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

Marianna Stella and Paul E. Engelhardt

University of East Anglia

Address for correspondence:
Marianna Stella
School of Psychology
University of East Anglia
Norwich Research Park
Norwich, NR4 7TJ
M.Stella@uea.ac.uk

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.

Keywords: dyslexia, reading disability, eye movements, sentence processing, syntactic ambiguity

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

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, 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, 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, Christianson, & Hollingworth, 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, Hollingworth, Halliwell, & Ferreira, 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, Altmann, Park, and Lombardino (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.[1] For example, the Verbal Efficiency

---

[1] One recent paper has also suggested that inhibitory processing might have a role in comprehension of subordinate-main garden path sentences (i.e. Hussey, Ward, Christianson, & Kramer (2015). However, we elected not to assess inhibition in our test battery as it is not clear that dyslexia is characterised by deficits in inhibitory processing (cf. Wang, Tasi, & Yang, 2012).

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 4th 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, and 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]

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;

[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.

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.

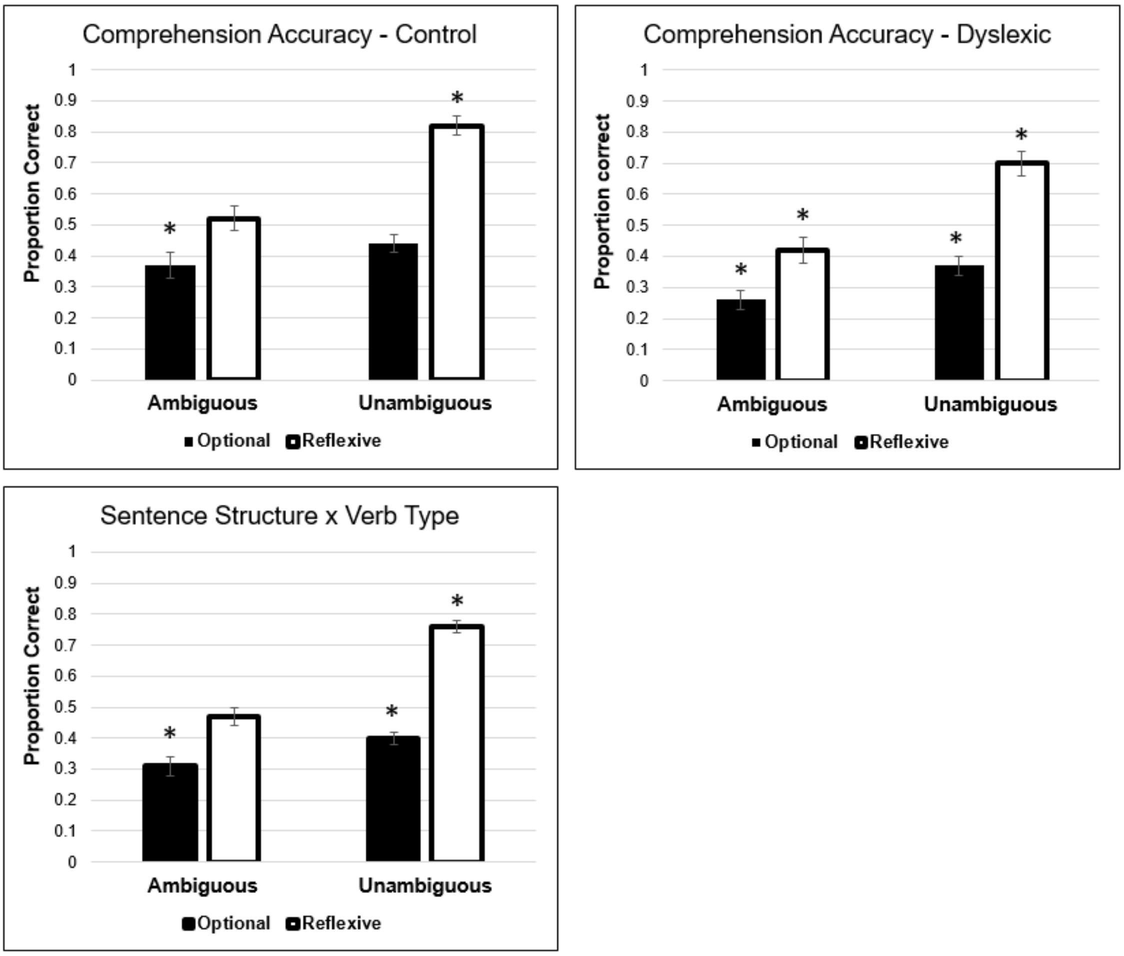

Figure 1. Top panels show the comprehension accuracy for controls (left) and dyslexics (right). The bottom panel shows the comprehension accuracy for sentence structure by verb type interaction. Error bars show the standard error of the mean. (*) indicate the significant one-sample t-tests.

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 $t(49) = 5.10$, $p < .001$.

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 cognitive factors on comprehension

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

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		Regressions		Regression Path Duration		
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
Controls									Disambiguating verb
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	
Controls									N + 1 word
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	
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.

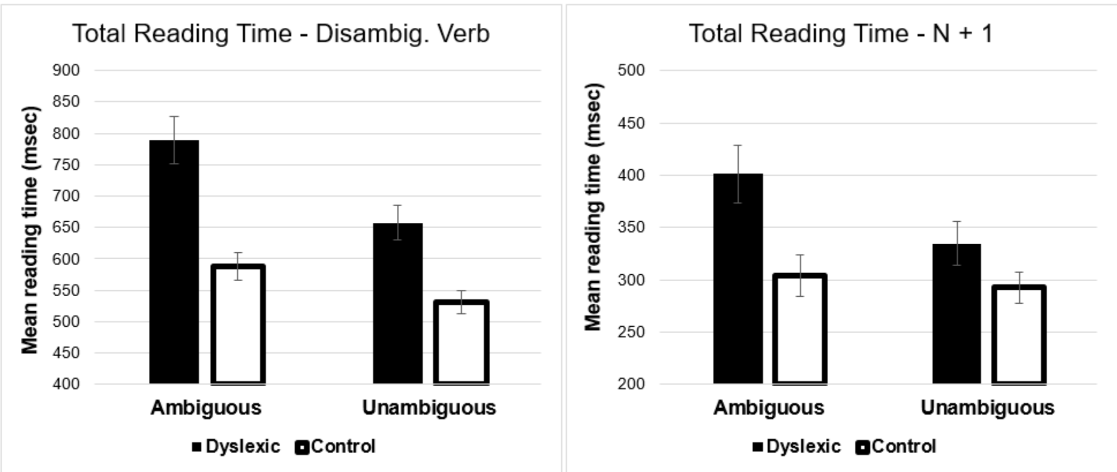

Figure 2. Interactions between sentence structure and group (control vs. dyslexia). Left panel shows the interaction for the disambiguating verb and the right shows the interaction at the spill over region. Error bars show the standard error of the mean.

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 cognitive 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 cognitive 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

---

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

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 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 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

[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.

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 higher 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

[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.

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 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.

References

Benson, N., Hulac, D. M., & Kranzler, J. H. (2010). Independent Examination of the Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV): What Does the WAIS-IV Measure? *Psychological Assessment*, *22*(1), 121–130. https://doi.org/10.1037/a0017767

Bishop, D. V. M., & Snowling, M. J. (2004). Developmental dyslexia and specific language impairment: same or different? *Psychological Bulletin*, *130*(6), 858–886. https://doi.org/10.1037/0033-2909.130.6.858

Bonifacci, P., & Snowling, M. J. (2008). Speed of processing and reading disability: A cross-linguistic investigation of dyslexia and borderline intellectual functioning. *Cognition*, *107*(3), 999–1017. https://doi.org/10.1016/j.cognition.2007.12.006

Breznitz, Z. (2001). The determinants of reading fluency: A comparison of dyslexic and average readers. In M. Wolf (Ed.), *Dyslexia, fluency and the brain* (pp. 245–276). Cambridge, MA: York Press.

Breznitz, Z. (2003). The Synchronization Phenomenon. In *Fluency in reading: Synchronization of processes* (1st edition, pp. 211–217). NY: Routledge.

Breznitz, Z. (2006). *Fluency in reading: Synchronization of processes*. Mahwah, NJ: Erlbaum. https://doi.org/10.4324/9781410617019

Breznitz, Z., & Misra, M. (2003). Speed of processing of the visual-orthographic and auditory-phonological systems in adult dyslexics: The contribution of “asynchrony” to word recognition deficits. *Brain and Language*, *85*(3), 486–502. https://doi.org/10.1016/S0093-934X(03)00071-3

Brown, W. (1910). Some experimental results in the correlation of mental abilities. *British Journal of Psychology*, *3*, 296–322. https://doi.org/10.1111/j.2044-

8295.1910.tb00207.x

Caplan, D., DeDe, G., Waters, G., Michaud, J., & & Tripodis, Y. (2011). Effects of age, speed of processing, and working memory on comprehension of sentences with relative clauses. *Psychology and Aging*, *26*(2), 439–450. Retrieved from http://psycnet.apa.org/journals/pag/26/2/439/

Caplan, D., & Waters, G. (1999). Verbal working memory and sentence comprehension. *Behavioral and Brain Sciences*, *22*(1), 77-94. Retrieved from http://journals.cambridge.org/abstract_S0140525X99001788

Chiappe, P., Siegel, L. S., & Hasher, L. (2000). Working memory, inhibitory control, and reading disability. *Memory & Cognition*, *28*(1), 8–17. https://doi.org/10.3758/BF03211570

Christianson, K., Hollingworth, A., Halliwell, J. F., & Ferreira, F. (2001). Thematic roles assigned along the garden path linger. *Cognitive Psychology*, *42*(4), 368–407. https://doi.org/10.1006/cogp.2001.0752

Christianson, K., Luke, S. G., Hussey, E. K., & Wochna, K. L. (2017). Why reread? Evidence from garden-path and local coherence structures. *Quarterly Journal of Experimental Psychology*, *70*(7), 1380–1405. https://doi.org/10.1080/17470218.2016.1186200

Christianson, K., Williams, C. C., Zacks, R. T., & Ferreira, F. (2006). Younger and older adults’ “good-enough” interpretations of garden-path sentences. *Discourse Processes*, *42*(2), 205–238. https://doi.org/10.1207/s15326950dp4202_6

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A Dual Route Cascaded Model of Visual Word Recognition and Reading Aloud. *Psychological Review*, *108*(1), 204–256. https://doi.org/10.1037/0033-

295X.108.1.204

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin and Review*, *12*(5), 769–786. https://doi.org/10.3758/BF03196772

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450–466. https://doi.org/10.1016/S0022-5371(80)90312-6

De Luca, M., Borrelli, M., Judica, A., Spinelli, D., & Zoccolotti, P. (2002). Reading Words and Pseudowords: An Eye Movement Study of Developmental Dyslexia. *Brain and Language*, *80*(3), 617–626. https://doi.org/10.1006/brln.2001.2637

De Luca, M., Di Pace, E., Judica, A, Spinelli, D., & Zoccolotti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia*, *37*(12), 1407–1420. https://doi.org/10.1016/S0028-3932(99)00038-X

DeDe, G., Caplan, D., Kemtes, K., & Waters, G. (2004). The Relationship Between Age, Verbal Working Memory, and Language Comprehension. *Psychology and Aging*, *19*(4), 601–616. https://doi.org/10.1037/0882-7974.19.4.601

Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (R.A.N): dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*(4), 471–479. https://doi.org/10.1016/0028-3932(76)90075-0

Eden, G. F., Stein, J. F., Wood, H. M., & Wood, F. B. (1994) Differences in eye movements and reading problems in dyslexic and normal children. *Vision research*, *34*(10), 1345-1358. https://doi.org/10.1016/0042-6989(94)90209-7

Edmonds, M. S., Vaughn, S., Wexler, J., Reutebuch, C., Cable, A., Tackett, K. K., & Schnakenberg, J. W. (2009). A Synthesis of Reading Interventions and Effects on Reading Comprehension Outcomes for Older Struggling Readers. *Review of Educational Research*, *79*(1), 262–300. https://doi.org/10.3102/0034654308325998

Engelhardt, P. E., Nigg, J. T., Carr, L. A., & Ferreira, F. (2008). Cognitive Inhibition and Working Memory in Attention-Deficit / Hyperactivity Disorder. *Journal of Abnormal Psychology*, *117*(3), 591–605. https://doi.org/10.1037/a0012593

Engelhardt, P. E., Nigg, J. T., & Ferreira, F. (2017). Executive function and intelligence in the resolution of temporary syntactic ambiguity: An individual differences investigation. *The Quarterly Journal of Experimental Psychology*, *70*(7), 1263-1281.

Ferreira, F., Christianson, K., & Hollingworth, A. (2001). Misinterpretations of garden-path sentences: Implications for models of sentence processing and reanalysis. *Journal of Psycholinguistic Research*, *30*(1), 3-20.

Ferreira, F., & Patson, N. (2007). The 'good enough'approach to language comprehension. *Language and Linguistics Compass*, *1*(1–2), 71–83. https://doi.org/10.1111/j.1749-818X.2007.00007.x

Fiorin, G., & Vender, M. (2009). The interpretation of pronominal expressions in dyslexic children. In *Proceedings of the 1st Patras International Conference of Graduate Students in Linguistics*. University of Patras.

Fisher, S. E., Francks, C., Marlow, A. J., MacPhie, I. L., Newbury, D. F., Cardon, L. R., … Monaco, A. P. (2002). Independent genome-wide scans identify a chromosome 18 quantitative-trait locus influencing dyslexia. *Nature Genetics*, *30*(1), 86–91.

https://doi.org/10.1038/ng792

Fodor, J. (2001). Language, thought and compositionality. *Royal Institute of Philosophy Supplements*, *48*, 227-242.

Fodor, J. D., & Inoue, A. (1998). Attach anyway. In J. D. Fodor & F. Ferreira (Eds.), *Reanalysis in sentence processing* (pp. 101–142). Dordrecht: Kluwer Academic Publishers.

Frazier, L., & Fodor, J. D. (1978). The sausage machine: A new two-stage parsing model. *Cognition*, *6*(4), 291–325. https://doi.org/10.1016/0010-0277(78)90002-1

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, *14*(2), 178–210. https://doi.org/10.1016/0010-0285(82)90008-1

Georgiou, G. K., Parrila, R., Cui, Y., & Papadopoulos, T. C. (2013). Why is rapid automatized naming related to reading? *Journal of Experimental Child Psychology*, *115*, 218–225. https://doi.org/10.1016/j.jecp.2012.10.015

Gibson, E. (1998). Linguistic complexity: Locality of syntactic dependencies. *Cognition*, *68*(1), 1–76. https://doi.org/10.1016/S0010-0277(98)00034-1

Hawelka, S., Gagl, B., & Wimmer, H. (2010). A dual-route perspective on eye movements of dyslexic readers. *Cognition*, *115*(3), 367–379. https://doi.org/10.1016/j.cognition.2009.11.004

Heiman, J. R., & Ross, A. O. (1974). Saccadic eye movements and reading difficulties. *Journal of Abnormal Child Psychology*, *2*(1), 53–61. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/4448880

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, *12*(4), F9–F15. https://doi.org/10.1111/j.1467-7687.2009.00848.x

Hussey, E. K., Ward, N., Christianson, K., & Kramer, A. F. (2015). Language and memory improvements following tDCS of left lateral prefrontal cortex. *PLoS ONE*, *10*(11), 1–31. https://doi.org/10.1371/journal.pone.0141417

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and Language*, *89*(1), 235–242. https://doi.org/10.1016/S0093-934X(03)00401-2

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(6), 1430–1440. https://doi.org/10.1037/0278-7393.21.6.1430

Jeffries, S., & Everatt, J. (2004). Working memory: Its role in dyslexia and other specific learning difficulties. *Dyslexia*, *10*(3), 196–214. https://doi.org/10.1002/dys.278

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*(1), 122–149. https://doi.org/10.1037/0033-295X.99.1.122

King, J., & Just, M. A. (1991). Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language*, *30*, 580–602.

LaBerge, D. (1981). Automatic information processing: A review. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 173–186). Hillsdale,NJ: Erlbaum.

LaBerge, D., & Samuels, S. J. (1974). Toward a theory of automatic information processing in reading. *Cognitive psychology*, *6*(2), 293-323. https://doi.org/10.1016/0010-0285(74)90015-2

Landauer, T. K., & Dumais, S. T. (1997). A Solution to Plato's Problem: The Latent Semantic Analysis Theory of Acquisition, Induction, and Representation of Knowledge. *Psychological Review*, *104*(2), 211–240. https://doi.org/10.1037/0033-295X.104.2.211

Landerl, K., Wimmer, H., & Frith, U. (1997). The impact of orthographic consistency on dyslexia: a German-English comparison. *Cognition*, *63*(3), 315–34. https://doi.org/10.1016/S0010-0277(97)00005-X

Lewis, R. L., Vasishth, S., & Van Dyke, J. A. (2006). Computation principles of working memory in sentence comprehension. *Trends in Cognitive Sciences*, *10*(10), 447–454. https://doi.org/10.1016/j.tics.2006.08.007

Linderholm, T., Cong, X., & Zhao, Q. (2008). Differences in low and high working-memory capacity readers' cognitive and metacognitive processing patterns as a function of reading for different purposes. *Reading Psychology*, *29*(1), 61–85. https://doi.org/10.1080/02702710701568587

Linderholm, T., & Van den Broek, P. (2002). The effects of reading purpose and working memory capacity on the processing of expository text. *Journal of Educational Psychology*, *94*(4), 778–784. https://doi.org/10.1037/0022-0663.94.4.778

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological review*, *95*(4), 492. https://doi.org/10.1037/0033-295X.95.4.492

Logan, G. D. (1997). Automaticity and reading: Perspectives from the instance theory of automatization. *Reading & Writing Quarterly: Overcoming Learning*

Difficulties, *13*(2), 123-146. https://doi.org/10.1080/1057356970130203

Logan, G. D. (2006). Out with the old, in with the new: More valid measures of switch cost and retrieval time in the task span procedure. *Psychonomic Bulletin & Review*, *13*(1), 139-144.

McCartney, K., Burchinal, M. R., & Bub, K. L. (2006). Best practices in quantitative methods for developmentalists. *Monographs of the Society for Research in Child Development*, *71*(3), 1–145. https://doi.org/10.1111/j.1540-5834.2006.07103001.x

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, *49*(2), 270–291. https://doi.org/10.1037/a0028228

Nation, K., & Snowling, M. (1998). Semantic processing and the development of word recognition skills: Evidence from children with reading comprehension difficulties. *Journal of Memory and Language*, *39*(1), 85–101. https://doi.org/10.1006/jmla.1998.2564

Nation, K., & Snowling, M. J. (1999). Developmental differences in sensitivity to semantic relations among good and poor comprehenders: Evidence from semantic priming. *Cognition*, *70*(1), B1–B13. https://doi.org/10.1016/S0010-0277(99)00004-9

Norton, E. S., & Wolf, M. (2012). Rapid Automatized Naming (RAN) and Reading Fluency : Implications for Understanding and Treatment of Reading Disabilities. *Annual Review of Psychology*, *63*, 427–452. https://doi.org/10.1146/annurev-psych-120710-100431

Novick, J. M., Hussey, E., Teubner-Rhodes, S., Harbison, J. I., & Bunting, M. F. (2013). Clearing the garden-path: Improving sentence processing through cognitive control training. *Language, Cognition and Neuroscience*, *29*(2), 186–217. https://doi.org/10.1080/01690965.2012.758297

Oakhill, J. V., & Cain, K. (2012). The Precursors of Reading Ability in Young Readers: Evidence From a Four-Year Longitudinal Study. *Scientific Studies of Reading*, *16*(2), 91–121. https://doi.org/10.1080/10888438.2010.529219

Olson, R. K., Kliegl, R., & Davidson, B. J. (1983). Dyslexic and normal readers' eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 9*(5), 816–825. https://doi.org/10.1037/0096-1523.9.5.816

Patson, N. D., Darowski, E. S., Moon, N., & Ferreira, F. (2009). Lingering misinterpretations in garden-path sentences: evidence from a paraphrasing task. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(1), 280–285. https://doi.org/10.1037/a0014276

Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, *11*(4), 357–383. https://doi.org/10.1080/10888430701530730

Perfetti, C. A. (1985). *Reading ability*. New York: Oxford University Press.

Perfetti, C. A. (1988). Verbal efficiency in reading ability. In M. Daneman, G. E. MacKinnon, & T. G. Waller (Eds.), *Reading research: Advances in theory and practice* (pp. 109–143). New York: Academic Press.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L. C. Ehri, & R. Treiman (Eds.), *Reading acquisition* (pp. 145–174). Hillsdale,NJ: Lawrence Erlbaum Associates, Inc.

Perfetti, C. A., & Hart, L. (2001). The lexical bases of comprehension skill. In D. Gorfien (Ed.), *On the consequences of meaning selection* (pp. 67–86). Washington, DC: American Psychological Association.

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. Vehoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors of functional literacy* (pp. 189–213). Amsterdam: John Benjamins.

Perfetti, C. A., & Hogaboam, T. (1975). Relationship between single word decoding and reading comprehension skill. *Journal of Educational Psychology*, *67*(4), 461–469. https://doi.org/10.1037/h0077013

Perfetti, C. A., Landi, N., & Oakhill, J. (2005). The Acquisition of Reading Comprehension Skill. In *The Science of Reading: A Handbook* (pp. 227–247). Oxford, UK: Blackwell Publishing Ltd. https://doi.org/10.1002/9780470757642.ch13

Prado, C., Dubois, M., & Valdois, S. (2007). The eye movements of dyslexic children during reading and visual search : Impact of the visual attention span, *47*, 2521–2530. https://doi.org/10.1016/j.visres.2007.06.001

Qian, Z., Garnsey, S., & Christianson, K. (2018). A comparison of online and offline measures of good-enough processing in garden-path sentences. *Language, Cognition and Neuroscience*, *33*(2), 227–254. https://doi.org/10.1006/cogp.2001.0752

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin*, *85*, 618–660.

Rayner, K. (1985). The Role of Eye Movements in Learning to Read and Reading Disability. *Remedial and Special Education*, *6*(6), 53–60. https://doi.org/10.1177/074193258500600609

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. https://doi.org/10.1037/0033-

2909.124.3.372

Reid, G. (2016). *Dyslexia: A practitioner's handbook*. Chichester, England: Wiley

Rose, J. (2009). *Identifying and teaching children and young people with dyslexia and literacy difficulties: an independent report.* Retrieved from http://dera.ioe.ac.uk/14790/1/00659-2009DOM-EN.pdf

Samuels, S. J., & Flor, R. F. (1997). The importance of automaticity for developing expertise in reading. *Reading & Writing Quarterly: Overcoming Learning Difficulties*, *13*(2), 107-121. https://doi.org/10.1080/1057356970130202

Schafer, J. L., & Graham, J. W. (2002). Missing data: Our view of the state of the art. *Psychological Methods*, *7*(2), 147–177. https://doi.org/10.1037/1082-989X.7.2.147

Shanahan, M. A., Pennington, B. F., Yerys, B. E., Scott, A., Boada, R., Willcutt, E. G., … DeFries, J. C. (2006). Processing speed deficits in attention deficit/hyperactivity disorder and reading disability. *Journal of Abnormal Child Psychology*, *34*(5), 585–602. https://doi.org/10.1007/s10802-006-9037-8

Simmons, F., & Singleton, C. (2000). The Reading Comprehension Abilities of Dyslexic Students in Higher Education. *Dyslexia*, *6*(3), 178–192. https://doi.org/10.1002/1099-0909(200007/09)6:3<178::AID-DYS171>3.0.CO;2-9

Slattery, T. J., Sturt, P., Christianson, K., Yoshida, M., & Ferreira, F. (2013). Lingering misinterpretations of garden path sentences arise from competing syntactic representations. *Journal of Memory and Language*, *69*(2), 104–120. https://doi.org/10.1016/j.jml.2013.04.001

Snowling, M. (1987). *Dyslexia: A cognitive developmental perspective.* Cambridge, MA, US: Basil Blackwell.

Snowling, M. J., Duff, F., Petrou, A., Schiffeldrin, J., & Bailey, A. M. (2011).

Identification of children at risk of dyslexia: The validity of teacher judgements using "Phonic Phases." *Journal of Research in Reading*, *34*(2), 157–170. https://doi.org/10.1111/j.1467-9817.2011.01492.x

Spearman, C. (1910). Correlation calculated from faulty data. *British Journal of Psychology*, *3*, 271–295. https://doi.org/10.1111/j.2044-8295.1910.tb00206.x

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*(3), 498–505. https://doi.org/10.3758/BF03192720

Van Dyke, J. A., & McElree, B. (2006). Retrieval interference in sentence comprehension. *Journal of Memory and Language*, *55*(2), 157–166. https://doi.org/10.1016/j.jml.2006.03.007

Wagner, R. K., Torgensen, J. K., Rashotte, C. A., & Pearson, N. A. (2013). *Comprehensive Test of Phonological Processing-Second Edition*. Austin, TX: PRO-ED.

Wanzek, J., & Vaughn, S. (2007). Research-based implications from extensive early reading interventions. *School Psychology Review*, *36*(4), 541–561. https://doi.org/10.1038/nphys2524

Wanzek, J., Wexler, J., Vaughn, S., & Ciullo, S. (2010). Reading interventions for struggling readers in the upper elementary grades: A synthesis of 20 years of research. *Reading and Writing*, *23*(8), 889–912. https://doi.org/10.1007/s11145-009-9179-5

Warner, J., & Glass, A. L. (1987). Context and distance-to-disambiguation effects in ambiguity resolution: Evidence from grammaticality judgments of garden path sentences. *Journal of Memory and Language*, *26*, 714–738.

https://doi.org/10.1016/0749-596X(87)90111-2

Waters, G., & Caplan, D. (2004). The relationship between age, verbal working memory, and language comprehension. *Psychology and Aging*, *19*(4), 601–616. https://doi.org/10.1037/0882-7974.19.4.601

Waters, G. S., & Caplan, D. (1996). Processing resource capacity and the comprehension of garden path sentences. *Memory & Cognition*, *24*(3), 342–355. https://doi.org/10.3758/BF03213298

Wechsler, D. (2014). *Wechsler Adult Intelligence Scale- Fourth Edition (WAIS-IV)*. San Antonio, TX: Psychological Corporation.

Wiseheart, R., Altmann, L. J. P., Park, H., & Lombardino, L. J. (2009). Sentence comprehension in young adults with developmental dyslexia. *Annals of Dyslexia*, *59*(2), 151–167. https://doi.org/10.1007/s11881-009-0028-7

Wiseheart, R., & Wellington, R. (2018). Identifying dyslexia risk for sport-related concussion management: Sensitivity and specificity of self-report and rapid naming. *Clinical Neuropsychologist*, *4046*, 1–20. https://doi.org/10.1080/13854046.2018.1474950

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, *91*(3), 415–438. https://doi.org/10.1037/0022-0663.91.3.415

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-Speed Processes, Timing, and Reading. *Journal of Learning Disabilities*, *33*(4), 387–407. https://doi.org/10.1177/002221940003300409