to working memory, but objects relatives were not correlated with working memory. This pattern of results is difficult to reconcile with the findings in Chapter 3, and most theoretical accounts of the processing of object relatives. We return to this issue in the General Discussion.

Discussion

Experiment 2 showed that dyslexic and control adolescents performed similarly in terms of comprehension accuracy, which highlights that in sentences that require competent use of semantic interpretation strategies, the phonological deficit that dyslexics experience does not have such a significant impact on their reading comprehension processes. This finding is also consistent with the adult data (see Chapter 3) and it indicates that from an younger age, readers are able to accurately interpret the meaning of sentences with relative clauses, regardless of whether they have dyslexia or not. It could be the case that the cognitive processes involved in processing complex semantics (i.e. association with real world events, suppression) have already significantly developed by the time an individual reaches adolescence.

At the relative noun, there were very few significant differences. Difficulty at this position in the sentence was expected to be driven primarily by differences in expectation-based processes (Hale, 2001; Levy, 2008). One obvious explanation for the lack of differences between adolescents and adults could be that because adolescents have less reading experience, perhaps they do not generate as strong of predictions as do adult university students, and thus, do not show significant differences at the relative noun. Again it is essential to mention that these differences are descriptive and not statistically different, as the two data sets were not entered in the same model for comparison.

At the relative verb, our findings showed that non-dyslexic adolescents required less time to read the sentences for the first time, while dyslexic adolescents showed results showed a lot longer reading times. This could indicate that although the phonological deficit is not affecting the dyslexic adolescents' comprehension, it has a substantial impact on their reading speed and the time that they need to correctly interpret sentences (Schultz et al., 2008). The intact phonological processing skills of control adolescent is what allows them to perform similarly to non-dyslexic adults. This discrepancy in first pass reading times between the two groups is similar to the results in adults, which further highlights the persistence of the impact that the phonological impairments have on the reading times of dyslexic individuals.

To summarise, this study has provided a valuable insight into the development of cognitive skills associated with the processing of sentences with relative clauses. Our results highlight the fact that the phonological processing impairment that dyslexics experience has a substantial secondary impact on their reading speed and in the time that they need in order to correctly comprehend a sentence with relative clause, regardless of their age. However, this phonological deficit or bottleneck in working memory processes does not appear to affect the dyslexics' comprehension of sentences with relative clauses. This indicates that when semantics play a more important role than syntax in a sentence, then dyslexic readers, both adolescents and adults perform similarly.

Table 4

Mean reading time for eye movement measures by group and experimental condition.

	First Run Reading		Total Reading		Regressions		Regression path	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Relative Noun								
Controls								
OR centre	342.0	168.5	1084.3	438.2	.38	.19	1111.7	687.6
SR centre	408.5	314.7	946.5	544.8	.25	.18	845.8	666.8
Dyslexics								
OR centre	324.3	95.7	1049.9	409.3	.27	.21	901.6	474.0
SR centre	336.5	118.3	841.6	333.2	.28	.13	888.5	440.5
Relative Verb								
Controls								
Object	343.5	97.8	1247.5	486.4	.36	.20	1007.3	386.1
Subject	285.2	70.4	1032.9	314.7	.23	.17	680.0	317.8
Dyslexics								
Object	481.0	146.5	1153.9	749.0	.28	.19	1543.7	969.3
Subject	473.7	190.2	1254.2	733.7	.29	.21	966.8	537.3

Table 5

Mixed ANCOVA analysis for eye movement measures for the relative noun.

	First Pass RT	Total RT	Regressions Out	Regression Path
2 x 2 (Type x Group)				
Type	N.S.	$F(1,24) = 5.00, p < .05$	N.S.	N.S.
Group	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
ANCOVA – with Verbal IQ				
Type	$F(1,23) = 4.30, p = .05$	N.S.	N.S.	N.S.
Group	N.S.	N.S.	N.S.	N.S.
Verbal IQ	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Verbal IQ	$F(1,23) = 5.15, p < .05$	N.S.	N.S.	N.S.
ANCOVA – with WM				
Type	N.S.	N.S.	N.S.	N.S.
Group	N.S.	N.S.	N.S.	N.S.
Working Memory	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Working Memory	N.S.	N.S.	N.S.	N.S.
ANCOVA – with PS				
Type	N.S.	N.S.	N.S.	N.S.
Group	N.S.	N.S.	N.S.	N.S.
Processing speed	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Processing speed	N.S.	N.S.	N.S.	N.S.

Note. Effect sizes η_p^2 are reported in parentheses. [a] indicates significant in F2 item analysis (see Appendix).

Table 6

Mixed ANCOVA analysis for eye movement measures for the relative verb.

	First Pass RT	**Total RT**	**Regressions Out**	**Regression Path**
2 x 2 (Type x Group)				
Type	N.S.	N.S.	N.S.	$F(1,24) = 18.35$, p < .001
Group	$F(1,24) = 16.60$, $p < .001$	N.S.	N.S.	$F(1,23) = 3.71$, $p = .07$
Type x Group	N.S.	$F(1,24) = 3.29$, $p = .08$	N.S.	N.S.
ANCOVA – with Verbal IQ				
Type	$F(1,23) = 4.46$, $p < .05$	$F(1,23) = 11.61$, $p < .01$	N.S.	N.S.
Group	$F(1,23) = 13.12$, $p < .01$	N.S.	N.S.	N.S.
Verbal IQ	N.S.	$F(1,23) = 6.62$, $p < .05$	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Verbal IQ	$F(1,23) = 5.19$, $p < .05$	$F(1,23) = 12.62$, $p < .01$	N.S.	N.S.
ANCOVA – with WM				
Type	N.S.	N.S.	$F(1,23) = 4.08$, $p = .06$	N.S.
Group	$F(1,23) = 12.11$, $p < .01$	N.S.	N.S.	N.S.
Working Memory	N.S.	N.S.	N.S.	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Working Memory	N.S.	N.S.	$F(1,23) = 5.07$, $p < .05$	N.S.
ANCOVA – with PS				
Type	N.S.	N.S.	N.S.	N.S.
Group	$F(1,23) = 12.87$, $p < .01$	N.S.	N.S.	N.S.
Processing speed	N.S.	$F(1,23) = 3.95$, $p = .06$	$F(1,23) = 3.79$, $p = .06$	N.S.
Type x Group	N.S.	N.S.	N.S.	N.S.
Type x Processing speed	N.S.	N.S.	N.S.	N.S.

Note. Effect sizes η_p^2 are reported in parentheses. [a] indicates significant in F2 item analysis (see Appendix).

Experiment 3

According to the Good Enough Theory, non-canonical sentences, such as passives, are frequently misinterpreted because readers tend to generate a shallow or superficial interpretations (Ferreira & Patson, 2007; Ferreira, Bailey, & Ferraro, 2002; Ferreira, et al., 2009). The explanation offered for these findings is that readers employ a small number of parsing heuristics, which permit a fast-and-frugal parse of linguistic input, especially in cases in which detailed algorithmic parsing is not necessary. One assumed parsing heuristic is the noun-verb-noun strategy which has readers interpret the first noun phrase of a sentence as the agent of the action and the noun phrase following the verb as the patient or theme. A second assumed heuristic involves semantic plausibility – with respect to real-world knowledge. In this case, readers tend to rely on their knowledge of states of affairs in the real world and when linguistic input deviates substantially from real-world plausibility, readers tend to "normalise" their interpretation. These two processing strategies have been investigated and confirmed in many different studies (Christianson et al., 2001, 2006; Ferreira, 2003; Patson et al., 2009).

To date, only a handful of studies have looked at the processing of implausible and passive sentences in children/adolescents (e.g. Gordon & Chafetz, 1990; Joseph et al., 2008; Savage, Lieven, Theakston, & Tomasello, 2003; Traxler, 2002). In general, we expected both groups of adolescents to show worse comprehension and to have longer reading times than the adults in our previous study (see Chapter 4), due to the low frequency of encountering implausible constructs and sentences in passive voice in everyday written language.

Moreover, if individuals with dyslexia rely to a greater extent on parsing heuristics, then we would expect that dyslexic adolescents would show more misinterpretations with passive sentences than for actives. This is because in this experiment, we only examined implausible sentences (see Table 1), as it was the subset of sentences that revealed striking results about adults' comprehension of constructs that are opposite of the expected interpretation that reflects real world expectations and the use of parsing heuristics. We also reduced the number of sentences for the adolescent study in order to have a shorter testing session that would prevent fatigue for younger participants. Thus, the passive-implausible condition should be affected by both the noun-verb-noun and semantic-plausibility strategy, whereas active sentences should only be affected by semantic plausibility.

Method

Participants

Same as Experiment 1.

Standardised Measures

Same as Experiment 1.

Apparatus

Same as Experiment 1.

Design and Procedure

For the sentence processing task, the design was a 2 × 2 (Sentence type × Group) mixed model, in which sentence type was within subject and group was between subjects. Participants read 14 critical sentences, half were active or half were passive. Critical sentences were based on items from Ferreira (2003). Trials were presented in a random order for each participant. The 14 critical items were rotated across two counterbalance lists, with active sentences changing to passive and vice versa (see Table 1). For all active and passive sentences, the correct response to the comprehension questions was “no”. The procedure followed was the same as in Experiment 1. For the reliability of the sentence processing task, we computed split-half reliabilities. Because there were 14 items in each of the within-subjects conditions, we used Spearman– Brown prophecy formula corrected coefficients (Brown, 1910; Spearman, 1910). The mean reliability was $\alpha = .76$.

Data Screening and Analysis

We analysed the comprehension and reading time data using standard mixed ANOVAs with subjects ($F1$) and items ($F2$) as random effects. With respect to eye movements and reading times, we examined the reading times for the entire sentence. We first report the comprehension results, and second the eye movements. For active and passive sentences, we report first pass reading times, total reading times, and proportion of trials with regression. To assess individual difference variables (i.e. working memory, processing speed and verbal intelligence), we conducted additional ANCOVAs in which each variable was co-varied separately. We were specifically interested in whether any group effects (dyslexic vs. control) changed with the inclusion of the covariate, and we were particularly interested in instances in which a group effect went from significant to non-significant with the inclusion of a covariate, suggesting shared variance.

Results

Comprehension Accuracy

The correlations between the demographic variables, the individual differences variables, and comprehension accuracy are presented in the Appendix. For comprehension accuracy, there was a significant main effect of group $F1(1,24) = 5.63$, $p < .05$; $F2(1,13) = 27.42$, $p < .001$ (see Figure 3), in which dyslexic participants showed poorer comprehension than the controls (.64 vs. .85). The other main effect and the interaction were not significant. As a follow up, we conducted one-sample *t*-tests to assess whether performance was significantly different from chance (i.e. 50/50). Control participants were above chance with both active $t(12) = 7.97$, $p < .001$ and passive sentences $t(12) = 4.52$, $p < .01$. In contrast, dyslexic participants were significantly above chance only with active sentences $t(12) = 2.19$, $p < .05$.

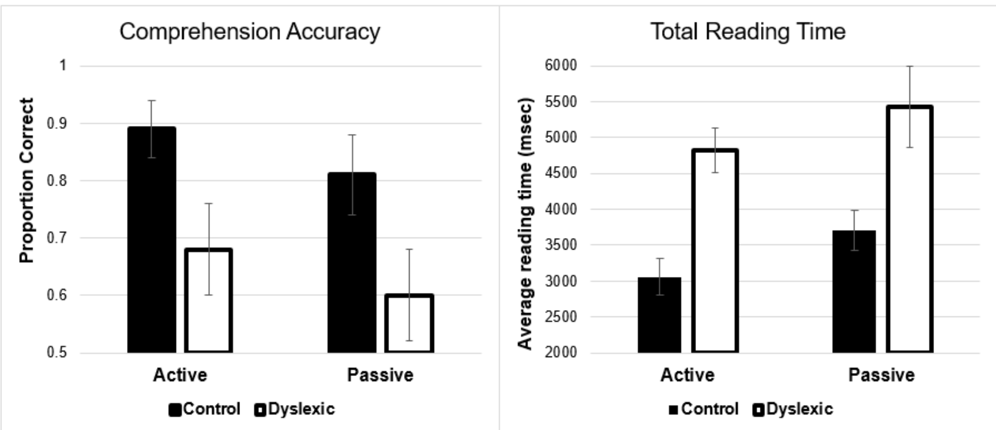

Figure 3. Left panel shows the mean comprehension accuracy, and columns indicated with an asterisk indicate performance significantly above chance. Right panel shows the total sentence reading times. Error bars show the standard error of mean.

Individual Differences. When the individual differences variables were included as covariates in a 2 × 2 (Sentence Type × Group) ANCOVA, the main effect of group was no longer significant (working memory: $F(1,23) = 3.66$, $p = .07$, verbal intelligence $F(1,23) = 2.75$, $p = .11$, and processing speed $F(1,23) = 2.07$, $p = .16$). Although, it remained marginal with working memory included.

Summary. Results indicated that dyslexic participants had lower comprehension accuracy compared to controls. When working memory, processing speed, and verbal skills were co-varied, the main effect of group was no longer significant.

Reading Times – Whole Sentence

The correlations between the demographic variables, the individual differences variables, and total reading times are presented in the Appendix. Total sentence reading times showed significant main effects of sentence type $F1(1,25) = 9.52$, $p < .01$; $F2(1,13) = 6.34$, $p < .05$ and group $F1(1,24) = 12.68$, $p < .01$; $F2(1,13) = 126.93$, $p < .001$.[14] Dyslexic participants and passive sentences showed longer total reading times (see Figure 3). The interaction was not significant.

Individual Differences. When the individual differences variables were included in the model, the main effect of group for total reading times remained significant (working memory: $F(1,23) = 8.69$, $p < .01$, verbal intelligence: $F(1,23) = 8.73$, $p < .01$, and processing speed: $F(1,23) = 6.43$, $p < .05$). We also observed a significant main effect of processing speed and a significant interaction between sentence type and processing speed (see Appendix).

Summary. Results indicated that dyslexic participants had longer total reading times compared to controls. When individual differences variables were included, the main effect of group remained significant.

Discussion

Experiment 3 showed that individuals with dyslexia were more likely to misinterpret sentences overall, but this difference was not robust to the inclusion of the individual differences variables. In contrast, in the reading time measure, total

[14] The main effect of sentence type is likely due to the length differences between actives and passives. That is, passive sentences confound length and syntactic complexity.

reading time was significantly elevated in individuals with dyslexia and this was robust to the inclusion of individual differences variables. With respect to parsing heuristics, we did not find evidence that individuals with dyslexia experienced greater difficulty with the passive sentences, than did the control participants, which is consistent with our findings for adults in Chapter 4. Our findings were also consistent with our other studies that individuals with dyslexia were slower to read both types of sentences compared to controls, which further highlights the significance of the phonological processing deficit and its impact on sentence reading (Bishop & Snowling, 2004).

Interestingly, there was a dissociation between the online and offline measures with respect to individual differences. Comprehension differences were not robust, particularly to verbal intelligence and processing speed, but the reading time differences were robust to individual differences, which suggests that dyslexia is clearly related to slower reading. The fact that there was a main effect of group on comprehension suggests that individuals with dyslexia rely to a greater extent on real-world knowledge indicating a semantic processing issue.

General Discussion

The main aim of this study was to examine how dyslexic and non-dyslexic adolescents comprehend and read sentences with complex syntax. We also explored the impact of three individual difference variables (i.e. working memory, processing speed and verbal intelligence) and how individual differences in these variables affected sentence comprehension and online processing measures. The second aim of the study was to explore whether typically-developing adolescents show similarities in their eye movements and reading times as dyslexic adults. In order to address the second aim, we further discuss our findings regarding the adult data from Chapters 2 – 4.

Adolescent Dyslexics vs. Non-Dyslexics

Comprehension. The first aim of the current study was to examine sentence processing in adolescence. For garden paths, we observed that dyslexic participants had worse comprehension. For relative clauses, consistent with adults, there was no effect of dyslexia status on comprehension. Finally, for implausible actives and passives, the participants with dyslexia again showed comprehension deficits. These group effects showed mixed findings with respect to individual differences variables. Across all three experiments, we found that group differences in comprehension (where there were group differences) were not robust to individual difference variables. This suggests that differences between dyslexics and non-dyslexics can be accounted for by individual differences. The second aim of the experiment was to determine how the results from the current study compared to the adult data (Chapters 2 – 4). This comparison is informative because of the developmental implications across the adolescent-to-adult time period.

For the garden-path sentences, the fact that control adolescents had slightly better comprehension for sentences containing optionally-transitive verbs could suggest that adolescents are less likely to make the inference that the main clause subject is the direct object of the subordinate clause verb. Whereas, adults do seem to have a greater tendency to make this (incorrect) inference. With respect to the dyslexic group, our finding that adolescent dyslexic participants had worse comprehension for sentences containing reflexive verbs suggests that the adolescent dyslexics potentially do not benefit from the semantic boost obtained from the reflexives. Many studies using these same sentences have shown that reflexives lead to better comprehension accuracy, because it is easier to shift to a reflexive reading of the subordinate clause verb, rather than leaving it intransitive (as with optionally-transitive verbs).

For the subject/object relative sentences, the nearly identical comprehension accuracy for adults and adolescents, highlights the consolidation of semantic processing skills by adolescence. We also found that regardless of their age, all participants showed similar comprehension. Both of these findings are of significance to the wider literature on dyslexia, as they indicate that the bottleneck in working memory and the phonological processing deficit might not have such a severe impact on the comprehension of sentences that focus more on semantics rather than grammatical or syntactical structures.

For the implausible sentences, the adolescent controls and adult controls showed nearly identical results. The dyslexics, however, showed worse comprehension in dyslexic adolescents than in dyslexic adults. This finding indicates that phonological impairments at a secondary level have a more substantial impact on comprehension of individuals who do not have much experience with constructs that reflect a situation that is not likely to occur in real life. Dyslexic adolescents' difficulties with reading could lead them to avoid reading tasks in general, which then does not provide them with experience with various types of written language and print. On the other hand, non-dyslexic adolescents are potentially engaging more in tasks and activities that involve reading and processing newly encountered texts, which provides them with further print exposure. This experience could be an important factor that affect the adolescents' strategies when encountering an implausible sentence (Ferreira, 2003).

Therefore, summing across all three of the current experiments, we see a trend in which individuals with dyslexia continue to show increases in comprehension from adolescence to adulthood. More specifically, the increases in comprehension of sentences with relative clauses and all implausible sentences can be traced to semantic processing, as the phonological deficit appears to not have such a severe effect on comprehension of sentences that include contradictions with real world events. On the other hand, the improvement of comprehension of garden path sentences and passive sentences is likely due to increases in syntactic processing abilities, as it appears that the more experience individuals with dyslexia have with various types of written language and syntactic constructs, the more their comprehension improves from adolescence to adulthood for sentences with complex syntax. For controls, we do not see evidence of increases across this age range, and in fact, for one type of sentence, the adolescents performed better than did the adults.

Reading Times. Turning our attention to the reading times, we found largely main effects of group across all three of the experiments. To summarise, there was a main effect of group on first pass reading times on the disambiguating verb and the N + 1 word in garden path sentences, which were robust to the inclusion of individual differences variables. There was also a main effect of group on first pass reading times at the relative verb in subject/object relative clauses, which was also robust to the inclusion of individual differences variables. Lastly, there was a main effect of group on total reading times in active/passive implausible sentences, which was also robust to the inclusion of individual differences variables. In all cases, individuals with dyslexia spent more time reading that did controls. As these fixation duration measures were all robust to the inclusion of individual differences, we think that longer reading times are specific to dyslexia status, and are consistent with the other eye tracking studies of dyslexia (De Luca et al., 2002; Eden, Stein, Wood, & Wood, 1994; Hawelka et al., 2010; Horowitz-Kraus & Breznitz, 2011). However, generally, we did not observe differences in terms of regressions or regression path durations.

The comparison of adolescent to adult data revealed that adolescent dyslexics generally spent longer reading the disambiguating verb in garden-path sentences (first pass and total reading time). In contrast, the control adolescents showed similar reading times as the control adults. For the subject/object relatives, the pattern of reading times was much more mixed, and there were no clear correspondences between adolescents and adults. The one clear thing was that both controls and dyslexic adolescents showed longer total reading times and longer regression path durations than did control and dyslexic adults. However, we did find that control adolescents had higher rates of regressions with the object relative sentences from both the relative noun and relative verb. The rate of regressions was similar to what Staub (2010) reported. Finally, for the active/passive implausible sentences, the control adolescents spent approximately 800 ms longer reading the passives compared to the control adults, and the dyslexic adolescents spent approximately 1200 ms longer on actives and 1500 ms longer on passives. Like with garden paths, these results suggest a developmental (dyslexia) trend in which there are differences between adolescents and adults.

Individual Differences

We assessed three individual differences variables in order to determine whether any group differences (control vs. dyslexics) could be traced to weakness in working memory, processing speed, or verbal intelligence. There are good theoretical reasons to assume that working memory would be linked to both the garden-path sentences and sentences containing object relatives. It is also known that individuals with dyslexia typically have lower working memory and are slower processors (Bonifacci & Snowling, 2008; Breznitz & Misra, 2003; Chiappe, Siegel, & Hasher, 2000; Gathercole, et al., 2006). Also, several recent psycholinguistic studies have identified that individual differences in verbal intelligence are the best predictor of sentence comprehension (e.g. Engelhardt et al., 2017; Van Dyke et al., 2014). Thus, we thought this set of individual differences variables would be important to assess in this study. Our participant sample (see Table 2) indicated that the two groups differed in processing speed and verbal intelligence, but not working memory. Before presenting the findings with respect to individual differences, we think it is important to raise the issue of power.

The current study had a relatively low number of participants, which means that the study was underpowered, especially with respect to the comparisons with the adult studies (Chapter 2 – 4). The power issue is even more important when considering the findings of the ANCOVA analyses. In many instances, especially for comprehension, the inclusion of all three of the individual differences variables, removed the effect of diagnostic group. That is, there seemed to be overlapping variance between the individual differences and the group differences in comprehension. We do not think these results suggest that all three variables are necessarily important to the comprehension of sentences with complex sentences. Instead, what we think these results suggest, is that when variance in individual differences is removed, there is not much variance left over. That is, excluding variance associated with high- vs. low-performers eliminates much of the total variance. The alternate possibility is that in adolescents there is much higher correlations between the individual differences variables, but this possibility is not borne out by the data (see Appendix). Given the small sample size, we feel that strong conclusions about the relationship between individual differences and sentence comprehension is just not possible based on the current data. However, what is clear is that group differences in comprehension can be largely accounted for by individual differences, whereas group differences in reading times largely cannot be accounted for by individual differences.

A Keith Rayner Hypothesis

In the "20 Years of Research in Eye Movements in Reading", Rayner outlined several key points concerning the eye movements of dyslexic readers. In particular, he made two key claims regarding developmental patterns. The first was that if dyslexic individuals were given texts that were appropriate for their reading ability, then their eye movements looked much more similar to non-dyslexics. The second was that if children were given texts that are more advanced than their reading age, then their eye movements (fixation durations, saccade lengths, and number of regressions) begin to look like those in individuals with dyslexia. These two parallel claims led to our second aim in the current study, and more specifically, whether control adolescents in the current study would show eye movements resembling those shown in the adult dyslexics in our earlier studies (Chapter 2 – 4).

We think our data do not support the claims that Rayner made. As outlined above, our data suggests that adolescent controls pattern much more similarly to adult controls than to adult dyslexics. Thus, there is not much of a developmental difference in typically-developing individuals from adolescents to adults. However, we did find that the dyslexic adolescents and dyslexic adults do show developmental trends, that is, in this time period, dyslexic individuals make gains in terms of comprehension accuracy, and show shorter first pass and shorter total reading times.

Despite the inconsistency with Rayner's hypothesis, our findings have provided an important insight into some of the processes involved in sentence processing in adolescents and how these develop in adulthood. The fact that dyslexic adolescents required more time to read all types of sentences than their non-dyslexic peers and the dyslexic adults, indicate the substantial impact that the phonological deficit has on dyslexics' reading speed not only for words but for sentences too. This is a secondary symptom of the phonological processing difficulties and our findings show that it has more severe effects in adolescence, while in adulthood the impact remains but it is not as severe. It is important to repeat that the differences between adolescents and adults described in this chapter are not statistically different, as the two data sets were not entered in the same model for comparison.

Limitations and Future Directions

There were several limitations with the current study. The first and most important is that the sample size was somewhat small. This was due to difficulties in recruitment. Thus, we would encourage a replication study with a larger sample, especially of dyslexic adolescents. This could help clarify some of the ambiguities with respect to the individual differences variables. A second limitation was the length of the testing session. This meant that we assessed a relatively small number of sentences in the eye tracking task, and a limited number of cognitive/neuropsychological measures. A third limitation was that we did not have a standardised measure of reading ability. This could be important given the claims made by Rayner, as his claims focused on age appropriate texts.

It is also important to note that the dyslexic adolescents scored lower in the verbal skills and processing speed components, both of which tasks are indices of general intelligence. This could suggest that the differences between dyslexic adolescents and dyslexic adults indicate a sampling issue, with university adult samples being a more homogenous group of higher functioning individuals, while the younger dyslexics may be confounded with generalised lower function. In terms of future directions, we think the most obvious avenue for future research is to examine a larger sample, possibly with multiple measures of each individual difference variable.

Conclusion

On the basis of the three experiments presented in this study, we think there are three main take home messages. The first is that adolescents with dyslexia show poorer comprehension and longer reading times than do control adolescents. The comprehension results were generally not robust to individual differences in working memory, processing speed, or verbal intelligence. In contrast, the reading time measures were robust to individual differences, and thus, a key feature of dyslexia in adolescence is increased reading times, rather than differences in regressions or regression path durations. The second take home message concerns the comparison of the current data to those of adult participants. We found that control adolescents patterned similarly to control adults, which suggests not much difference in sentence processing performance between typically-developing adolescents and typically-developing adults. In contrast, we did observe substantial differences between the dyslexic adolescents and dyslexic adults. The older (dyslexic) participants, in this case, showed higher comprehension and lower reading times. The final take home message concerns the claims made by Rayner, and here, we did not find evidence consistent with the claims that control adolescents show a similar pattern to adult dyslexics.

Appendix

Experiment 1

Table A

Bivariate correlations between demographic variables, individual differences variables, and comprehension

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Age	-	.32	-.01	-.05	-.04	.16	.42*	-.00	.42*	.40*	.09	.29
2. Gender		-	.00	-.13	-.20	.03	.14	-.28	.37	.14	.13	.05
3. Dyslexia status			-	.58**	.51**	-.34	-.51**	-.43*	-.20	-.28	-.54**	-.53**
4. RAN numbers				-	.88**	-.18	-.18	-.48*	-.32	-.35	-.48*	-.45*
5. RAN letters					-	-.28	-.14	-.42*	-.42*	-.42*	-.51**	-.51**
6. Digits backward						-	.50*	.24	.06	.11	.20	.26
7. Vocabulary							-	.26	.16	.32	.47*	.49*
8. Symbol search								-	-.13	.02	.16	.08
9. Ambiguous optional									-	.89**	.42*	.57**
10. Ambiguous reflexive										-	.51**	.67**
11. Unambiguous optional											-	.60**
12. Unambiguous reflexive												-

Note. *$p < .05$, **$p < .01$. Gender: 0 = female and 1 = male. Dyslexia status: 1 = dyslexic, 0 = control

In the section below, we report the marginally significant main effects and interactions from Experiment 1.

At the disambiguating verb, first pass reading times showed a marginally significant structure x verb x group interaction $F(1,24) = 3.69$, $p = .07$ (see Figure A in Appendix), which remained marginally significant when verbal intelligence was included in the model $F(1,23) = 3.33$, $p = .08$. Total reading times showed a marginally significant main effect of group $F(1,24) = 3.86$, $p = .06$.

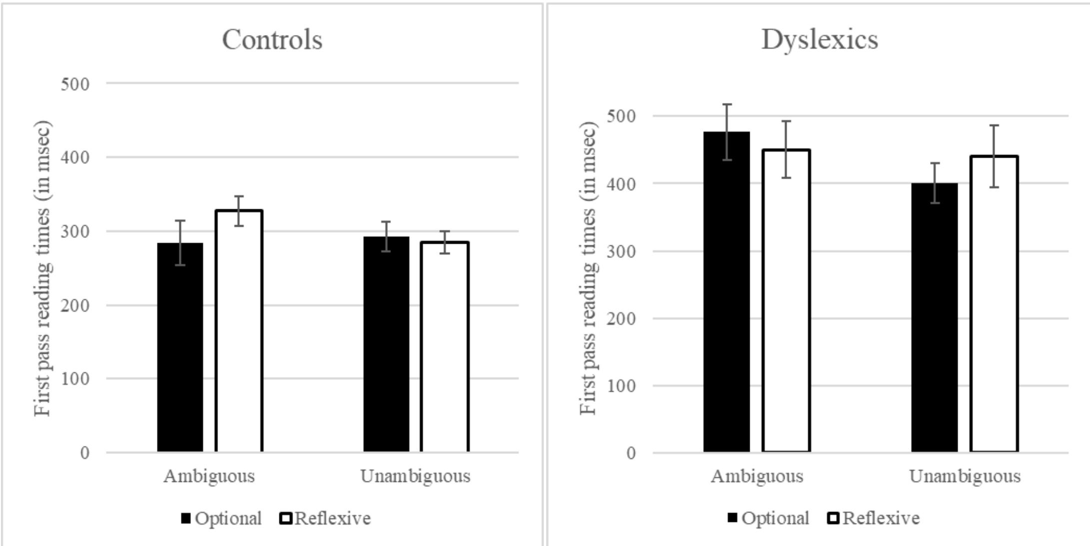

Figure A. Interaction between structure x verb x group. Left panel shows the interaction for the control group and the right shows the interaction for the dyslexic group. Error bars show the standard error of the mean.

Regressions showed a marginally significant main effect of structure when working memory was covaried $F(1,23) = 3.28$, $p = .08$ and a marginally significant structure x verbal intelligence interaction, when verbal intelligence was included in the model $F(1,23) = 3.66$, $p = .07$ (see Figure B). Finally, regression path durations showed a marginally significant structure x group interaction $F(1,24) = 4.19$, $p = .05$ (see Figure C).

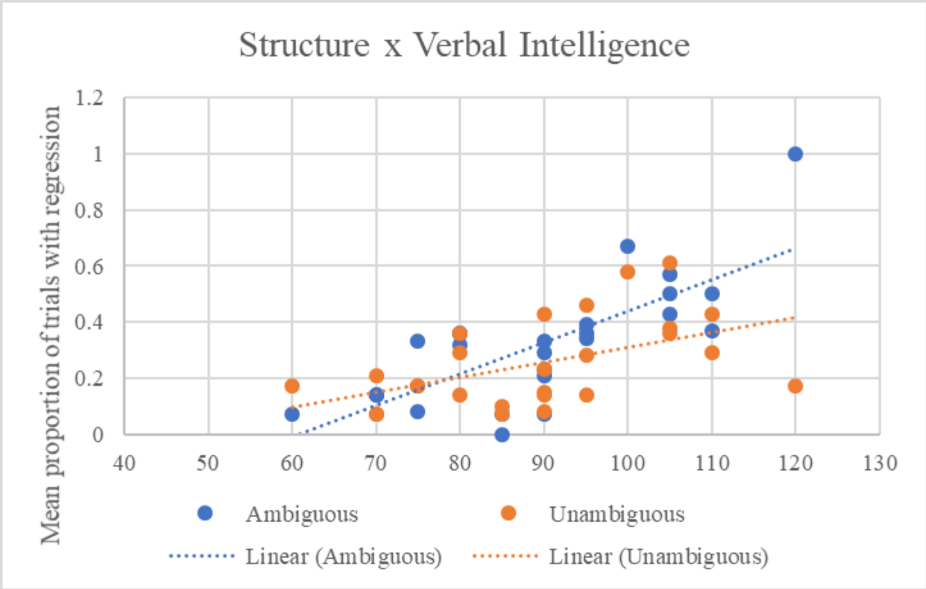

Figure B. Scatter plot showing the structure × verbal intelligence interaction.

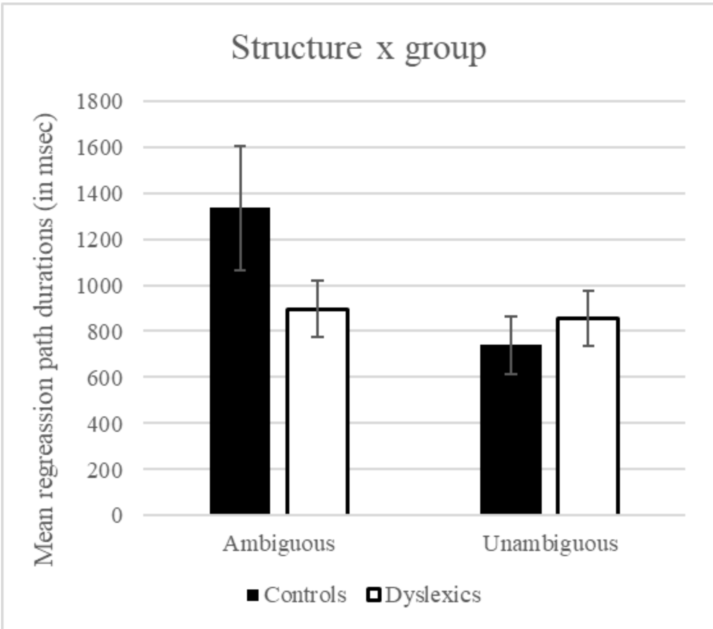

Figure C. Interaction between structure x group for regression path durations. Error bars show the standard error of the mean.

At the N+1 word, total reading times showed a marginally significant main effect of verb $F(1,24) = 3.50$, $p = .07$. There was also a marginally significant main effect of group when working memory was covaried $F(1,23) = 3.31$, $p = .08$. When verbal intelligence was included in the model, total reading times showed a marginally significant main effect of structure *F*(1,23) = 3.39, *p* = .08 and an interaction between verbal intelligence and structure *F*(1,23) = 3.83, *p* = .06 (see Figure D).

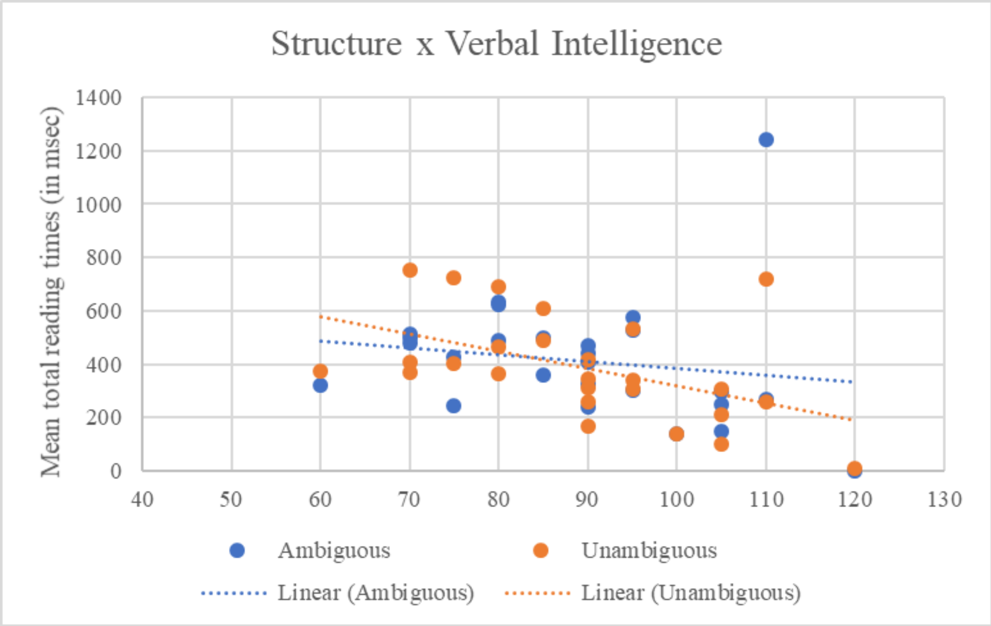

Figure D. Scatter plot showing the structure × verbal intelligence interaction.

Regressions showed a marginally significant main effect of verb *F*(1,24) = 3.84, *p* = .06. In regression path durations, when verbal intelligence was covaried, there was a marginally significant main effect of verb *F*(1,23) = 3.49, *p* = .08, as well as a verb x verbal intelligence interaction *F*(1,23) = 3.95, *p* = .06 (see Figure E).

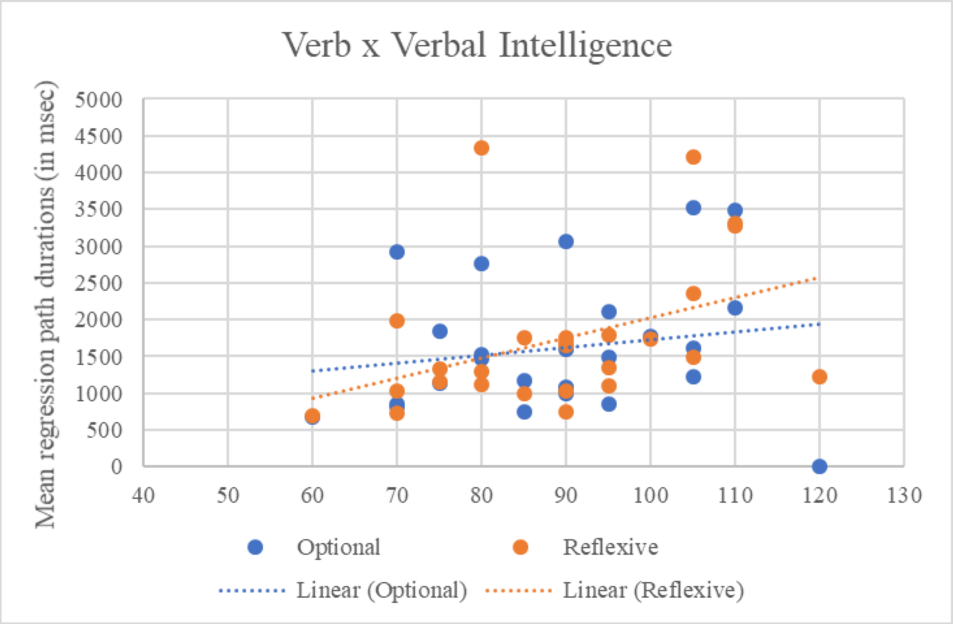

Figure E. Scatter plot showing the verb × verbal intelligence interaction.

Table B

Bivariate correlations between individual differences variables, comprehension, and eye movement measures.

	Optionally transitive				Reflexive			
	First Pass	Total RT	Reg. Out	Reg. Path	First Pass	Total RT	Reg.Out	Regress.Path
Disambiguating verb								
Dyslexia Status	.63**	.30	-.28	-.24	.54**	.44*	-.27	-.10
Verbal Intelligence	-.32	.06	.63**	.57**	-.20	.06	.74**	.56**
Working Memory	-.47*	-.20	.28	.04	-.25	-.20	.20	.16
Processing Speed	-.44*	-.50**	.09	.01	-.47*	-.61**	.05	-.16
Comp. ambiguous	-.42*	.10	.17	.40*	-.37	.01	.27	.34
Comp. unambiguous	-.54**	-.22	.31	.43*	-.48*	.03	.43*	.46*
N+1 word								
Dyslexia Status	.45*	.40*	-.16	-.01	.44*	.38	-.05	.08
Verbal Intelligence	-.67**	-.29	.12	.17	-.47*	-.38	.27	.40*
Working Memory	-.39	-.25	.04	-.09	-.26	-.29	.22	.14
Processing speed	-.31	-.51**	-.13	-.31	-.41*	-.35	-.06	-.29
Comp. ambiguous	-.18	-.22	.38	.43*	-.40*	-.15	.13	.47*
Comp. unambiguous	-.53**	-.53**	.02	-.01	-.19	-.09	-.20	.44*

Note. *$p < .05$, **$p < .01$.

Experiment 2

Table A

Bivariate correlations between demographics, individual differences, and comprehension

Variable	1	2	3	4	5	6	7	8	9	10
1. Age	-	.32	-.01	-.04	-.04	.16	.42*	-.00	.25	.32
2. Gender		-	.00	-.13	-.20	.03	.14	-.28	.43*	.10
3. Dyslexia status			-	.58**	.51**	-.34	-.51**	-.43*	-.24	-.25
4. RAN numbers				-	.88**	-.18	-.18	-.48*	-.28	-.44*
5. RAN letters					-	-.28	-.14	-.42*	-.49*	-.33
6. Digits backward						-	.50*	.24	.40*	.17
7. Vocabulary							-	.26	.39	.18
8. Symbol search								-	-.03	.10
9. Object relative									-	.18
10. Subject relative										-

Note. **p* < .05, ***p* < .01. Gender: 0 = female and 1 = male. Dyslexia status: 1 = dyslexic, 0 = control

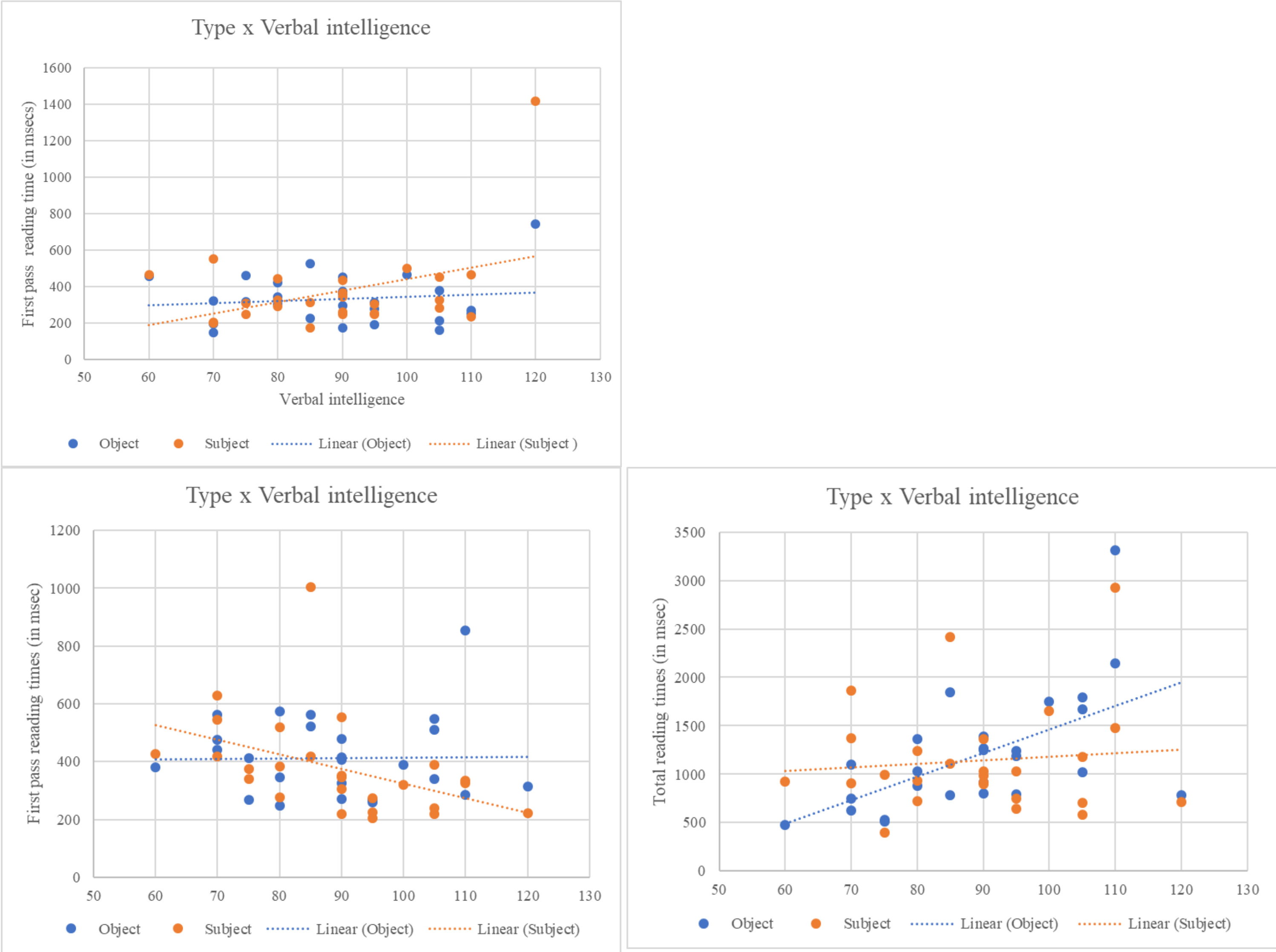

Figure A. Interactions between sentence type and verbal intelligence, for first pass (left panel) and total reading times (right panel) Top panel shows the interactions for the relative noun and the bottom panels for the relative verb.

Experiment 3

Table A
Bivariate correlations between demographics, working memory, verbal skills, processing and comprehension accuracy.

Variable	1	2	3	4	5	6	7	8
1. Age	-	.32	-.01	.16	.42*	-.002	.40*	.29
2. Gender		-	.00	.03	.14	-.28	.21	.18
3. Dyslexia Status			-	-.34	-.51**	-.43*	-.41*	-.38
4. Working memory				-	.50*	.24	.16	.39
5. Verbal Intelligence					-	.26	.29	.32
6. Processing speed						-	.53**	.35
7. Active							-	.61**
8. Passive								-

Note. *p < .05, **p < .01. Gender: 0=female, 1=male; Dyslexia: 1=dyslexic, 0=control

Table B
Bivariate correlations between demographics, working memory, verbal skills, processing and total reading time.

Variable	1	2	3	4	5	6	7	8
1. Age	-	.32	-.01	.16	.42*	-.002	.02	.21
2. Gender		-	.00	.03	.14	-.28	.004	.04
3. Dyslexia Status			-	-.34	-.51**	-.43*	.66**	.49*
4. Working memory				-	.50*	.24	-.39	-.39*
5. Verbal Intelligence					-	.26	-.37	-.25
6. Processing speed						-	-.44*	-.58**
7. Active							-	.83**
8. Passive								-

Note. *p < .05, **p < .01. Gender: 0=female, 1=male; Dyslexia: 1=dyslexic, 0=control

Chapter 6

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General Discussion

This thesis was motivated by the gap in research in sentence processing in dyslexia, as well as the view that dyslexic readers' potential sentence reading difficulties are a secondary symptom of the phonological deficit (Bishop & Snowling, 2004). The experiments in this thesis have provided additional evidence and insights into the comprehension and reading difficulties that dyslexic adults and adolescents face in sentence comprehension. At the same time, results from this thesis also have important theoretical contributions to the field of psycholinguistics. First and foremost, our findings provided significant insight into the differences that individuals with dyslexia show with respect to sentence comprehension and processing. This has been an important step towards bridging the gap in psycholinguistics between research on typically-developing readers and readers with dyslexia. Our results have also contributed to psycholinguistic debates about the role of working memory in sentence processing and the cognitive factors involved in syntactic processing.

Results Overview

Chapter 2 examined the processing and comprehension of sentences with a temporary syntactic ambiguity. The processing of garden-path sentences has previously focused on typically-developing readers (Christianson et al., 2001, 2006; Ferreira et al., 2001), and in this chapter, we measured how adults with dyslexia process and comprehend syntactically ambiguous sentences and what differences they showed compared to non-dyslexics. Our findings were consistent with many previous studies, in that slower reading and comprehension difficulties were evident in individuals with dyslexia. Dyslexic participants showed poorer comprehension compared to non-dyslexics in both ambiguous and unambiguous sentences. This difference between the two groups for the ambiguous sentences indicates that dyslexic readers engaged in partial reanalysis of those types of sentences.

In this chapter, we also investigated working memory and processing speed, and their role as cognitive factors, which could affect the comprehension and processing of garden-path sentences. Our findings suggested that working memory is more associated with syntactic processing than is processing speed. Offline comprehension revealed substantial overlapping variance between dyslexia status and working memory (Caplan & Waters, 1999; DeDe et al., 2004). Furthermore, individual differences in working memory were related to structural content, reanalysis and assignment of thematic roles in sentences with temporary syntactic ambiguity (Caplan & Waters, 1999; King & Just, 1991). These findings highlighted the significance of working memory in sentence processing and comprehension, as well as the fact that the bottleneck in working memory experienced by individuals with dyslexia can affect their comprehension of garden path sentences (Gathercole et al., 2004; Ramus & Szenkovits, 2008, 2011).

With respect to eye movements, despite their poorer comprehension, dyslexic readers showed longer reading times than the controls, particularly in the ambiguous sentences and this was observed in both interest areas (i.e. the disambiguating verb and N + 1). The group differences, as well as the interaction between sentence structure and group at the disambiguating verb remained robust even with the inclusion of working memory in the model. The bottleneck in working memory processes for dyslexic adults appears to further affect their reading speed and the time that they need to read and revise garden path sentences (Ramus & Szenkovits, 2011).

Chapter 3 focused on examining the comprehension and processing of syntactically complex sentences that contain object and subject relative clauses. The research on dyslexics' processing of these types of sentences has been very limited, and as was the case for garden-path sentences, the majority of studies have examined typically-developing individuals. Past research has highlighted that object relative clauses are more difficult to comprehend than subject relative clauses (e.g. Gordon, et al., 2001; King & Just, 1991; Traxler et al., 2002). Two theories have been put forward to explain the comprehension difficulty associated with object relatives, the Syntactic Prediction Locality Theory (SPLT) (Gibson, 1998) and the Surprisal account (e.g. Hale, 2001; Levy, 2008). The first account focuses on the high working memory demands for processing object relative clauses, while the second one suggests that the difficulty arises from the violation of the readers' expectations about the structure of the sentence.

With respect to dyslexia, Wiseheart et al.'s (2009) study examined the comprehension of sentences with subject and object relative clauses in adults with and without dyslexia and it was the closest to our studies in terms of motivation and theoretical background. They showed that dyslexic readers had poorer comprehension accuracy than non-dyslexics, which was inconsistent with our findings. Our results showed that individuals with dyslexia had similar comprehension accuracy to non-dyslexics, which shows that the phonological deficit might not be affecting at a secondary level the comprehension of sentences with semantic complexity (Bishop & Snowling, 2004). With respect to eye movements, our dyslexic participants showed significantly longer reading times than the controls. Also regarding the individual differences examined in that chapter, we found that neither working memory nor verbal intelligence were associated with differences between the two groups, as the presence of dyslexia appeared to have an independent impact the reading times regardless of individual differences in working memory and verbal intelligence.

It is important here to examine further the differences between our study and Wiseheart et al.'s (2009), as these indicate the underlying reasons for the discrepancy in the results. The most important difference is the experimental paradigm. Wiseheart et al. (2009) used a picture-sentence verification task in which two pictures were available on the screen with the sentence. Thus, the comprehension decision was made when the sentence was still visible. In contrast, in our paradigm there was an intervening maths problem and participants were answering very specific comprehension questions, regarding thematic roles and the association of specific nouns with specific verbs.

This difference in the two paradigms could potentially explain some of the disparity in the findings of the two studies. Wiseheart et al. (2009) found worse comprehension in individuals with dyslexia, but generally higher accuracy than what we reported. The generally higher accuracy in Wiseheart et al. (2009) than the one we reported could be explained by the fact that participants in Wiseheart et al.'s (2009) study selected the comprehension response while the sentence was visible which could allow for further revision of the sentence before choosing a comprehension response. The second difference concerns the sample, in our study participants were all university students, and in Wiseheart et al. (2009), participants were younger and that sample also showed differences in working memory. The age discrepancy is important because our participants may have more exposure to complex syntax given their enrolment in higher education.

Due to the multiple differences in the method and paradigms used in the two studies, apart from the type of sentences examined, it is very difficult to make meaningful comparisons that could help us reach a definitive conclusion about the processing of relative clauses in dyslexia. Future work is essential in order to address the differences between what we have reported and those reported by Wiseheart et al. (2009). Careful consideration of the participant sample and the experimental paradigm will be critically important.

In Chapter 4, we investigated the processing and comprehension of passive sentences and the use of parsing heuristics in individuals with dyslexia. We also examined individual differences in working memory and verbal intelligence. We further investigated the association of these individual differences variables on comprehension and reading times, as well as their role in parsing heuristics. Our results showed that individuals with dyslexia had differences in comprehension compared to controls, and more specifically, their comprehension accuracy was poorer in passive sentences and implausible sentences. Regarding reading times, we found that dyslexic readers showed longer reading times than non-dyslexics and all participants spent more time reading passive sentences and implausible sentences, compared to active and plausible sentences.

When we included the two individual differences variables in that experiment, verbal intelligence appeared to predict comprehension accuracy of implausible sentences, as participants with lower scores in verbal intelligence tended to show poorer comprehension with implausible sentences. Therefore, verbal intelligence seemed to be more associated with semantic processing abilities. Furthermore, our results regarding working memory showed interactions with both plausibility and structure type, as participants with lower working memory spans showed lower comprehension accuracy in passive-implausible sentences. Thus, working memory showed a stronger link with noun-verb-noun and semantic plausibility heuristics, and our findings suggested that individuals with poorer working memory abilities rely more on real-world knowledge and therefore tend to make more misinterpretations when reading semantically implausible sentences. However, both groups had similar scores in verbal intelligence and working memory, which did not lead us to conclusive inferences about the role of the bottleneck in working memory for dyslexic adults.

Finally, Chapter 5 examined the comprehension and reading times of adolescents with and without dyslexia using the same three types of sentences as Chapters 2 – 4. With garden-path sentences, dyslexic adolescents showed poorer comprehension accuracy than non-dyslexics in three out of the four conditions (ambiguous with both types of verbs and unambiguous with optionally transitive verbs). However, dyslexic and non-dyslexic adolescents did not show significant group differences in comprehension of sentences that contained object and subject relative clauses, despite the fact that the dyslexics' comprehension was poorer than the controls. In the third experiment reported in Chapter 5, where the focus was on active and passive implausible sentences, dyslexic adolescents showed poorer comprehension accuracy and longer reading times in general compared to non-dyslexic adolescents, while all participants showed longer reading times in the passive sentences compared to active sentences.

The second aim of Chapter 5 concerned the comparison between the data on adolescents and our previous findings of adult participants. It is important to consider the limited sample size of the adolescents, which make the comparisons with the adult samples exploratory at best. Furthermore, all comparisons between adolescents and adults are descriptive and not statistically different, as the two data sets were not entered in the same statistical model for comparison. Regarding the comprehension of garden-path sentences, dyslexic adolescents showed poorer comprehension than dyslexic adults in sentences with reflexive verbs, which could suggest an impairment in semantic processing as the adolescents struggled with interpreting the reflexive meaning of the intransitive verb. With respect to eye movements and reading times, dyslexic adolescents spent more time reading compared to adults with dyslexia, while non-dyslexic adolescents showed similar reading times to control adults.

The adolescent results for sentences with relative clauses showed the same pattern for comprehension as the findings for adults, where there was not a significant difference between the two groups. In reading times, adolescents only showed very few significant differences at the relative noun. On the other hand, the adult participants showed longer reading times on sentences with object relative clauses, while dyslexic adults spent significantly more time in total reading both types of sentences.

With respect to active and passive sentences, the comparison of adolescent and adult data suggested that dyslexic adolescents showed worse comprehension accuracy than dyslexic adults. However, the results of non-dyslexic adolescents and non-dyslexic adults for implausible sentences showed many similarities. Regarding the eye movement findings, dyslexic adolescents spent a lot more time reading both active and passive sentences compared to the dyslexic adults.

Summary

All experiments in this thesis aimed to provide a further insight into how individuals with dyslexia comprehend and process sentences with complex syntax. With respect to comprehension, dyslexics showed poorer comprehension than the controls in two out of the three types of sentences, in both adolescents and adults. Most of the comprehension difficulties persisted regardless of the inclusion of additional cognitive factors. This suggests that the difficulties could be derived from the presence of dyslexia itself as a reading disorder which affects multiple areas of processing, including the processing of complex syntax. As it has been hypothesised by Bishop and Snowling (2004) and as our findings showed, these comprehension difficulties are a secondary result of the phonological processing deficit that affects individuals with dyslexia.

However, the fact that these differences were not present in the case of sentences with relative clauses was particularly surprising, as it contradicted our previous argument about the difficulties that dyslexia creates for processing of syntax, as well as the results from one previous study on dyslexia and relative clause sentences (Wiseheart et al., 2009). The methodological differences between Wiseheart et al.'s (2009) study and our experiments could explain the contradictory results. They also highlight the potential that in sentence containing relative clauses, semantics plays a more important role than syntax. Finally, it could be the case that dyslexia might not cause impairments in that area, which could help explain the similar results in comprehension between dyslexics and controls.

With respect to eye movements and the individual differences, our findings were consistent across most areas of all types of sentences. Dyslexic participants spent much more time reading and this did not translate into improved sentence comprehension. Individual differences in working memory appeared to have a significant effect on processing difficulty, as the multiple thematic roles and the complexity in syntax in each sentence type could have an impact in the overload of working memory capacity of the participants. The bottleneck in working memory storage and processing capacity that dyslexics are affected by could also highly impact their comprehension accuracy and reading times (Ramus, 2003; Ramus & Szenkovits, 2008). It was also evident that participants with dyslexia tended to make more regressions out of the interest areas in each sentence and to reread the sentences more than the controls.

In the examination of the use of parsing heuristics, our findings were not conclusive regarding whether participants' responses to the comprehension questions were based on heuristics or not, as our data on reading times did not provide evidence of differentiation between the two possible sources of comprehension errors in active and passive, plausible and implausible sentences.

Finally, our experiments provided a valuable basis for exploration of the development of sentence processing and comprehension from adolescence to adulthood. As adolescents have been an understudied age group, our findings did not align with Keith Rayner's hypothesis and showed that non-dyslexic adolescents, even when asked to read sentences which might present additional difficulties for their age, perform just as well as non-dyslexic adults. However, dyslexic adolescents show poorer comprehension and even longer reading times than dyslexic adults in all types of sentences. Figure 1 helps with visualising the trajectories of comprehension accuracy that the different age and clinical groups showed in the three types of sentences, which were ranked with respect to syntactic and semantic difficulty. It is evident that individuals without dyslexia continue to develop their reading comprehension skills and that improves when they reach adulthood, while dyslexic adolescents improve too, but not as much as their non-dyslexic peers. This slowdown in development of sentence comprehension persists especially in cases of sentences with particularly complex syntax, like garden-path sentences, with dyslexic adults showing substantially poorer comprehension.

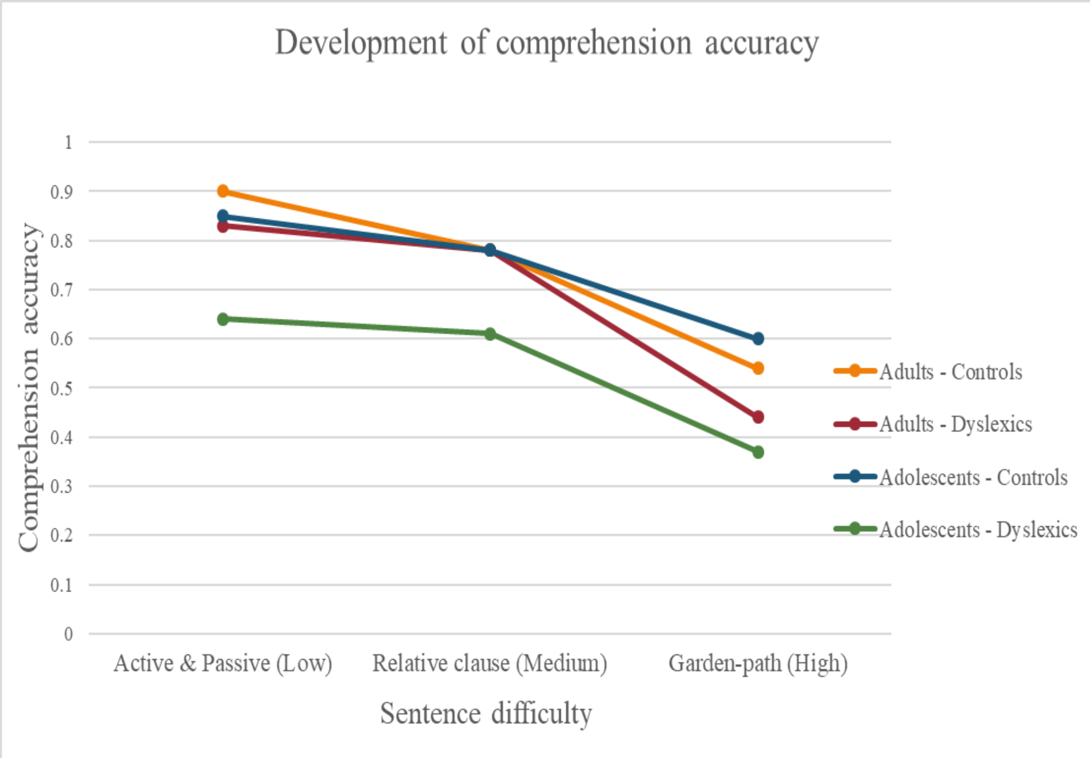

Figure 1. Subgroups' average comprehension accuracy in the three types of sentences examined.

Limitations

The dyslexic and non-dyslexic samples for the adult experiments reported in this thesis were either university students, studying in undergraduate and postgraduate degrees or university graduates. However, the majority of individuals with dyslexia do not succeed academically to go to higher education. Thus, our studies could have shown a more representative image of dyslexic adults and even greater differences between dyslexics and non-dyslexics, if we had samples of community-recruited dyslexic participants.

However, we chose samples of dyslexic university students and graduates, as we aimed to exclude any educational differences as a potential confound. More specifically, the majority of the non-dyslexic adult participants were in the first or second year of their undergraduate courses, while dyslexic participants were in the final year of their undergraduate degree or they were postgraduate students. Therefore, our dyslexic samples were more highly educated than the non-dyslexic ones, which further highlights that any educational differences were excluded due to the additional years of study in higher education that the dyslexic participants have completed.

As measures of the individual differences variables of working memory, processing speed and verbal intelligence, we used standardised tests from assessment batteries (WAIS-IV, WISC-V and CTOPP 2), as well as a reading and a rotation span from the Engle lab (Unsworth et al., 2005). However, the number of tests varied from experiment to experiment, as we attempted to examine multiple cognitive factors. This was particularly the case for the adolescent experiments, in which we chose to limit the number of tests in order to avoid fatigue of the younger age group, which could have affected their performance in the sentence processing task. As a result, it would be beneficial for future research to use the same number of tasks that assess working memory, processing speed and verbal intelligence in all age groups examined.

With respect to our statistical analyses, it is worth mentioning that we decided to use ANOVA due to the fact that they prioritise and give more variance to any covariates added that we wanted to examine in our experiments, like working memory. Since we wanted to examine whether the group difference would persist or be removed in the presence of an additional cognitive factor, the ANOVA and ANCOVA were the statistical models that seemed to fit our aims best. However, it is worth mentioning that there was the potential to use Linear Mixed Effects models (LME) for our analyses, as these models have important advantages. An important possibility offered by mixed-effects modelling is to bring effects that unfold during the course of an experiment into account, and to consider other potentially relevant covariates as well. Furthermore, they offer the possibility to include simultaneously predictors that are tied to the items (e.g., frequency, length) and predictors that are tied to participants (e.g., handedness, age, gender) (Baayen, Davidson, & Bates, 2008). These models could give us the opportunity in the future to explore in further detail the cognitive factors involved in sentence processing and comprehension.

A final comment should be made about the role of potential co-occurring difficulties. Other developmental disorders have high percentages of prevalence with dyslexia, such as Attention Deficit Hyperactivity Disorder (ADHD) (Willcutt et al., 2005) and dyspraxia (Kirby, Sugden, Beveridge, Edwards, & Edwards, 2008; Pauc, 2005). Despite this, there is the potential that symptoms associated with alternative developmental disorders could have played a role in the difficulties shown by dyslexic readers in the present studies. For example, comorbid symptoms of ADHD in the dyslexic groups could have caused additional difficulties in maintaining attention of the sentence processing task and thus, they could have had an impact on the participants' comprehension accuracy. Therefore, additional measures and questionnaires about the presence of comorbid disorders would be beneficial in future research for each of these disorders.

Future Directions

The experiments and discussions in this thesis have provided an initial investigation to the processing of sentences in dyslexia and have supported the proposal that the sentence comprehension and processing difficulties may be part of a set of secondary symptoms deriving from the phonological deficit that dyslexia is usually associated with.

As noted in the introduction (Chapter 1), there has been extensive neuroimaging research into the areas of the brain that dyslexia might be associated with, as well as with respect to the areas involved in sentence reading. Therefore, fMRI could be implemented with adults and adolescents with dyslexia whilst reading sentences with complex syntax to determine where these individuals show differences in activation of the posterior (Wernicke's area, angular gyrus and striate cortex) and anterior regions (Broca's area and anterior portion of the superior temporal sulcus), if any compared to controls (Bavelier et al., 1997; Shaywitz et al., 1998).

Furthermore, imaging methods with higher temporal resolution, such as electroencephalography (EEG) and magnetoencephalography (MEG) have been used to measure the activation of particular brain areas during reading syntactically complex sentences. For example, N400 is an ERP component associated with how easily a word's meaning can be integrated with context (Kutas & Federmeier, 2011) and the P600 component is activated by syntactic violations (Hagoort et al., 1993). Qian et al. (2018) argued that the semantic P600 effect provides evidence for both syntactic and semantic processing routes, while the absence of the N400 effect could suggest a stronger link with the Good Enough Processing hypothesis. Analysing such components and effects in adolescents and adults with dyslexia would provide additional evidence for our findings and the processing difficulties of sentences in dyslexia that could be attributed to various processes that contribute to achieving an accurate interpretation of sentences with complex syntax.

Another method to examine sentence processing in dyslexia could be with the application of pupillometry measures. The measurable change of the size of the pupil of the eye has been extensively reported as a response to mental activity (Hess & Polt, 1964), especially in cases of activation of functions of working memory and tasks that have high mental processing demands (Piquado, Isaacowitz, & Wingfield, 2010). Just and Carpenter (1993) examined the online changes in pupil size of university students while reading sentences. They reported that reading sentences with greater syntactic complexity resulted in larger pupil sizes than when the participants read sentences with less complex syntactic structure, but of the same length. Therefore, our findings on syntactic processing could be examined with respect to changes in pupil size to provide additional evidence for the comprehension difficulties of dyslexic readers in the types of sentences examined in this thesis.

Implications

The literature on reading interventions for individuals with dyslexia and particularly children has been extensive (for reviews, see Chard, Ketterlin-Geller, Baker, Doabler, & Apichatabutra, 2009; Edmonds et al., 2009; Torgesen, 2006; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wanzek, Wexler, Vaughn, & Ciullo, 2010) but the majority of the programmes have focused on word and nonword reading. However, the primary goal of reading is to comprehend meaning from text and the majority of an individual's adult life is surrounded by multiple sources of text. Moreover, there is a wide range of factors that contribute to comprehension, like word decoding, reading fluency, understanding the meaning of individual words, relating content to prior knowledge about the world and real-life situations, and monitoring understanding (Carlisle & Rice, 2000). Therefore, interventions that are aimed at sentence-level reading would be highly beneficial, especially for adolescents and adults.

Interventions for older children and adolescents that tend to focus on the text level reading, are aimed at encouraging the use of reading strategies. However, the implementation of those strategies vary, as the assessments used are usually researcher developed and the bridging between word-level and text-level comprehension strategies are often overlooked. Taking into consideration our findings regarding the sentence comprehension and processing of adolescents with and without dyslexia, further reading comprehension interventions focused on sentence-level reading are required.

Regarding our findings about the significant role of working memory in sentence processing and comprehension, it would be highly beneficial for working memory training programmes to include these processes. We recommend that dyslexia diagnoses and assessments of language comprehension should pay particular attention to individual differences in working memory, and specifically, age standardised working memory assessments. Furthermore, working memory training has been shown to have a potential positive effect on individuals with working memory deficits, as well as children with cognitive disorders, like ADHD (Melby-Lervåg & Hulme, 2013). Several adaptive working memory training interventions have supported children with working memory deficits (Holmes et al., 2009). By taking into account our findings about the role of working memory in sentence comprehension, it would be of high importance to attempt to implement working memory interventions that also measure sentence comprehension. Future working memory and sentence comprehension interventions would be highly beneficial for individuals with dyslexia and these programmes could provide valuable insight into whether the improvement of working memory could also affect sentence comprehension in dyslexic readers. This would require additional evidence as prior research has shown that working memory retraining does not generalise to other types of tasks (Holmes et al., 2009; Melby-Lervåg & Hulme, 2013; Novick et al., 2013).

Research into strategies and behaviours that support reading have also examined several compensatory strategies that allow the readers to draw on minimal cognitive resources and to conserve momentum for processing components like verbal inefficiency and text difficulty. Strategies like these include the adjustment of reading rate, pauses to allow for further processing and to resolve confusion, rereading and regressive eye movements back to previous parts of text (Walczyk et al., 2007). These strategies could be another layer that provides explanation for the eye movement patterns and reading times that our dyslexic participants showed in the present experiments. Therefore, the application and further examination of such strategies provide substantial advantages in understanding better the techniques and compensatory strategies that individuals with dyslexia might be using to process sentences and read in general.

Conclusion

The experiments in this thesis have provided a better and more holistic understanding of how adults and adolescents with dyslexia comprehend and process sentences with complex syntax, as well as the cognitive risk factors and individual differences that are associated with dyslexia. These issues have remained largely unexplored until now.

Differences were demonstrated between dyslexic and non-dyslexic readers in comprehension of two out of the three types of sentences examined, suggesting that the difficulties in sentence comprehension derive from dyslexia status and are overarching across adolescence and adulthood. However, the fact that there was no difference in comprehension in sentences containing relative clauses indicate that dyslexia might not create deficits in all aspects of reading skills. These findings indicate that future investigations of sentence comprehension and processing are vital in order to provide further evidence on this relatively unexplored area of psycholinguistics. Our experiments also showed that consistently across all types of sentences and age groups, dyslexic readers require more time to read sentences with complex syntax, without that however necessarily resulting in better comprehension.

This thesis has made a unique contribution to the wider literature in dyslexia. We have attempted to examine aspects of language processing in dyslexia, which have been previously largely ignored. This thesis has highlighted the substantial impact that the underlying phonological processing deficit has for individuals with dyslexia, not only for single-word reading, but also for sentence processing and comprehension. It has also emphasised the significance that the bottleneck in working memory has for dyslexic readers while attempting to simultaneously hold and recall details about the meaning of a syntactically complex sentence.

Finally, this thesis attempted to explore the development of sentence comprehension and processing via our adolescent experiments, which highlighted the similarities that non-dyslexic adolescents show with the non-dyslexic adults, as well as the additional difficulties that dyslexic adolescents showed compared to dyslexic adults in interpreting the meaning of the sentences they read. The research undertaken as part of this thesis has provided an invaluable insight into the way that dyslexic individuals approach sentence reading tasks and the strategies they use to compensate for their phonological impairments. This is an essential starting point to inform reading interventions that could support individuals with dyslexia to demonstrate their full potential and enjoy reading.

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