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Neural and visual correlates of perceptual decision making in adult dyslexia

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Abstract

Humans have to make decisions based on visual information numerous times every day—for example, judging whether it is a friend or simply a nice stranger who is waving at us from the other side of the street, or whether the content of a contract we are about to sign is correct. In particular, perceptual decisions based on good reading comprehension might disadvantage people affected by the specific learning disorder dyslexia, characterised by impairments in reading and writing. In recent years, neuroscience has begun to uncover the neural basis of these impairments in children and adults. However, it remains unknown what neural differences might underlie impaired processing of the physical properties of written words, such as font type and style.

The current thesis sought to characterise the neural and oculomotor temporal correlates of font-modulated reading comprehension while also probing a more fundamental deficit in non-linguistic sensory perceptual decision making in adult dyslexia by using a combination of electrophysiological and eye-tracking methods. The first of our three studies (Chapter 2), investigated the impact of italics—a commonly used font style for highlighting important content—on reading comprehension in a sentence reading lexical decision task. Overall, the performance of dyslexics was worse than that of non-dyslexics. Cluster-based event-related potential (ERP) analysis revealed that brain responses within the first 300 ms following the target (decision) word differed in amplitude and spatial distribution between dyslexics and non-dyslexics when processing italicised text. The two ERP components we observed within this period showed a dissociation in peak time, spatial profile, and their ability to predict behavioural performance. These findings emphasise the importance of choosing font style carefully to optimise word processing and reading comprehension by dyslexics.

Based on these differences, our second study (Chapter 3) asked whether a specific dyslexia font can be used to alleviate difficulties with reading comprehension in adult dyslexia, and what effects such a font has on cognitive and oculomotor mechanisms. Using standardised texts coupled with validated comprehension questions, we demonstrated that reading comprehension across all participants was better on trials presented in the dyslexia font OpenDyslexic compared to those

presented in traditional Times New Roman font. These benefits were larger among dyslexics. Conversely, participants' reading speed was unaffected by OpenDyslexic. Our eye-tracking data showed increases in visual search intensity and ease of visual processing on OpenDyslexic trials in the form of decreases in median fixation duration and fixation to saccade ratio, as well as a smaller number of falsely programmed forward saccades among dyslexics. These findings provide empirical evidence for the efficacy of OpenDyslexic in longer texts and its ability to improve the visual reading strategy.

Finally, recent evidence has shown that adults with dyslexia exhibit obvious fundamental deficits spanning multiple sensory systems when performing simple perceptual decision tasks, such as integrating beeps and flashes. These deficits extend beyond the well-established linguistic difficulties. Particularly, dyslexics reading impairments are believed to be a consequence of deficient integration of congruent audio-visual information. However, it remains unclear whether dyslexic adults exhibit similar impairments when integrating audio-visual evidence in a non-linguistic perceptual decision task with noisy real-world objects. To address this question, and informed by our previous work in non-dyslexics, we used a linear multivariate discriminant analysis to investigate the extent to which audio-visual integration affects early sensory evidence encoding ('early') or later decision-related stages ('late') in dyslexia. We found increased decision accuracy and slower response times during audio-visual trials for both groups. However, overall, dyslexics showed worse performance than non-dyslexics. When comparing audio-visual to visual trials, we observed that dyslexics exhibited an increase in the magnitude of an EEG component situated between the early and late processing stages. Conversely, non-dyslexics exhibited increased component amplitudes for a later post-sensory EEG component, consistent with a post-sensory influence of audio-visual integration. Our results suggest that adult dyslexics benefit from congruent audio-visual evidence of noisy perceptual stimuli to a similar extent but rely on a different neural process to achieve these improvements.

In conclusion, our results provide novel insights into the neural dynamics, visual and cognitive mechanisms underlying adult dyslexics' perceptual decision making. They further offer empirical evidence and practical suggestions for easily implementable applications that can improve text comprehension by everyone.

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List of Publications

The results in Chapter 2 have been published as a pre-print:

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A subset of the results in Chapter 2 have also been presented orally and their abstract published as:

Franzen, L., & Philiastides, M. G. (2016, March). Legal Lexical Decision Making in Adult Dyslexia: Indications for Neurophysiologically Different Processing of Italic Font. In E. Abdulaal (Ed.), *The Tenth British Dyslexia Association International Conference* (p. 56). Oxford.

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Author's Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Léon Franzen

Abbreviations

ADD	Attention Deficit Disorder
ADHD	Attention Deficit and Hyperactivity Disorder
BNC	British National Corpus
BOLD	Blood-oxygen-level dependent
CON	Controls
CPP	Central Parietal Positivity
CRN	Correct-related negativity
DSM-5	Diagnostic and statistical manual of mental disorders (5th Ed.)
DYS NO-R.	Dyslexic non-recognisers
DYS R.	Dyslexic recognisers
EEG	Electroencephalography
ERN	Error-related negativity
ERP	Event-related potential
fMRI	Functional magnetic resonance imaging
GLMM	Generalised linear mixed effects model
MEG	Magnetoencephalography
MMN	Mismatch negativity
RSVP	Rapid Serial Visual Presentation
RT	Response time
VWFA	Visual word form area

Chapter 1. General introduction

Humans are faced with a multitude of decisions that must be made on the basis of noisy sensory information. Imagine sitting in the back row of a lecture theatre having to understand the text and visuals on the lecturer's slide while simultaneously listening to her words and deciding whether you should raise your hand to respond to her question. Such ordinary decisions can be described as 'perceptual decision making', which is the process of combining information gathered by our sensory systems to select one choice out of a set of potential alternatives (Gold & Shadlen, 2007; Heekeren, Marrett, & Ungerleider, 2008). While seemingly ordinary, the efficient performance of such perceptual decisions can be hindered by various deficits in visual and auditory perception, as well as cognitive skills including processing speed and attention. Specifically, adults affected by the neurobiological learning disorder dyslexia (American Psychiatric Association, 2013) have been found to suffer from deficits in these areas of cognition (e.g., Beidas, Khateb, & Breznitz, 2013; Hämäläinen, Salminen, & Leppänen, 2013; Laycock & Crewther, 2008). These deficits have been shown to impede efficient, fast-paced decision making on linguistic (Horowitz-Kraus & Breznitz, 2008; Kunert & Scheepers, 2014; Taroyan & Nicolson, 2009) as well as non-linguistic decision tasks (Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012).

In recent years, the neuroscientific community has taken a strong interest in understanding the behavioural and neural correlates underlying deficits in what was initially termed 'congenital word blindness' (Morgan, 1896). Although brain imaging and psychophysical research have shed light on specific neural and behavioural differences associated with a dyslexic phenotype, the physiological mechanisms behind practical applications, such as fonts, have been overlooked. To address this gap, this thesis investigates how dyslexia and font affect the temporal brain dynamics, eye movements, and behavioural performance of adult dyslexics on visual and audio-visual perceptual decision making tasks. This introductory chapter provides a summary of the literature in relevant fields of perceptual decision making. Furthermore, it provides the reader with a definition of dyslexia and reviews deficits associated with dyslexia on linguistic and non-linguistic perceptual decision tasks before outlining the outstanding questions motivating this thesis.

1.1 Neural mechanisms of perceptual decision making

1.1.1 Unisensory (visual)

The neurobiological basis of visual perceptual decision making has been intensively studied in human primates and non-dyslexic humans in recent years (for reviews, see Gold & Shadlen, 2007; Heekeren et al., 2008; Kelly & O'Connell, 2015). In general, the brain's computation of perceptual decisions has been shown to follow a cascade of fast processing stages in non-human primates (e.g., Gold & Shadlen, 2001; Roitman & Shadlen, 2002; for a review, see Gold & Shadlen, 2007) as well as in humans (e.g., Donner, Siegel, Fries, & Engel, 2009; Heekeren, Marrett, Bandettini, & Ungerleider, 2004; Philiastides, Heekeren, & Sajda, 2014; Philiastides & Sajda, 2006; Polanía, Krajbich, Grueschow, & Ruff, 2014; Wyart, de Gardelle, Scholl, & Summerfield, 2012). These stages have been described within the framework of sequential sampling models, which postulate that the brain integrates and accumulates noisy sensory evidence over time up to a decision threshold (Ratcliff, 1978; Smith & Ratcliff, 2004; Usher & McClelland, 2001), at which point a choice is reached and a response initiated.

Temporal neural components. Specifically, visual perceptual decisions involving discrimination between images of objects (such as faces, cars, or houses) have been well-characterised using functional magnetic resonance imaging (fMRI) (e.g., Heekeren et al., 2004; Tremel & Wheeler, 2015) and electrophysiology (Diaz, Queirazza, & Philiastides, 2017; Philiastides & Sajda, 2006; Philiastides, Ratcliff, & Sajda, 2006; Ratcliff, Philiastides, & Sajda, 2009). The latter studies by Philiastides and colleagues, exploiting the temporal precision of the electroencephalogram, have reported two distinct temporal components involved in perceptual decision making, referred to as 'early' and 'late,' which are associated with the encoding of sensory evidence and the post-sensory accumulation of decision-related information up to a decision boundary, respectively. These two components seem to occur consistently around 170 and 300 ms after the visual presentation of a noisy visual stimulus in humans (Diaz et al., 2017; Philiastides & Sajda, 2006). Evidence shows that the feedforward processing of early sensory evidence is a crucial step in the perceptual decision making architecture reflecting processing of the quality of the stimulus (Philiastides & Sajda, 2006). However, post-sensory processing of decision evidence and its accumulation in a decision variable as proposed by Gold and Shadlen (2007) seems to be a better predictor of behavioural decision outcome in perceptual decisions (Ratcliff et al., 2009). A recent study in humans has shown ramp-like signals over centroparietal electrodes during this post-sensory processing step, with a slope that varied according to the strength of the evidence and matched predictions of a sequential sampling model (Philiastides et al., 2014). More support for ramp-like signals during post-sensory processing comes from findings showing that the rate of this ramp-like build-up is dependent on the amount of available sensory evidence, with steeper build-ups leading to faster and more accurate decisions in primates (Roitman & Shadlen, 2002; Shadlen & Newsome, 2001). In line with this view, O'Connell and colleagues (2012) have described a decision component that seems to generalise across sensory modalities (supramodal), referred to as central parietal positivity (CPP). This component fulfils all criteria of a decision variable in the traditional sense (Kelly & O'Connell, 2013; O'Connell et al., 2012), showing similar timing and spatial activity distribution to the aforementioned late component. In addition, evidence exists for a third neural component that is temporally situated between the two components. It has been found to vary with task difficulty in a visual face versus car discrimination task (Philiastides et al., 2006), which led Heekeren and colleagues (2008) to propose that its role within a perceptual decision making framework is the allocation of attentional resources depending on a task's demands.

Spatial neural network. Overall, a flexible network of dynamic interactions between sensory, parietal, and frontal cortices has been implicated as cornerstone of visual perceptual decisions (Filimon, Philiastides, Nelson, Kloosterman, & Heekeren, 2013; Heekeren et al., 2008; Katz, Yates, Pillow, & Huk, 2016; Kelly & O'Connell, 2015; Philiastides et al., 2014; Philiastides, Auksztulewicz, Heekeren, & Blankenburg, 2011; Siegel, Buschman, & Miller, 2015). This network likely represents post-sensory decision-related activity with evidence accumulation being strongest in inferior temporal, parietal, and prefrontal regions (Heekeren et al., 2008).

1.1.2 Multisensory (audio-visual)

Behavioural enhancements. Realistic perceptual decisions often involve more than one modality. In most cases, one is concurrently presented with multiple pieces of visual and auditory information that must be integrated into a unified percept by the human brain to form a perceptual decision. Previous research on audio-visual decision making with non-dyslexics has frequently reported that additional or transient sounds facilitate visual perception. In this respect, speech (Sadaghiani, Maier, & Noppeney, 2009) and auditory sound—informative (Gleiss & Kayser, 2014a, 2014b; Kayser, Philiastides, & Kayser, 2017) and uninformative (Chen, Huang, Yeh, & Spence, 2011; Kim, Peters, & Shams, 2012)—can improve decision performance (i.e., accuracy) on visual discrimination tasks. In this process, perceptual weights were found to be assigned to audio-visual cues based on their reliability (e.g., Boyle, Kayser, & Kayser, 2017) in line with principles of statistical optimality (Drugowitsch, Deangelis, Klier, Angelaki, & Pouget, 2014; Rohe & Noppeney, 2016).

Similarly, response times have been found to be shorter during audio-visual decisions on a variety of tasks (Brang, Taich, Hillyard, Grabowecky, & Ramachandran, 2013; Crosse, Butler, & Lalor, 2015; Drugowitsch et al., 2014; Molholm et al., 2002; Romei, Murray, Merabet, & Thut, 2007; Sperdin, Cappe, Foxe, & Murray, 2009). Such behavioural gain (i.e., higher decision accuracy and shorter response times) was also found when the stimulus difficulty (i.e., the strength of available sensory evidence) of one modality (i.e., visual) varied while the difficulty of the other (i.e., auditory) was kept constant (Kayser et al., 2017). Enhancing effects of congruent multisensory evidence are further supported by results of decreasing response time with an increasing number of modalities in a uni-, bi-, or trimodal target detection task (Diederich & Colonius, 2004).

Temporal neural components. To date, the exact mechanisms and temporal dynamics of audio-visual multisensory integration, as well as the neural substrates behind behavioural gain modulation, have not been univocally identified in the human brain and are a matter of an ongoing debate (for recent reviews, see Angelaki, Gu, & DeAngelis, 2009; Bizley, Jones, & Town, 2016; C. Kayser & Shams, 2015). Multisensory neural integration may happen as early as in primary sensory cortices (for a review, see Kayser & Logothetis, 2007). The notion of temporally early and functionally specific multisensory processes is based on a number of electrophysiological studies reporting differences between unisensory and multisensory audio-visual stimuli within 200 ms post-stimulus onset (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Molholm et al., 2002; Romei et al., 2007; Romei, Murray, Cappe, & Thut, 2009; Sperdin et al., 2009; Stekelenburg & Vroomen, 2007; Talsma, Doty, & Woldorff, 2007). However, since the predictive power of these early effects on the decision outcome has often been limited, these studies do not provide conclusive evidence of whether such effects warrant being labelled multisensory integration effects. This label would imply their direct relevance to the outcome of a decision. Instead, these early effects could also represent the combination of multisensory signals, and therewith simply a merge of information.

In an attempt to shed more light on this question, a recent study by Kayser and colleagues (2017) linked a neural component occurring around 350 ms post-stimulus onset (later than previously reported) to the behavioural outcome of a decision on an audio-visual motion discrimination task in humans. Another effort at clarifying the time course of audio-visual integration effects and their relationship to behaviour examined the effect of visual speech (i.e., lipreading) on the auditory perception of natural speech in a quiet versus noisy environment (Crosse, Di Liberto, & Lalor, 2016). These authors reported integration effects at latencies between 200 and 250 ms post-stimulus onset and demonstrated that higher difficulty (i.e., more background noise) led to greater behavioural audio-visual gain. Overall, the existing literature provides evidence primarily for early, and only occasionally for later, neural effects, with later time windows being linked to the behavioural outcome of a decision.

Spatial neural network. Spatial findings add to the debate on the neural substrates of audio-visual integration. Previous research has shown that multisensory computations (i.e., cross-modal effects) are distributed processes occurring at various levels of the processing hierarchy in humans and adapt to task demands (Bizley et al., 2016; Kayser & Shams, 2015). For example, primary sensory areas, such as primary visual cortex, can be modulated by auditory sounds in the absence of any visual stimulation (Vetter, Smith, & Muckli, 2014). Concurrent visual input was also shown to amplify the neural response in primary auditory cortex in a complex object categorisation task (Werner & Noppeney, 2010). This object categorisation task was similar to a paradigm used in this thesis, helping these authors to dissociate the functional roles of primary sensory and higher-association areas including primary, superior temporal, and prefrontal cortices. The latter region could be linked to multisensory facilitation.

The role of attention. In this thesis, we consider attention as one mediating aspect of decision making since it has been shown to lead to effects at various time points during decision making (for a review, see Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Specifically, electrophysiological work has revealed early modulation of a neural signal's amplitude within ˜200 ms post-stimulus onset for selective attention (Talsma et al., 2007), spatial attention (Talsma & Woldorff, 2005), and endogenous auditory attention (Sheedy et al., 2014) tasks. There is also evidence that attention affects the decision process from work looking at neural oscillations, particularly activity in the alpha-band (Gleiss & Kayser, 2014b, 2014a; Lou, Li, Philiastides, & Sajda, 2014; Thut, Nietzel, Brandt, & Pascual-Leone, 2006). In the multisensory context, as proposed by Schroeder, Lakatos, Kajikawa, Partan, and Puce (2008), attention may be a facilitator but most likely not a sole explanation for multisensory enhancements. Overall, these exemplary findings illustrate the important role of attention in unisensory and multisensory perceptual decision making.

All in all, one of the many remaining questions in the field of audio-visual perceptual decision making is whether temporal neural components related to early encoding of sensory evidence, later post-sensory decision-relevant or auxiliary processing can be mechanistically linked to the outcome of audio-visual categorisation decisions on noisy everyday objects.

1.2 Reading: A form of linguistic audio-visual perceptual decision making

The acquisition of reading skills involves multisensory perceptual processes such as the visual perception of letters and words, and the auditory perception of tones and human speech. To gain proficiency one has to develop phonological awareness, which is an established percept of an auditory sound mapped onto its corresponding orthographic visual letter shape (Ehri, 2014). Hence, various forms of audio-visual linguistic sensory evidence have to be combined and memorised (i.e., through repetition and training) during the development of reading to establish such phonological percepts. Once established, these percepts must be retrieved from the mental storage during the process of visual word recognition. Together with accessing one's own mental lexicon and semantic evaluation of a word's context, phonological percepts form the basis of numerous linguistic decisions on the word level during reading. Identifying every word in a text using this cascade of basic processes constitutes a separate linguistic decision (for details on the cognitive process of word recognition, see for example Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).

These linguistic decisions during reading show similarities to the non-linguistic visual perceptual decisions described above, as they follow a similar cascade of neural events (Dien, 2009; Grainger, Kiyonaga, & Holcomb, 2006; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006). Similar to non-linguistic perceptual decision making, word recognition is a fast, incremental and serial process (Rayner & Clifton, 2009) that takes place within the span of a few hundreds of milliseconds (Sereno & Rayner, 2003). Sensory visual evidence, conveyed in the form of written letters, has to be encoded first, before its phonological pattern and semantic context can be analysed and integrated in higher cognitive areas including parietal and frontal cortices to form a decision on which appropriate word to choose from the mental lexicon (Holcomb & Grainger, 2006). Therefore, this thesis argues that the process of word recognition is a form of perceptual decision-making in the context of reading.

1.2.1 Neural responses to faces and words

Empirical evidence for similarities between visual perceptual decision making (i.e., tasks using complex stimuli such as faces) and word recognition come from a number of reaction-time object and word discrimination tasks, such as face versus car image (Diaz et al., 2017; Lou et al., 2014; Philiastides et al., 2014; Philiastides & Sajda, 2007; Philiastides & Sajda, 2006; Philiastides et al., 2006; Ratcliff et al., 2009) and lexical real words versus false font or symbol string discrimination (Appelbaum, Liotti, Perez, Fox, & Woldorff, 2009; Brem et al., 2009). Previous research using these tasks has revealed that the electrophysiological responses to faces and words peak at similar latencies over occipitotemporal electrodes and show comparable scalp topographies, embodied by the well-characterised negative event-related potential (ERP) component N170 for faces (Rousselet et al., 2010; Rousselet, Pernet, Bennett, & Sekuler, 2008) and words (Brem et al., 2009; Pegado et al., 2014). These similarities come as no surprise knowing that the human brain uses proximate category-selective regions that tune specifically to these distinct pieces of complex sensory evidence, namely the fusiform face area for faces (Heekeren et al., 2004; Kanwisher, McDermott, & Chun, 1997) and the visual word form area (VWFA) for words (Cohen et al., 2000; McCandliss, Cohen, & Dehaene, 2003; Nobre, Allison, & McCarthy, 1994). Both lower-level areas are located in the inferior temporal cortex, which is part of the ventral visual processing stream. This stream is an important pathway in visual perceptual decision making (Gold & Shadlen, 2007) and word recognition (Carreiras, Armstrong, Perea, & Frost, 2014; Olulade, Flowers, Napoliello, & Eden, 2013; Vinckier et al., 2007). It has also been shown that learning to read enhances the magnitude and precision of electrophysiological responses to both types of stimuli (Pegado et al., 2014). Overall, these findings suggest that words and faces are well-suited stimuli for the study of similar neural temporal components in linguistic and non-linguistic perceptual decision making.

1.2.2 Neural temporal components of reading

Reading is a complex cultural task that has developed only relatively recently from an evolutionary perspective. While the human brain is approximately 60,000 years old, alphabetic code has only been used for about 5,000 years (Breznitz, 2008). Within this time span the human brain has been able to develop a fast, incremental and serial process for word recognition (Rayner & Clifton, 2009), which takes approximately 400-500 ms to complete in non-impaired readers (Grainger et al., 2006; Hauk, Davis, et al., 2006; Holcomb & Grainger, 2006). Generally accepted theories of word recognition (Coltheart et al., 2001; Norris, 2013) postulate the existence of a series of processing stages, consisting of orthographic analysis (i.e., visual letter perception), phonological analysis (i.e., grapheme to phoneme translation), lexical analysis (i.e., word-frequency, neighbourhood size, etc.), and semantic analysis (i.e., the meaning and context of a word), which are performed to select and retrieve a word from one’s mental lexicon or decode an unknown word during reading (Bentin et al., 1999; Carreiras et al., 2014; Grainger et al., 2006; Holcomb & Grainger, 2006). These stages are serial, yet interactive (Norris, 2013).

Recent advances in non-invasive electrophysiology have allowed researchers to characterise the neural temporal correlates of these serial stages extensively in humans (e.g., Bentin et al., 1999). The beginning reader has to tune to print symbols (i.e., develop efficient neural processing to letters and written text) in the presented orthography (i.e., the script) during the development of her reading skills (Brem et al., 2010; Eberhard-Moscicka, Jost, Raith, & Maurer, 2015). The process of tuning to words is reflected in early electrophysiological components (P150/P1 and N170/N1), and can be observed when contrasting neural activity for orthographic versus non-orthographic processing, and differing word forms (Appelbaum et al., 2009; Bentin et al., 1999; Grainger et al., 2006; Holcomb & Grainger, 2006; Sereno, Brewer, & O'Donnell, 2003; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005). With increasing expertise, the amplitude of these components (Brem et al., 2006) and predominantly N170/N1 latency (Brem et al., 2009) is diminished in response to seeing a word (Pegado et al., 2014). This processing step has traditionally been tested with paradigms that compare letters or words to false font or symbol strings, and seems to be script- and language-invariant (Maurer, Zevin, & McCandliss, 2008; Wong et al., 2005). Both early ERP components were also found to be independent of attention during letter processing in a letter versus pseudo-letter task in non-impaired adults (Herdman & Takai, 2013).

The subsequent step of the word-recognition cascade, termed lexical analysis, has been associated with ERP components peaking around 250 ms after the presentation onset of a word (Grainger et al., 2006; Holcomb & Grainger, 2006). However, word-frequency (i.e., a measurement of lexicality) effects have been reported to start as early as 135 ms post-stimulus onset (Hauk & Pulvermüller, 2004; Sereno, Rayner, & Posner, 1998). Similarly, a different process, namely phonological analysis (i.e., the processing of the implicit sounds accompanying a written word), has also been found to start around 250 ms but extends out to around 350 ms post-stimulus onset (Bentin et al., 1999; Grainger et al., 2006). These findings illustrate the flexibility in the serial organisation of the word-recognition cascade (for a review of the early ERP components of word recognition, see Dien, 2009). A word's meaning (i.e., its semantics), considered its most complex property, is last to be processed. The semantic analysis of entire words is represented by ERP components occurring around 400 ms after presentation onset of a word such as the well-known N400 (Bentin et al., 1999; Grainger et al., 2006; Helenius, Salmelin, Service, & Connolly, 1998; Holcomb & Grainger, 2006; Van Petten, 1995). Recently, however, semantic contributions to the smallest meaningful units of words (i.e., a morpheme) were shown to occur even as early as 250 ms post-stimulus onset in the left superior temporal gyrus on a lexical decision task (Cavalli, Colé, et al., 2016).

This well-established timeline comes as no surprise since eye movement accounts of lexical access have shown that on average between 250 and 300 ms are available for lexical analysis until the eyes move on to the next word (Sereno & Rayner, 2003). This suggests that most word-recognition processes must be triggered if not completed by this point in time.

1.2.3 The effects of font type and font properties

As previous literature has shown orthographic analysis (i.e., the first processes of the neural word-recognition cascade) is modulated by component features of words (i.e., lines as sub-elements of letters) that are unique to a familiar script. For instance, the simple contrast between valid Roman letter shapes and fake letters composed of the same line elements was found to affect the early neural ERP components of orthographic analysis such as the N1 in adults (Herdman & Takai, 2013). This and similar findings (Appelbaum et al., 2009) point to the crucial role of component features (Grainger, Rey, & Dufau, 2008), which give rise to the overall letter and word shape, in visual word recognition.

One property that can change the appearance of a letter and word substantially is font. A font describes a set of characters (i.e., letters and punctuation marks) that follow the same design. This design can vary vastly between two fonts (Figure 1.1a), thereby creating an entirely different letter and word shape as illustrated by the comparison of words written in Arial regular to others written in Gigi regular (Chauncey, Holcomb, & Grainger, 2008). Interestingly, the authors reported changes in ERP amplitude around 150 ms after the presentation onset of a primed word; a time point converging with the previously described findings on orthographic analysis and letter shape perception (Appelbaum et al., 2009; Herdman & Takai, 2013; Keage, Coussens, Kohler, Thiessen, & Churches, 2014). These studies underline the importance of font for early neural processes during word recognition. Notwithstanding the insights of these studies, investigations into the neural effects of different font types and styles remain rare.

However, a growing body of literature provides ample empirical evidence for effects of different fonts and their properties on behavioural reading performance. Enhancements in reading rate have been reported for Times New Roman when compared to Courier (Mansfield, Legge, & Bane, 1996), the more distinctive font Verdana when compared to Sassoon Primary (Wilkins et al., 2007), the more fluent font Courier when compared to Mistral (Sanchez & Jaeger, 2015), and a sans-serif font (i.e., fonts without additional horizontal lines added to end points of letters M vs M) when compared to a serif font (Yager, Aquilante, & Plass, 1998). Similarly, font properties including larger font size (Bernard, Liao, & Mills, 2001; Chung, Mansfield, & Legge, 1998; Franken, Podlesek, & Možina, 2014; Russell & Chaparro, 2001), increases in letter spacing for small text (Chung, 2007), and the interplay of intra- and inter-word spacing were also found to enhance readability (Dobres, Wolfe, Chahine, & Reimer, 2018) and lexical processing. Particularly, intra- and inter-word spacing exerted positive effects on saccade target selection and the word segmentation processes (i.e., comparing Cambria, Times New Roman, Consolas, and Georgia; Slattery & Rayner, 2013). Such enhancements due to wider spacing were attributed to decreases in spatial crowding (Chung, 2007).

Letter identification, another crucial reading skill, was also found to be improved with Arial compared to Times New Roman font (Woods, Davis, & Scharff, 2005). In this respect, letter identification efficiency was reported to vary across fonts with less complex letter forms yielding higher efficiencies (Pelli, Burns, Farell, & Moore-Page, 2006). Lastly, font and its properties have also been found to improve reading recall, a measure of reading comprehension, as shown for disfluent fonts (Diemand-Yauman, Oppenheimer, & Vaughan, 2010; French et al., 2013) and larger print size (i.e., 48-point versus 18-point; Price, McElroy, & Martin, 2016). Serifs increased the subjective comprehensibility of scientific abstracts as well (Kaspar, Wehlitz, von Knobelsdorff, Wulf, & von Saldern, 2015). Nevertheless, the reading effort of a disfluent font such as Old English was reported to be increased when compared to Times New Roman (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006).

This extensive literature stands in opposition to a number of findings reporting no effect or even declining performance with certain font types and properties that have also been shown to enhance performance. For instance, font type did not lead to higher reading rate in fast or slow readers (i.e., Georgia versus Consolas) (Rayner, Slattery, & Bélanger, 2010) nor did serifs (Arditi & Cho, 2005; Yager et al., 1998). Serifs were also found not to effect legibility (Arditi & Cho, 2005) or fixation duration in online reading (Beymer, Russell, & Orton, 2008). Further contradictory findings show that the retention of content was better with a smaller disfluent font in a classroom setting (i.e., 12-point versus 18-point) (Diemand-Yauman et al., 2010), and letter identification was only weakly dependent on size (Pelli et al., 2006). Also, visual search and information retrieval on web pages was comparable between two commonly used fonts (i.e., Arial and Times New Roman) that have repeatedly been found to lead to different performance (Ling & Van Schaik, 2006).

Among commonly used font styles (i.e., regular, bold and italic) one that deserves special attention in the context of this thesis is the italic style. Since most specific attributes of a font are systematic and share a common design (Gauthier, Wong, Hayward, & Cheung, 2006; Sanocki, 1987), creating an italic font style only changes a letter's, and in turn a word's, slant. As such, italics are recommended for emphasising important content by writing manuals (Adams, 2013), whereby this content is supposed to appear more salient with faciliatory effects on reading comprehension. However, empirical evidence for this theoretical account remains inconclusive. On the one hand, improvements in text retention with italics were reported in the context of education materials (Diemand-Yauman et al., 2010), whereas on the other hand, reading recall was worse for text presented in italics compared to a regular font style (Price et al., 2016). Even poor readers with dyslexia did not benefit as they exhibited worse reading comprehension when presented with an italicised font (Rello & Baeza-Yates, 2013, 2016).

Independently of performance, font preference has also been reported to vary with font properties. Preference was higher for sans-serif fonts (Josephson, 2008;

Ling & Van Schaik, 2006), rounder compared to angular fonts (Velasco, Woods, Hyndman, & Spence, 2015), larger font size (14-point preferred over 12-point; Bernard et al., 2001), and regular compared to italic font styles (Rello & Baeza-Yates, 2013, 2016).

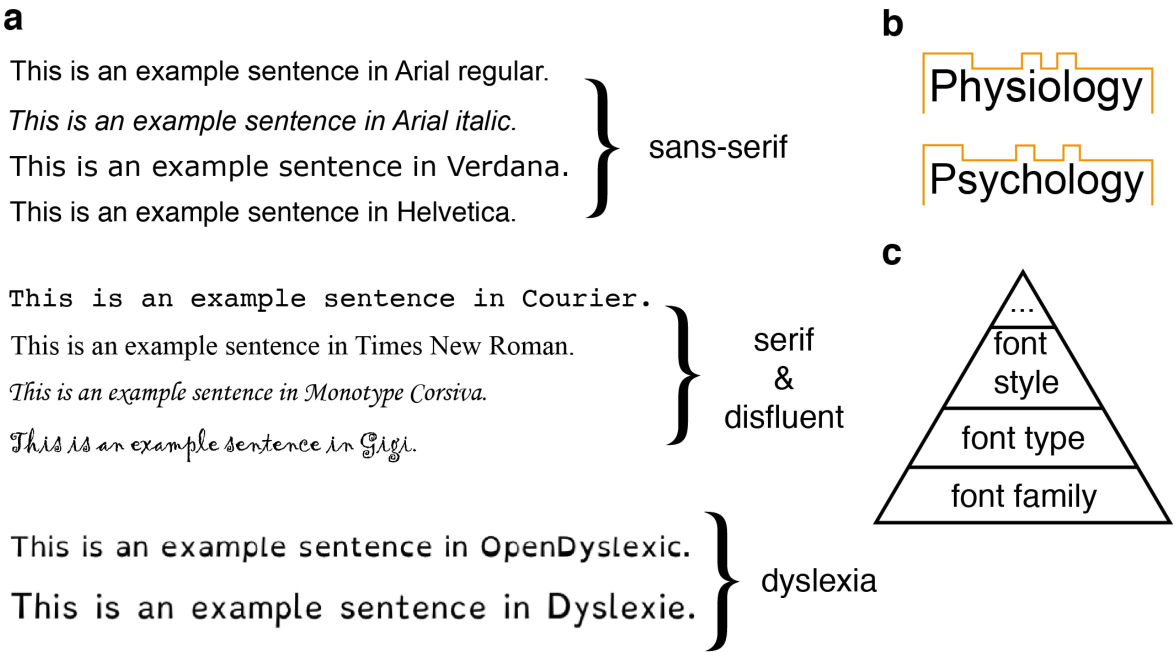


Figure 1.1. Examples of font types, contour lines, and typesetting terminology. a) Example sentences written in varying font types and styles and the same point size that investigations reviewed in this chapter have used. b) Illustration of the visual word shape. Two words with similar contour line but different meaning. c) Hierarchy of typesetting terminology. Font family (bottom layer and umbrella term), font type (category), font style (characteristic of a category such as italic), and more specific characteristics including weight, etc.

As this review of the literature on fonts demonstrates, font type and certain properties undoubtedly affect reading performance. However, it has also become evident that previous literature on the behavioural effects of font reports contradictory findings. Since fonts, even from the same categories (e.g., sans-serif fonts or italic styles), vary greatly in their design properties, reports of behavioural effects are highly dependent on the direct comparisons employed. These differences may help to explain the observed multitude of findings, but simultaneously illustrate the need for more thorough investigations of the effects of comparable commonly used fonts. In this respect, we identified a specific lack of research on the neural correlates of processing common fonts and font styles. We aim to bridge this gap in the current thesis by comparing the neural effects of Arial italic and Arial regular in the context of sentence reading comprehension (see Chapter 2).

1.2.4 The effect of font and text legibility on eye movements

During the process of reading our eyes need to process a multitude of visual information in short succession. The physiological limitations of the human eye, specifically the fact that humans have sufficient visual acuity to decode letters only in the fovea (i.e., within an angular diameter of 2° of visual angle around the centre of the visual field; Steinmann, 2003, cited in Land, 2006), results in numerous small eye movements during reading. These eye movements include fixations (i.e., stops for decoding the finest information of high spatial frequency such as letters) and saccades (i.e., jumps to move the eyes from one fixation to the next). Fixation time and saccade distance are two measures that are believed to allow inferences about cognitive processes during reading (Rayner & Reingold, 2015), and have been found to be modulated by numerous perceptual and linguistic (e.g., Reingold, Reichle, Glaholt, & Sheridan, 2012; Sheridan & Reingold, 2012) factors. In the context of this thesis, we will focus on literature that has investigated the effects of different fonts and manipulations of text legibility on eye movements.

Several studies have provided insights into the effects of different font types and properties on eye movements to date. The analytical focus of these investigations has been placed on the number of fixations, fixation durations, and saccade length/amplitude. A few studies have demonstrated that an easier to decode font (i.e., a more legible font due to clean design) results in fewer fixations (Slattery & Rayner, 2010), shorter fixation time (Rayner et al., 2006; Sanchez & Jaeger, 2015; Slattery & Rayner, 2010) and longer saccades (Rayner et al., 2006). Similar effects of shorter fixation times were shown if two consecutive words were presented in a congruent font during priming as opposed to two incongruent fonts (Sheridan & Reingold, 2012). The presence or absence of serifs also affected fixation durations and saccade length, with non-serif fonts resulting in shorter fixation durations, shorter saccades, more forward saccades and more regressions (Rayner et al., 2010). However, existing evidence on the effect of serifs is ambiguous as another study found no effect of serifs on eye movement behaviour (Beymer et al., 2008).

Previous literature is unambiguous concerning manipulations of text properties such as text spacing and size. A number of studies have demonstrated consistent effects of spacing in the form of reduced spacing leading to shorter average fixation duration (Rayner et al., 2010; Slattery & Rayner, 2013), but a higher number of fixations (experiment 1 in Slattery & Rayner, 2013). Further, more regressions and longer saccades were reported for reduced spacing conditions (Rayner et al., 2010). The spacing effect was examined in more detail in the second experiment of Slattery and Rayner's (2013) study, who reported that an interaction of reduced intra-word but increased inter-word spacing shortened participants' average fixation duration. This effect was larger for the serif font Georgia compared to Consolas and speaks to the importance of distinguishable word forms in word identification. Another investigation reported that target words of similar length written in the monospaced font Courier (i.e., fixed-width spacing) were skipped more often when compared to the proportional font Arial (Hautala, Hyönä, & Aro, 2011), however, this effect might be biased by the authors' comparison of two fonts that also varied in stroke width and the presence of serifs. Lastly, larger font sizes have repeatedly been shown to yield shorter fixation durations (Beymer et al., 2008; Franken et al., 2014) but more fixations (Franken et al., 2014).

These findings support the assumption that the degree of processing difficulty of a font is not only reflected in the behavioural performance of non-impaired readers but also their eye movements. Given that a substantial number of readers suffer from the developmental condition dyslexia, which manifests in poor reading skills and has frequently been associated with aberrant eye movements (for a review, see Quercia, Feiss, and Michel (2013), effects of font on eye movements during reading may even be magnified in this group. A first attempt at investigating this relationship suggested that, indeed, eye movements vary with font in adult dyslexia (Rello & Baeza-Yates, 2016). However, little analytic attention has been paid to quantitative evaluations of the psychophysiological mechanisms underlying the intended behavioural enhancements of specific dyslexia fonts using standardised stimuli. Building on the aforementioned work, we aimed to investigate the effects of one specific dyslexia font (i.e., OpenDyslexic) on eye movements and reading comprehension in adult dyslexic individuals (see Chapter 3).

1.3 Differences in dyslexia

Developmental dyslexia is a specific learning disorder that is neurobiological (Klingberg et al., 2000; Lyon, Shaywitz, & Shaywitz, 2003; Saygin et al., 2013; Williams & Casanova, 2010) and genetic (Carrion-Castillo, Franke, & Fisher, 2013) in origin. Dyslexia has a long history; Pringle Morgan (1896) described the first instance of developmental dyslexia in a 14-year-old adolescent terming it 'word blindness.' Already this early description illustrated that deficits in the visual component of reading are a vital part of dyslexia. Nowadays, dyslexia 'refers to a pattern of learning difficulties characterised by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities' (American Psychiatric Association, 2013, p. 67) that persist into adulthood (Shaywitz et al., 2003; Swanson & Hsieh, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Consequently, only a fraction of dyslexics obtains higher academic degrees (Warnke, 1999). Its estimated prevalence rates in the general population range from 5 to 15% (American Psychiatric Association, 2013; Shaywitz, 1998; Shaywitz et al., 2003), with seemingly higher rates in males than females (Arnett et al., 2017; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Dyslexia has also been found to be language- and culture-independent (Lyon et al., 2003; Vellutino et al., 2004), even though the degree of severity varies with the depth of an orthography (Vellutino et al., 2004).

1.3.1 Dyslexia definition

For the purpose of this thesis, we adopted the following two definitions by the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) (American Psychiatric Association, 2013) and Lyon and colleagues (2003), since, taken together, they offer a more comprehensive definition of dyslexia that includes various symptoms stemming from a multitude of aetiologies. The resulting comprehensive dyslexia profile illustrates the spectrum of manifestations of this disorder.

The DSM-5 (American Psychiatric Association, 2013) defines dyslexia as a clinical diagnosis that is classed under the rubric specific learning disorder (66) with a specific impairment in reading (315.00 F81.0) or in written expression (315.2 F81.81). 'Specific learning disorder is a neurodevelopmental disorder with a biological origin that is the basis of abnormalities at a cognitive level that are associated with the behavioural signs of the disorder. The biological origin includes an interaction of genetic, epigenetic, and environmental factors, which affect the brain's ability to perceive or process verbal or non-verbal information efficiently and accurately' (American Psychiatric Association, 2013, p. 68). Dyslexia is one of the most common manifestations of specific learning disorders. It is characterised by difficulties with learning to map the sounds of one's language onto its written letters and to read printed words. The learning difficulties have to be persistent, and not only transitory (American Psychiatric Association, 2013). Lyon and colleagues (2003) add that 'these difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience' (Lyon et al., 2003, p. 2).

1.3.2 Cognitive profile and behavioural performance

Previous research has led to numerous valuable insights into the cognitive underpinnings of dyslexia. Dyslexics exhibit a different general cognitive profile represented by deficits in working memory capacity, speed of processing, attention, letter reading fluency, orthographic parsing time, phonology and text comprehension among others (Beidas et al., 2013; Horowitz-Kraus, 2014; Swanson & Hsieh, 2009). Specifically, individuals diagnosed with dyslexia have also shown significant difficulty with word decoding speed (Lefly & Pennington, 1991; Shaywitz et al., 2003; van der Leij & van Daal, 1999) and accuracy (Snowling & Melby-Lervåg, 2016; Verhoeven & Keuning, 2018) that is often accompanied by difficulties with text comprehension (Elbro & Petersen, 2004). Additionally, reports of comorbid disorders such as Attention Deficit Disorder (ADD), Attention Deficit and Hyperactivity Disorder (ADHD) (e.g., Knivsberg & Andreassen, 2008), and disorders of the motor system (Ramus, 2003) exist.

1.3.3 Eye movements and oculomotor control

Eye-tracking can provide another perspective on cognitive processes and a window into the human brain. This technique has allowed researchers to reveal altered eye movement patterns in dyslexia during reading (Bucci, Brémond-Gignac, &

Kapoula, 2008; Bucci, Nassibi, Gerard, Bui-Quoc, & Seassau, 2012; De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hutzler & Wimmer, 2004; Lassus-Sangosse, N'guyen-Morel, & Valdois, 2008; Prado, Dubois, & Valdois, 2007; Razuk, Barela, Peyre, Gerard, & Bucci, 2018; Trauzettel-Klosinski et al., 2010; Vagge, Cavanna, Traverso, & Lester, 2015). Similarly, different eye movements have equally been reported for non-reading tasks such as smooth pursuit (Eden, Stein, Wood, & Wood, 1994; Pavlidis, 1981), antisaccade (Biscaldi, Fischer, & Hartnegg, 2000), saccadic reaction time (Fischer & Weber, 1990; Fischer, Biscaldi, & Otto, 1993), visual search (Bucci et al., 2012; Razuk et al., 2018), and fixation stability tasks (Eden et al., 1994; Fischer & Hartnegg, 2000; Raymond, Ogden, Fagan, & Kaplan, 1988). Conversely, a number of early eye movement studies have reported no differences between participants with and without dyslexia on a range of stimulus tracking (Brown et al., 1983; De Luca et al., 1999; Olson, Kliegl, & Davidson, 1983; Stanley, Smith, & Howell, 1983; Vagge et al., 2015), target spot fixation (Black, Collins, De Roach, & Zubrick, 1984), fixation stability (De Luca et al., 1999; Raymond et al., 1988), letter naming (Jones, Obregón, Louise Kelly, & Branigan, 2008) and also reading (Hyönä & Olson, 1995) tasks. More findings have suggested that the oculomotor system may be intact in dyslexia, even though it appears to be immature and its (attentional) control affected (Bucci et al., 2012; Fischer & Weber, 1990; Fischer et al., 1993). Hence, previous literature evidenced that changes in oculomotor behaviour occur in dyslexia. However, as outlined above, the literature is partly contradictory, and therefore the exact role of aberrant eye movements in dyslexia (i.e., whether it is a cause or concomitant symptom) is yet to be determined.

1.3.4 Structural and functional neurobiology

On the neural level, a large body of research identified distinct structural (Casanova, El-Baz, Giedd, Rumsey, & Switala, 2010; Klingberg et al., 2000; Saygin et al., 2013; Williams & Casanova, 2010; Williams, El-Baz, Nitzken, Switala, & Casanova, 2012) and functional neural profiles (Kolb & Whishaw, 2009; Norton, Beach, & Gabrieli, 2015; Price & Mechelli, 2005; Shaywitz, Mody, & Shaywitz, 2006; Shaywitz et al., 2003, 1998; Shaywitz & Shaywitz, 2005) in dyslexia. These aberrant neural profiles show differences in temporal electrophysiological components during the recognition of letters, words and symbols (Araújo, Bramão, Faísca, Petersson, & Reis, 2012; Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013; Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999), diminished functional activation (i.e., lower blood-oxygen-level dependent (BOLD) activity) of left occipital areas of the reading network (Norton et al., 2015; Price & Mechelli, 2005; Shaywitz et al., 2006, 2003; Shaywitz & Shaywitz, 2005), impaired audio-visual integration (Hahn, Foxe, & Molholm, 2014; Kronschnabel, Brem, Maurer, & Brandeis, 2014), and different connections of spatial networks for reading (Finn et al., 2014). Together, these differences illustrate the neurobiological basis of dyslexia.

1.4 Perceptual decision making in dyslexia

Reading strategy. As the preceding sections illustrated, word recognition is a culturally learned skill that involves the tuning of a complex network of fast neural processes to print. Skilled and non-impaired readers perform word recognition, and therewith reading, on the lexical level (i.e., an entire word), whereas beginning (Araújo, Faísca, Bramão, Petersson, & Reis, 2014) and adult dyslexic readers (Helenius, Salmelin, Service, & Connolly, 1999) were found to use a more laborious sub-lexical reading strategy (i.e., parts of words) or employ a visual reading strategy that is overly relying on the general visual word form (Snow, Burns, & Griffin, 1998). Relying on the visual word form (i.e., the contour line; Figure 1.1b) for word decoding emphasises the importance of the first and last letters of a word, termed logographic reading (Goswami, 2015a). The latter technique can lead to the selection of a semantically erroneous word with similar word shape or first letters from the mental lexicon (as observed by Helenius, Salmelin, Service, and Connolly, 1999), making it more error-prone.

1.4.1 Visual linguistic decision making in adult dyslexia

Behavioural deficits. Reading strategy is an important component of speeded linguistic decision tasks such as lexical decision, semantic congruency, and reading comprehension tasks. Previous literature on such tasks including the lexical decision task, first introduced by (Meyer & Schvaneveldt, 1971), has shown worse behavioural performance in the form of lower accuracy rates and slower reaction times (Araújo et al., 2012, 2014; Hasko et al., 2013; Horowitz-Kraus & Breznitz, 2008; Kast, Elmer, Jancke, & Meyer, 2010; Paizi, De Luca, Zoccolotti, & Burani, 2013; Taroyan & Nicolson, 2009) for dyslexics of all ages; particularly those who have not compensated for their developmental deficit (Horowitz-Kraus & Breznitz, 2012). Interestingly, even in the absence of a confounding speed-accuracy trade-off, a lexical decision task demonstrated that dyslexics exhibited generally slower processing and lower accuracy for rhyme-inconsistent words. This finding led the authors to conclude that dyslexics are mostly affected by a general word-recognition speed deficit and the use of a sub-lexical reading strategy (Kunert & Scheepers, 2014). Similarly, findings of a dyslexia-related performance difference on a semantic congruency, but not on a single-word lexical decision task (Helenius, Salmelin, et al., 1999), reports of dyslexics of all ages committing more false-positive errors for homophones during semantic decisions (O'Brien, Van Orden, & Pennington, 2013), and negative effects of longer words in developmental dyslexia (Araújo et al., 2014; Barton, Hanif, Eklinder Björnström, & Hills, 2014; De Luca, Barca, Burani, & Zoccolotti, 2008; Verhoeven & Keuning, 2018), provide more evidence for the use of a sub-lexical or logographic word-recognition strategy.

Neural deficits. Differences between dyslexics and non-dyslexics on reading and lexical decision tasks extend to the neural level as well. Dyslexics have been found to exhibit differential activity in several temporal ERP components. These components range from initial time points after the visual presentation of a word or symbol string (i.e., the P1 around 100 ms) (Taroyan & Nicolson, 2009) over the N170/N1 (Hasko et al., 2013; Kast et al., 2010; Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012), N400 (Hasko et al., 2013; Schulz et al., 2008), and P400 and P500 (Taroyan & Nicolson, 2009), to the error/correct-related negativities (i.e., ERN and CRN) post-response (Horowitz-Kraus & Breznitz, 2008). Specifically, differences in the initial components (i.e., the P1 and N1 occurring within 250 ms post-stimulus onset) suggest inefficient tuning to print in dyslexic adults (Mahé et al., 2012), which normally evolves during childhood in non-dyslexics (Brem et al., 2010). Most of the aforementioned studies report significant attenuation or delay of these ERP components resulting in a neural difference in dyslexia. These temporal findings are complemented by literature showing diverging scalp activity profiles. In these studies, dyslexics' ERP components showed a rather bilateral activity profile in response to words (Araújo et al., 2012; Hasko, Bruder, Bartling, & Schulte-Körne, 2012; Schulte-Körne, Bartling, Deimel, & Remschmidt, 1999; Taroyan, Nicolson, & Fawcett, 2007), as opposed to the left lateralisation frequently observed in non-dyslexics.

So far, this review has illustrated that dyslexia is characterised by differences in cognitive skills, behavioural performance, and temporal neural processing on linguistic single-word and sentence-level decision tasks. Findings that suggest the use of a visual reading strategy (i.e., logographic or sub-lexical) point to the potential impact of font type and font style. Some exploratory attempts have shown a negative impact of font type and style on behavioural performance and preference in dyslexia (French et al., 2013; Rello & Baeza-Yates, 2013, 2016). However, no investigation with an analytical focus on the effects of font style on neural temporal processing has been reported. We address this question in Chapter 2.

Dyslexia fonts. In an attempt to reduce the general struggles of readers suffering from dyslexia with reading text presented in certain font styles (e.g., italics and serifs), designers started to develop specific dyslexia fonts. These fonts synthesise properties that have proven to facilitate reading performance, legibility of text, and visual processing including increased spacing (Chung, 2007; Dotan & Katzir, 2018; Masulli et al., 2018; Rayner et al., 2010; Sjoblom, Eaton, & Stagg, 2016; Slattery & Rayner, 2013; Zorzi et al., 2012), rounder shapes (Velasco et al., 2015), and the absence of serifs (Woods et al., 2005) among others. Particularly, omitting serifs aims to reduce typical visual symptoms of dyslexia such as visual crowding (Callens, Whitney, Tops, & Brysbaert, 2013; Gori & Facoetti, 2015). The properties of these fonts target the alleviation of typical visual dyslexia symptoms such as the moving and blurring of letters, letter transpositions, substitutions, and omissions. A number of these so-called dyslexia-friendly fonts have been published including OpenDyslexic (https://www.opendyslexic.org), Dyslexie (https://www.dyslexiefont.com), Read Regular (https://www.readregular.com), and EasyReading (https://www.easyreading.it). Recent scientific evaluations of these fonts' efficacy show both improvements (Bachmann & Mengheri, 2018; Marinus et al., 2016; Rello & Baeza-Yates, 2013) and absent improvements (Kuster, van Weerdenburg, Gompel, & Bosman, 2018; Rello & Baeza-Yates, 2016; Wery & Diliberto, 2017; Zikl et al., 2015) in performance, whereby they paint an inconclusive picture. Specifically, the physiological (i.e., eye movements) and cognitive mechanisms underlying adult dyslexics' reading performance on standardised texts presented in these fonts remain elusive. We hence present an examination of the effects of the dyslexia font OpenDyslexic on reading comprehension and eye movements in Chapter 3.

1.4.2 Visual and auditory non-linguistic perceptual decisions

As the adopted dyslexia definitions outlined, the traditional and pervasive view postulates deficits in phonological skills as the core impairment, since these deficits are among the most common deficits present in those with dyslexia (Ramus, 2003; Saksida et al., 2016; Snowling, 1980, 1981). However, in recent years, this traditional view has been called into question by a growing body of evidence showing that children and adults with dyslexia exhibit deficits on simple sensory-perceptual tasks spanning auditory and visual modalities (for reviews, see Hämäläinen, Salminen, & Leppänen, 2013; Laycock & Crewther, 2008; Schulte-Körne & Bruder, 2010; Stein, 2001). These findings suggest a more fundamental deficit marked by impairments on a variety of non-linguistic decision tasks.

Visual deficits. Evidence for deficits in visual sensory perception comes from tasks examining the discrimination of coherent (Talcott, Hansen, Assoku, & Stein, 2000) and rapid motion (Demb, Boynton, Best, & Heeger, 1998), objects (Mayseless & Breznitz, 2011), and different contrasts (Pammer & Wheatley, 2001). Specifically, neural latency differences were shown for rapidly moving stimuli at low contrasts (for reviews, see Laycock & Crewther, 2008; Schulte-Körne & Bruder, 2010) and early components when discriminating objects from pseudo-objects (Mayseless & Breznitz, 2011). Dyslexics also exhibited worse neural adaptation in response to repetitive presentation of images of everyday objects and human faces (Perrachione et al., 2016), and suffered from visual crowding even in the absence of letters, with larger effects for an increasing number of distractors (Moores, Cassim, & Talcott, 2011). Another report went one step further by linking visual temporal processing, embodied by a perceptual speed factor, directly to reading ability (McLean, Stuart, Coltheart, & Castles, 2011).

However, previous literature also comprises contradictory reports showing no impairments in similar sensory-perceptual skills. These reports found no deficits during motion detection (Tsermentseli, O’Brien, & Spencer, 2008), visual object conflict processing (Bakos, Landerl, Bartling, Schulte-Körne, & Moll, 2017), picture naming (Trauzettel-Klosinski, Dürrwächter, Klosinski, & Braun, 2006), and the discrimination of non-phonologically mapped symbols (Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). Thus, evidence for visual sensory impairments exists but appears to be mediated by other factors.

Auditory deficits. On auditory tasks, perceptual deficits have been shown in the context of a pure tone selective choice task (Nicolson & Fawcett, 1994), frequency modulated tones (Stoodley, Hill, Stein, & Bishop, 2006), auditory frequency discrimination for pitch but not for tone duration (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999), and neural discrimination of temporal order within complex tone patterns (Kujala et al., 2000). In this domain, neural responses such as the well-known mismatch negativity (MMN) often represent behavioural deficits (for reviews of auditory deficits in dyslexia, see Hämäläinen, Salminen, & Leppänen, 2013; Schulte-Körne & Bruder, 2010). Computational models using the Bayesian framework provided more mechanistic insights by demonstrating that dyslexics' deficiency in benefitting from stimulus repetition during tone discrimination is due to elevated levels of perceptual noise and an inability to update their 'prior' with information obtained on previous trials (Jaffe-Dax, Raviv, Jacoby, Loewenstein, & Ahissar, 2015). These mechanisms may also apply to visual perceptual tasks. As one might expect, behavioural and neural auditory deficits in dyslexia also extend to more complex tasks including speech perception (e.g., Di Liberto et al., 2018; Hornickel & Kraus, 2013).

Multisensory deficits. The literature reviewed above illustrates that dyslexics' deficits extend to purely sensory non-linguistic tasks in two unisensory domains. Since developing phonological awareness is an audio-visual process, it is also conceivable that deficits may be located further downstream in the neural processing hierarchy in heteromodal brain areas that are implicated in audio-visual stimulus integration. Impairments at this stage could add to the low-level deficits observed for separate modalities or give rise to phonological impairments by themselves. Research employing simple audio-visual sensory tasks (e.g., beeps and flashes of light or symbols) have revealed deficits in audio-visual stimulus integration in dyslexia (e.g., Widmann et al., 2012). One consistent finding is a larger temporal window of integration (TWIN) during audio-visual temporal order judgement tasks (Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Laasonen, Service, & Virsu, 2002; Wallace & Stevenson, 2014). Audio-visual deficits were also shown to extend to a word-speech lexical decision task (Kast, Bezzola, Jäncke, & Meyer, 2011), where no benefit of available audio-visual over visual information was found. A smaller benefit of additional lip movements on auditory word detection in noise-masked speech was reported in the literature (van Laarhoven, Keetels, Schakel, & Vroomen, 2018). In light of these deficits, Wallace and colleagues (2014) postulated that a prolonged TWIN might lead to greater ambiguity among sensory information with deleterious consequences for perceiving audio-visual stimuli as congruent. The perception of audio-visual congruency is a foundation for the development of phonological awareness and in turn efficient reading.

Such audio-visual behavioural deficits receive further support from dyslexia specific differences in the neural architecture known to be involved in integrating audio-visual inputs and phonological conversion (for a review, see Hahn et al., 2014). These include diminished activation of the superior temporal cortex in dyslexic adolescents (Kronschnabel et al., 2014) and adults (Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009), and reduced connectivity in temporo-parietal brain areas. In sum, these findings point towards impairments in fundamental unisensory and audio-visual perceptual skills resulting in sluggish or absent audio-visual integration in dyslexia (Mittag, Thesleff, Laasonen, & Kujala, 2012).

Sensory theories and mediators. The aforementioned sensory deficits have also been explored from a theoretical perspective. Particularly visual sensory deficits have given rise to the magnocellular theory of dyslexia (Stein, 2001, 2018a, 2018b; Stein & Walsh, 1997). This theory is based on findings of thinner and disorganised magnocellular layers in the lateral geniculate nucleus in dyslexics (Giraldo-Chica, Hegarty, & Schneider, 2015; Livingstone, Rosen, Drislane, & Galaburda, 1991). It links impairments in sensory-perceptual skills such as contrast sensitivity (Pammer & Wheatley, 2001; Schulte-Körne & Bruder, 2010), visual sequencing and rapid focusing of visual attention (Vidyasagar & Pammer, 2010), and the control of saccadic eye movements (Laycock & Crewther, 2008; Stein, 2018b). Specifically, the magnocellular theory's link to the mediating factor attention lets it appear attractive, since previous research has provided evidence for specific impairments in various components of attention and parallel visual processing on non-linguistic tasks (Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Paganoni, Turatto, Marzola,

& Mascetti, 2000) that represent a non-verbal visual deficit (Lobier, Zoubrinetzky, & Valdois, 2012) in dyslexia.

Phonological theory and causality of impairments. To date, the two most prominent competing dyslexia theories, namely the phonological and magnocellular theory, postulate that their respective main deficit plays a causal role in dyslexia (Goswami, 2015a; Ramus, 2003; Ramus et al., 2003; Saksida et al., 2016; Stein, 2001, 2018a, 2018b; Vellutino et al., 2004). Opposed to the magnocellular theory mentioned above, the phonological theory postulates that deficient mapping of phonological speech sounds onto their written letter counterparts, also called phonological recoding, lies at the heart of dyslexia causing a multitude of commonly reported deficits (e.g., Snowling, 1981; Vellutino et al., 2004).

Some proponents of the phonological theory argue that implicating mainly visual skills as a cause of reading impairments is too simple, since the acquisition of reading is a linguistic process during which auditory perception plays an undeniably crucial role as well (Goswami, 2015a). One argument brought forward in recent years is that the sensory deficits reported in dyslexia are a result of livelong reduced reading experience, whereby all sensory skills involved in reading do not receive the same amount of training, which in turn would give rise to the observed sensory deficits (Goswami, 2015a). Support for the central role of phonological recoding skills and their amount of experience is illustrated by the finding of a spatial cuing deficit only in children with phonological recoding deficits. More support comes from reports showing that phonological variables explained more variance than visual sensory variables (Saksida et al., 2016). The involvement of some phonological component such as experimental designs using letters and oral reports in several attention studies has been interpreted as more evidence that weakens the causal argument presented by sensory theories of dyslexia (Goswami, 2015b).

On the contrary, although evidence for aspects of the phonological deficit theory is ample, its proponents admit that in principle cross-modal deficits can arise from separate visual and auditory sensory dysfunctions (Goswami, 2015a). If we simply follow the cortical hierarchy of bottom-up processing of visual and auditory sensory evidence, it may appear obvious that any deficits in visual or auditory primary cortices could give rise to deficits in subsequent audio-visual integration and phonological components processed in secondary cortices and higher association areas (Stein, 2018b). Therefore, it is further argued that if genes associated with dyslexia, which are involved in the neural migration of neurons in sensory areas, give rise to sensory deficits, these deficits should already be apparent at birth and not only during the development of reading skills (Goswami, 2015a). Since both fundamental arguments draw back on ample supporting evidence, reconciliation may only be achievable by longitudinal studies, starting in infancy, that closely monitor the development of cognitive skills alongside one's reading experience. Furthermore, such longitudinal investigations would benefit from strict inclusion criteria and extensive cognitive characterisation of the recruited sample to increase the likelihood of establishing causal links for the spectrum disorder dyslexia. In this respect, preliterate infants and illiterate adults constitute two additional groups who can offer complementary insights when compared to individuals suffering from developmental dyslexia (Goswami, 2015a). Based on this ongoing debate, one part of this thesis attempts to probe a non-linguistic perceptual decision making deficit by using images of faces and cars alongside motor responses to avoid tapping into phonological components (Chapter 4). However, it may not be able to provide conclusive causal evidence for either theory due to the nature of studying an adult population with years of reading experience.

1.5 Aims of the current thesis

The presented thesis aims to establish an understanding of the temporal neural and visual components characterising linguistic and non-linguistic perceptual decision making in adult dyslexics. To this end, we exploited the high temporal resolution of the electroencephalography (EEG) and high-frequency eye-tracking for investigating the impact of different fonts, font styles, and audio-visual non-linguistic perceptual evidence integration in dyslexia in three consecutive experiments. As highlighted in this introductory chapter, there is a large body of literature that has demonstrated numerous deficits associated with dyslexics' linguistic and non-linguistic perceptual decision making. However, it remains unknown (1) whether certain font types and styles pose problems for the dyslexic brain, (2) if we can alleviate such problems by choosing a 'dyslexia optimised' font, and (3) if dyslexics' deficits are specific to, or independent of, visual linguistic tasks.

Our first study addressed this gap by investigating the temporal components of a font style commonly used to emphasise important content—Arial italic—in the context of a sentence comprehension lexical decision task (Chapter 2). Further, in dyslexia, a multitude of visual symptoms and aberrant eye movement patterns related to written text perception have been reported. Motivated by this literature, our second study explored the possibility of alleviating adult dyslexics' struggles with visual text perception and reading comprehension using the specific dyslexia font OpenDyslexic. We investigated the physiological and cognitive mechanisms (i.e., eye movements and cognitive processing speed) underlying changes in reading performance on standardised paragraphs presented in this dyslexia font (Chapter 3). Finally, based on recent evidence of dyslexics' deficits on purely sensory non-linguistic tasks, our third study intended to shed more light on whether dyslexics exhibit a fundamental deficit in exploiting additional auditory perceptual evidence. By capitalising on trial-by-trial variability in the EEG, we provide mechanistic insights into dyslexics' audio-visual perceptual decision making in the absence of any linguistic (i.e., phonological) requirements using 'real-world' stimuli, such as faces, cars, and speech (Chapter 4).

Chapter 2. Neural dynamics of the impact of font style on lexical decision making in adult dyslexia

2.1 Summary

Good reading comprehension is indispensable in many situations including contract-based transactions that have become so prevalent in our everyday lives. People with dyslexia often exhibit impairments in this important cognitive process. Although the effects of italics—a commonly used style for highlighting important content in a range of documents—and font in general, have been explored with behavioural measures, their impact on human brain dynamics remains poorly understood. Here, we used electroencephalography to investigate the specific effects of italics in a sentence reading lexical decision task in adult dyslexics and an age-matched non-dyslexia group. Overall, the performance of dyslexics was worse. Cluster-based event-related potential analysis revealed that brain responses within the first 300 ms following the decision stimulus differed in amplitude and spatial distribution between dyslexics and non-dyslexics when processing italicised text. An initial ERP component over occipitotemporal electrode sites started to differ between the groups as early as 167 ms following the onset of short italicised decision words. A subsequent ERP component over centrofrontal electrodes showed differences lasting until about 300 ms post-stimulus onset. Inter-individual amplitude differences in this centrofrontal neural signal were predictive of behavioural performance across participants, further highlighting the role of fast post-sensory linguistic processes in lexical decision making. Crucially, our findings emphasise the importance of choosing font style carefully to optimise word processing and reading comprehension by everyone.

2.2 Introduction

High levels of literacy are essential in many social and economic exchanges. This is particularly the case for exchanges involving legal contracts, which comprise almost exclusively large amounts of text. When dealing with these documents, impaired orthographic and semantic processing during reading can have detrimental consequences. One group that often falls short of developing efficient reading processes includes people diagnosed with dyslexia, a heterogeneous learning disability characterised by, inter alia, deficits in the acquisition of efficient reading (Lyon et al., 2003).

These general behavioural deficits increase as readability decreases with certain types of fonts—also known as typefaces (Rello & Baeza-Yates, 2013, 2016). Italic fonts, in particular, play a crucial role in contracts, where they are commonly used to emphasise important content (Adams, 2013) as it is believed they help facilitate reading comprehension and retentiveness. Yet dyslexics exhibit a strong aversion and compromised reading performance with italic fonts (Rello & Baeza-Yates, 2013, 2016) compared to non-dyslexics. These deficits are exacerbated when dyslexics are required to read under time pressure—as is often the case with many legal documents—since they have difficulties with fast visual information processing (Warnke, 1999) and reading speed (Lefly & Pennington, 1991). As such, the use of italicised font style is particularly discouraged (British Dyslexia Association, 2018).

Previous human EEG studies suggest that the efficient visual processing of words is a fast and incremental neural process (Rayner & Clifton, 2009), with important orthographic and (sub)lexical steps being performed within 250 ms after encountering a word (Dien, 2009). Correspondingly, differences between meaningless false font strings and actual words (Proverbio, Vecchi, & Zani, 2004) as well as differences associated with changes in font type (Chauncey et al., 2008) have been reported as early as 150 ms post-stimulus in non-dyslexics.

Dyslexics' difficulties with fast orthographic word processing have also been linked to differences in early temporal components such as the P150/P1 (Araújo et al., 2012; Taroyan & Nicolson, 2009), the word N170/N1 in children (Hasko et al., 2013; Maurer et al., 2007, 2011) and adults (Brem et al., 2006; Helenius et al., 1999; Helenius et al., 1998; Maurer et al., 2008; Salmelin, Kiesilä, Uutela, Service, & Salonen, 1996; Schlaggar & McCandliss, 2007). More specifically, the word N170/N1 component has been associated with the so-called visual word form area (e.g., Brem et al., 2006), located in the left posterior regions of the fine-grained reading network (Price & Devlin, 2011; Price & Mechelli, 2005; Shaywitz et al., 2003), and is believed to play an important role in the fast visual processing of word shapes (McCandliss et al., 2003; Schlaggar & McCandliss, 2007).

While these findings demonstrate the presence of early neural correlates of visual word processing, the temporal dynamics underlying changes in font style in complex reading tasks along with their effects on lexical decision making between dyslexics and non-dyslexics remain poorly understood. Here, we collected EEG data during a sentence reading lexical decision task—presented in the context of legal language—to investigate differences in the brain dynamics of adults with and without dyslexia during processing of italic font and to demonstrate how these lead to changes in behaviour.

2.3 Materials and methods

2.3.1 Participants

Fifty-one (28 dyslexics, 23 controls) male, right-handed, native English-speaking adults participated in this study ($Mean\ age_{dyslexics}$ = 22.68, $SD_{dyslexics}$ = 4.10 and $Mean\ age_{controls}$ = 24.22, $SD_{controls}$ = 5.84). Twenty-eight of those were diagnosed with dyslexia as identified by providing proof of an official diagnosis by a qualified specialist. The age they were given their diagnosis ranged from 5 to 30 years. All subjects had self-reported normal or corrected-to-normal vision and reported no history of neurological disorders. Participants were current or former university students. Written informed consent was obtained from all participants in accordance with the guidelines of the Centre for Cognitive Neuroimaging at the University of Glasgow. All participants were paid £12 for their participation. This study was approved by the ethics committee of the College of Science and Engineering at the University of Glasgow (ethics application CSE300150102).

Only right-handed adult participants were recruited due to differences in the prevalence of left-hemisphere language dominance based on handedness (Pujol, Deus, Losilla, & Capdevila, 1999). This was of particular importance since recent findings show differences in functional brain organisation and lateralisation in adult dyslexics (Finn et al., 2014). Additionally, we included only male participants due to the prevalence of dyslexia in men (gender ratio of 4:1) (Shaywitz et al., 1990). From the original group, four participants had to be excluded from the analysis. One control participant was excluded due to an excessive number of no-choice trials (i.e., 50 trials). The other three participants, two controls and one dyslexic, were excluded due to excessive noise in the recorded EEG data.

We administered a questionnaire to all participants with dyslexia upon finishing the task, which revealed that the majority of the dyslexics (78%) did not consciously perceive the difference in font style (i.e., Arial regular versus italic) during the experiment at all, or only did so towards the very end of the experiment. In contrast, all but one of the control participants indicated that they had recognised the difference in font style. This information was used for defining subgroups during subsequent analyses of the behavioural and neural data. This subdivision resulted in three groups with 21 dyslexic non-recogniser (DYS NO-R.), 6 dyslexic recogniser (DYS R.) and 20 control (CON) participants. Importantly, we used the comparison of the dyslexic non-recogniser to the control group as our main group contrast. Due to its small sample size, we treated the dyslexic recogniser group separately mainly for reference purposes only and to keep the main dyslexic non-recogniser group as homogenous as possible.

2.3.2 Stimuli and experimental procedure

Our task combined the comprehension of meaningful sentences as in Connolly, Phillips, and Forbes (1995), with a final decision on one congruent or incongruent real word (i.e., the ‘decision word’), made after the sentence itself. Entire sentences taken from various real-life legal contracts with differing content were presented using the Rapid Serial Visual Presentation (RSVP) technique (e.g., Rayner & Clifton, 2009). Participants were shown each sentence, centrally, word-by-word at a speed of 200 ms per word (Figure 2.1a). This speed corresponds to the average reading speed of a skilled reader reading between 250 and 350 words per minute, and approximates the average fixation duration when reading text (Rayner & Clifton, 2009; Sereno & Rayner, 2003). Overall, participants were presented with 20 practice and 320 experimental sentences of 20 words and 1 decision word each. Note that only experimental sentence trials were analysed. Although the RSVP technique does not allow for a preview benefit, it was used in order to reduce the likelihood of introducing confounding eye movement artefacts into the EEG data, which are typically observed during regular sentence reading (Eden et al., 1994; Prado et al., 2007).

Following the presentation of each sentence and after a short, jittered delay period (between 1 and 3 seconds), a decision word was presented for 1.5 seconds. Participants were instructed to indicate whether the decision word was included or not in the preceding sentence by pressing one of two keys with their index or middle finger of their right hand, respectively. The decision words were counterbalanced for high and low word-frequency between font styles (see Table 2.1 for examples of word-frequency) as assessed by the British National Corpus (BNC) frequency per million words (BNC Consortium, 2007). A written word-frequency of <40 per million was taken as the cut-off value for low-frequency words. In addition, their character length, ranging from 2 to 13 letters, was balanced between conditions in order to exclude confounding effects of word length (see Table 2.1 for examples of word length; Hauk, Patterson, et al., 2006; Paizi et al., 2013). Only words appearing between position 5 and 15, within their respective 20-word sentence, qualified as decision words. The delay time between encountering the decision word within the sentence—if included—and its appearance as the decision word was kept constant at a rate of 4 seconds. The decision word was either included in the preceding sentence or presented in a different sentence throughout the experiment. However, we ensured that decision words not included in their preceding sentence were matched with the sentence on a contextual level as well as possible (see Table 2.1 for examples of congruency). A trial was counted as missed and excluded from the analysis if no response was given within the available 1.5 second decision period. Across all participants, this resulted in 2% of total trials being excluded.

All sentences and their subsequent decision words were shown in black writing in one of two distinct font styles—Arial regular or Arial italic—on a light grey background (RGB value: [128, 128, 128]). This change in Arial font style served as a perceptual manipulation. We chose Arial font, as it is a sans-serif font that is frequently used in contracts. In addition, Arial regular font has been used in previous behavioural and eye-tracking experiments and appears to be easily legible for dyslexics (Rello & Baeza-Yates, 2013, 2016). Thus, the task should be less challenging for dyslexic participants, and emphasise the italic font style manipulation without adding serifs as a confounding factor.

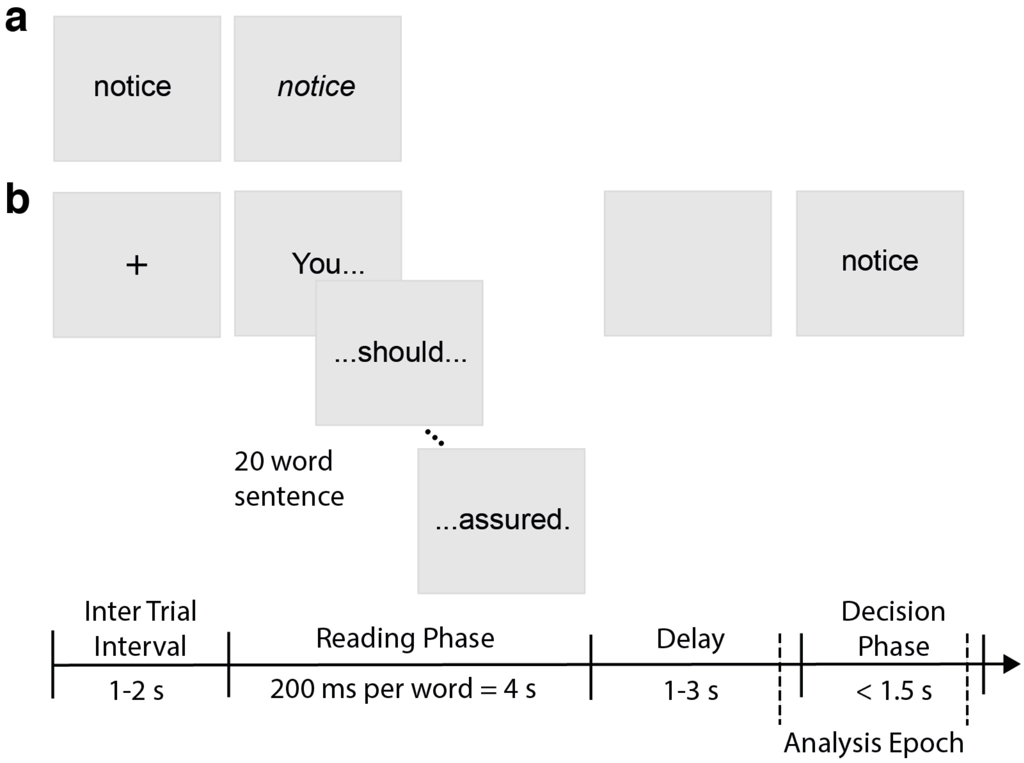


Figure 2.1. Experimental design and example of stimuli. a) Left: example of a word in Arial regular font; right: example of the same word in Arial italic font. All words were presented as shown in black Arial font on a light grey background. **b)** Schematic representation of the experimental task showing the order of presented events for one trial. Participants were presented with a sentence of 20 words using the RSVP technique (200 ms per word) during the 'reading phase' and had to decide whether the decision word in the 'decision phase' was presented in its preceding sentence. A blank grey screen of variable delay (1-3 s) was shown in-between the offset of the sentence and the onset of the decision word. Participants had up to 1.5 s to indicate their choice during the 'decision phase' starting with the onset of the decision word. Dashed vertical lines indicate the time period of the epoch included in all subsequent EEG analyses. Each trial was followed by an 'inter trial interval' that varied randomly between 1 and 2 s.

The experiment was designed and run using PsychoPy (version 1.83; Peirce, 2008). The 320 experimental trials were split into four blocks that each contained 80 sentences each. Both conditions—Arial regular and Arial italic—were counter-balanced and sentences randomised within each block. Upon finishing the task, dyslexic participants were asked to complete a questionnaire with items referring to their dyslexia including the age of diagnosis, past and current symptoms as well as task inherent properties such as the conscious recognition of italics during the experiment.

Condition	Sentence	Decision Word
Short word of high-frequency (congruent)	For the Annual Medical Plan, the first travel date must fall within three months of purchase of the corresponding insurance.	fall
Short word of low-frequency (incongruent)	*However, C2Phone will not accept any liability for items damaged in transit, therefore the usage of recorded postage is recommended.*	*repair*
Long word of high-frequency (congruent)	*On receiving an application, the committee will consider if it is appropriate to determine a market rent as a reference.*	*committee*
Long word of low-frequency (incongruent)	The customer must take adequate steps to look after the leased equipment appropriately and maintain it in a satisfactory condition.	precautions

Table 2.1. Example of relevant stimuli conditions. Sentences were presented word-by-word at a rate of 200 ms per word. The decision word was shown for a maximum of 1.5 seconds.

2.3.3 Behavioural analysis

For our behavioural analysis, we split decision words into two bins based on their word length. Accordingly, we henceforth refer to ‘short words’ (≤ 6 letters) and ‘long words’ (> 6 letters). This distinction is important because of reports showing evidence for the perception and processing of short words of up to six letters as one unit (McCandliss et al., 2003). Since we abstract letter identities to identify words (Sanocki & Dyson, 2012), it is likely that distinct font styles affect a word’s orthographic percept differently dependent on its length by altering its shape or word form (i.e., its contour line). Changing the font style from regular to italic alters a word’s perceived shape only slightly by manipulating its angle whilst keeping most other font properties constant. This change seems to be particularly relevant for short words that can be quickly decoded as one unit with a single fixation whilst having relatively similar phonologic properties. Longer words often stand out perceptually merely due to their length whereby the effect of a small change in font style, as used in this study, might become secondary or even get abolished.

We quantified behavioural effects using separate generalised linear mixed effects models (GLMMs) for decision accuracy and response time using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015) in *RStudio* (RStudioTeam, 2016), and specifying a *binomial logit* and a *gamma* model, respectively. GLMMs are preferable over conventional ANOVA analysis due to their principled methods of modelling heteroskedasticity and non-spherical error variance. Their ability to account for inter-participant and inter-item variation by incorporating random effects in a model's design gives them more power. These models also allow for the mixing of continuous and categorical variables as well as the use of a variety of link functions for accommodating differently distributed responses (Baayen, Davidson, & Bates, 2008). Despite their advantages, we have to note that GLMMs are context dependent whereby the results of one predictor vary depending on the other predictors included. To avoid context dependency biasing our results, our two models used the maximal random effects structure justified by the design including random correlations (Barr, Levy, Scheepers, & Tily, 2013). Furthermore, both models included all main effects and interactions of the three predictors: *group* (control, dyslexic recogniser and dyslexic non-recogniser), *font style* (Arial regular and Arial italic) and *word length* (short and long) as well as by-subject and by-item random slopes and random intercepts for all relevant main effects and interaction terms. The three predictors were entered in mean-centred form (deviation coding). Given that the variable *group* had three levels, two different coding variables were required, treating the control group as a baseline group. Post-hoc likelihood-ratio X^2 model comparisons were employed to evaluate the significance of the main effects revealed by the GLMM analysing their predictive power on decision accuracy. Post-hoc model comparisons are necessary because GLMM's p-values are an approximation and significance in a frequentist sense can only be reliably established comparing models with and without the predictor in question directly.

2.3.4 EEG data acquisition

Continuous EEG data was acquired in an electrostatically shielded and sound-attenuated room from a 64-channel EEG amplifier system (BrainAmps MR-Plus, Brain Products, Germany), with Ag/AgCl scalp electrodes placed according to the international 10-20 system on an EasyCap (Brain Products GmbH, Germany). In addition, all channels were referenced to the left mastoid during recordings, and a chin electrode acted as ground. Input Impedance of all channels was adjusted to <50kΩ. Data were sampled at a rate of 1000 Hz and underwent online (hardware) filtering with a 0.0016–250 Hz analogue band-pass filter. Trial specific information including experimental event codes and button responses were recorded simultaneously with the EEG data using Brain Vision Recorder (BVR; version 1.10, Brain Products, Germany). These data were collected and stored for offline analysis.

2.3.5 EEG data pre-processing

Offline data pre-processing was performed with MATLAB (version 2015a, The MathWorks, 2015, Natick, Massachusetts) by applying a software-based 0.5–40 Hz band-pass filter to remove slow DC drifts and higher frequencies (> 40 Hz) as we were mainly interested in slower evoked responses that fall within the selected frequency range. These filters were applied non-causally (using MATLAB '*filtfilt*') to avoid phase-related distortions. Additionally, the EEG data were re-referenced to the average voltage across all channels.

Subsequently, we removed eye movement artefacts such as blinks and saccades using data from an eye movement calibration task completed by participants before the main task. During this task participants were instructed to blink repeatedly upon the appearance of a black fixation cross on light grey background in the centre of the screen before making several lateral and horizontal saccades according to the location of the fixation cross on the screen. Using principal component analysis, we identified linear EEG sensor weights associated with eye movement artefacts, which were then projected onto the broadband data from the main task and subtracted out (Parra, Spence, Gerson, & Sajda, 2005). Trials with excessive noise in the EEG signal were rejected manually by visual inspection (< 3% of all analysed trials across participants).

2.3.6 Main EEG data analysis

To identify temporal activity related to orthographic word processing in the EEG data, we used a sliding window approach on our stimulus-locked ERP data. Namely, for every participant, data were averaged within time windows of 50 ms length, centred on specific time points across the epoch, starting at 100 ms prior to the presentation of the decision word and ending at 900 ms after its onset. These windows were shifted in increments of 3 ms. Our statistical analysis focused on stimulus-locked data lasting up to 600 ms post-stimulus onset, in order to avoid any period that might include confounding motor preparatory signals ($M_{RT\ all\ trials}$ = 892 ms, $SEM_{RT\ all\ trials}$ = 17 ms).

We tested for neural differences between the dyslexic non-recogniser and control groups employing a univariate non-parametric cluster-based permutation analysis as implemented in the LIMO-EEG-Toolbox (Pernet, Chauveau, Gaspar, & Rousselet, 2011) for MATLAB. First, we averaged across trials separately for each within-subject condition (Arial regular and Arial italic) and each subject, to identify relevant EEG components independent of word length. Second, we proceeded to compare ERP amplitudes between the two groups of interest (dyslexic non-recogniser and control) to identify contiguous spatial and temporal clusters exhibiting differences in ERP amplitude using a non-parametric permutation analysis, while at the same time correcting for multiple comparisons (Maris & Oostenveld, 2007; Pernet, Latinus, Nichols, & Rousselet, 2015).

Specifically, every sample from an electrode-time pair was compared between the two groups; separately for each font condition. Our permutation procedure involved randomly shuffling participants without replacement in order to generate two new random groups by reassigning each subject to one of the two testing groups. Sampling without replacement was chosen due to reports of this approach being most reliable for a limited number of samples (Pernet et al., 2015). We repeated this procedure 1,000 times and performed between-group two-sample t-tests for every sample from each electrode-time pair. Samples exceeding a threshold of $\alpha < .05$ were grouped in spatiotemporal clusters according to a neighbourhood matrix. This matrix specified spatial adjacency between electrodes using 3.7 cm as the maximum neighbourhood distance. We set the minimum number of significant channels in a cluster to two in order to correct for multiple comparisons without losing interesting information, for example at the beginning or end of a temporal cluster, due to a conservative approach (Pernet et al., 2011). Next, a maximum cluster-mass permutation distribution was obtained by recording the sum of t-values of the maximum significant spatiotemporal cluster for each of the 1,000 random permutation iterations. This resulted in a randomised cluster-level summary statistic under the null hypothesis that was used to determine an appropriate threshold ($p < .05$) for assessing the statistical significance of the differences in the original data. This procedure is comparable to spatiotemporal cluster-based non-parametric permutation test reported in Maris & Oostenveld (2007).

For conciseness the visual presentation of our results focuses on comparisons that yielded at least one significant cluster of electrodes showing a difference between groups. In the following results section, we chose to focus on trials presented in italic font for two reasons. First, reports of worse performance and strong behavioural aversion against italicised text by individuals with dyslexia (Rello & Baeza-Yates, 2013, 2016) suggested a specific focus on this font style in order to obtain unconfounded results that can shed light on the neural dynamics potentially underlying group-differences for this particular font style. Second, we did not find a significant difference for any cluster of electrodes when contrasting groups on trials presented in Arial regular font.

This analysis was complemented by unbiased effect size calculations (Hedges' g for between-subject designs as described in Lakens, 2013), which compared differences in mean amplitude for significant spatiotemporal clusters between dyslexic non-recognisers and controls (henceforth, *g*). The interpretation of Hedges' g effect sizes is comparable to the benchmarks reported for Cohen's *d* (0.2 = small effect, 0.5 = medium effect, $\geq$ 0.8 = large effect; Cohen, 1988). In this context, an effect size of 0.5 can be interpreted as a difference of two means by half a standard deviation (Lakens, 2013). Effect size calculations for one-sample tests were performed using the '*mes*' function of the Measures of Effect Size Toolbox (Hentschke & Stüttgen, 2011) in MATLAB.

We repeated this procedure for trials displaying only short decision words—Arial regular short and Arial italic short—to identify specific perceptual neural components that are simply a result of perceptual effects of italic font during lexical decision making. Due to physiological acuity limitations, only high spatial frequency information of short words can be extracted in its entirety with a single fixation (Rayner, 1998). Letters of short words extracted during a fixation are processed in parallel and as such their visual word form gains importance as they are believed to be perceived as one unit (McCandliss et al., 2003). Short words are also psycholinguistically more consistent and thereby can make our perceptual effect of font more trackable. In contrast, long words are often perceptually more salient simply due to their length and rarer occurrence in written text. In their case, gaze duration increases almost linearly with the number of letters (Rayner, Sereno, & Raney, 1996). For these reasons, and to avoid diluting our perceptual effect of font by these factors, we also tested short words separately.

Furthermore, since trial-to-trial changes are of particular importance when attempting to link neural activity to visual stimulus parameters (Rousselet et al., 2008) and decision making (e.g., Philiastides & Sajda, 2007), we complemented our ERP analysis with a robust multilinear single-trial regression analysis (using MATLAB '*robustfit*'). In perceptual decision making behavioural and neural responses vary from trial-to-trial, even given nominally identical stimuli within the same stimulus category (Sajda, Philiastides, & Parra, 2009). In an attempt to increase the signal-to-noise ratio by cancelling out 'random' noise, trial-to-trial variability is normally masked (Philiastides & Sajda, 2006). However, this trial-wise variation caries important signals (Stokes & Spaak, 2016), which is underlined by single-trial approaches increased sensitive to uncover the effects of certain subtle stimulus properties (Rousselet et al., 2008). Hence, by uncovering the systematic covariation between neural and behavioural signals, single-trial analyses are complementary to trial averaged data as employed by our cluster-based ERP analysis, and provide the possibility to establish a more mechanistic link between neural and behavioural responses without discarding valuable information (Sajda et al., 2009). These more detailed insights into trial-by-trial changes of activity are an important aspect, particularly when employing a variety of stimuli. Our single-trial regression approach examined whether activity in neural components of interest (identified using our cluster-based permutation analysis) observed over distinct electrode and temporal clusters, covaried together across individual trials. We computed (β) parameter estimates by regressing z-scored single-trial peak ERP amplitudes of separate spatiotemporal clusters against each other. These single-trial ERP peak amplitudes were computed by averaging ERPs across all electrodes within the relevant electrode clusters before selecting the peak amplitude (using MATLAB '*max*' or '*min*') within a 100 ms window around a component's group grand average peak time. To quantify a potential functional link between our distinct spatiotemporal neural components, we compared the resulting ß parameter estimates (across subjects) against the null hypothesis (that is, ß parameter estimates come from a distribution with mean equal to 0) using a two-sided paired t-test.

Lastly, we employed robust bend correlations (Pernet, Wilcox, & Rousselet, 2013) to test the extent to which activity in our neural components of interest (using peak amplitudes computed from each participant's ERP grand average) could predict behavioural mean accuracy on italic short word trials across all participants. We also used robust bend correlations for correlating individual mean response time with each component's peak time (using the peak timing of the previously identified peaks) separately across participants. This part of our analysis intended to rule out differences in response time as the main reason for the observed neural differences. These correlations were complemented by Bayes factors using the bf.corr function as part of the bayesFactor toolbox (Krekelberg, 2018).

2.4 Results

2.4.1 Behavioural results

Overall, mean accuracy was at least 67%, independent of group or condition illustrating all groups were able to perform the task well above chance (Figure 2.2a). First, we ran a mixed effects model for accuracy with predictors: *group* (control, dyslexic recogniser and dyslexic non-recogniser), *font style* (Arial regular and Arial italic) and *word length* (short and long) and their interactions.

We found main effects of *group* ($Z = -3.43$, $p <.001$; Table 2.2) and *font style* ($Z = -2.34$, $p =.0195$; Table 2.2), without any significant effects of word length or interactions (for details, see Table 2.2; Figure 2.2a). The group effect was specifically found for the contrast between the control and dyslexic non-recogniser group, with dyslexic non-recognisers showing significantly worse performance [$M_{\text{CON}} = 75.11$, $SEM_{\text{CON}} = 0.55$; $M_{\text{NO-R}} = 68.45$, $SEM_{\text{NO-R}} = 0.59$] across all conditions (Table 2.2; Figure 2.2a and 2.2c). These two main effects were confirmed via likelihood-ratio X^2 model comparisons, which separately contrasted the goodness of fit of a full model with all predictors against our alternative model without one of the two main effects. Removing the main effect of the dyslexic non-recogniser group or font style from the full model each decreased the goodness of fit significantly (X^2 (1) = 10.5, p =.001 and X^2 (1) = 5.38, p =.02, respectively). Since GLMMs are context dependent, we confirmed the behavioural results above by means of a second model predicting accuracy, which only included the two main groups analysed in our EEG analyses (i.e., dyslexic non-recogniser and control) as two separate levels of the predictor group. This model yielded main effects of font style and group (X^2 (1) = 5.62, p =.018 and X^2 (1) = 9.39, p =.002, respectively); similar to the model with all three groups. Given comparable explained variance by all fixed and random effects in both models ($R^2_{allGroups}$ =.036; $R^2_{mainGroups}$ =.041), we decided to retain the larger model using the maximal random effects structure for completeness.

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*Z*	*p*
Font style	**-0.0941**	**-0.1731**	**-0.0152**	**0.0456**	**-2.336**	**0.020**
Word length	-0.0153	-0.1011	0.0706	0.0403	-0.349	0.727
CON-DYS NO-R.	**-0.3331**	**-0.5236**	**-0.1428**	**0.0972**	**-3.429**	**0.001**
CON-DYS R.	-0.1881	-0.4769	0.1002	0.1471	-1.279	0.201
Font style * word length	-0.0171	-0.1802	0.1459	0.0832	-0.206	0.837
Font style * CON-DYS NO-R.	-0.0561	-0.2199	0.1075	0.0835	-0.673	0.501
Font style * CON-DYS R.	0.0324	-0.2109	0.2756	0.1241	0.261	0.794
Word length * CON-DYS NO-R.	-0.0649	-0.2421	0.1124	0.0905	-0.717	0.473
Word length * CON-DYS R.	0.1908	-0.0740	0.4554	0.1351	1.412	0.158

Table 2.2. Generalised linear mixed effects model fixed effect parameter estimates for accuracy. Effects with significant predictive power after post-hoc likelihood-ratio X2 model comparisons in bold. Group labelling as follows: CON = controls; DYS NO-R. = dyslexic non-recognisers; DYS R. = dyslexic recognisers.

Next, we ran a mixed effects model for response time with the same three predictors and their interactions as the previous model but found no significant main effects or interactions (for details, see Table 2.3; Figure 2.2b). Note, however, that on average there was a systematic trend for the dyslexic non-recognisers to indicate their decisions with longer response times (t = -1.76, p =.079; Table 2.3; Figure 2.2b and 2.2d). Similar to our analysis of decision accuracy, we confirmed the absence of a significant effect of any predictor, but particularly of the predictor group (X^2 (1) = 2.61, p =.106), on response time employing a GLMM that only comprised the two main groups as separate levels of the predictor group.

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*t*	*p*
Font style	0.0045	-0.0085	0.0175	0.0066	0.68	0.496
Word length	0.0061	-0.0071	0.0192	0.0067	0.90	0.366
CON-DYS NO-R.	-0.0940	-0.1987	0.0108	0.0535	-1.76	0.079
CON-DYS R.	-0.0480	-0.2070	0.1109	0.0811	-0.59	0.554
Font style * word length	-0.0102	-0.0318	0.0114	0.0110	-0.92	0.355
Font style * CON-DYS NO-R.	-0.0052	-0.3132	0.0209	0.0133	-0.39	0.695
Font style * CON-DYS R.	0.0069	-0.3280	0.0466	0.0203	0.34	0.734
Word length * CON-DYS NO-R.	-0.0135	-0.0402	0.0132	0.0136	-0.99	0.322
Word length * CON-DYS R.	-0.0117	-0.0519	0.0285	0.0205	-0.57	0.568

Table 2.3. Generalised linear mixed effects model fixed effect parameter estimates for response time. Group labelling as follows: CON = controls; DYS NO-R. = dyslexic non-recognisers; DYS R. = dyslexic recognisers.

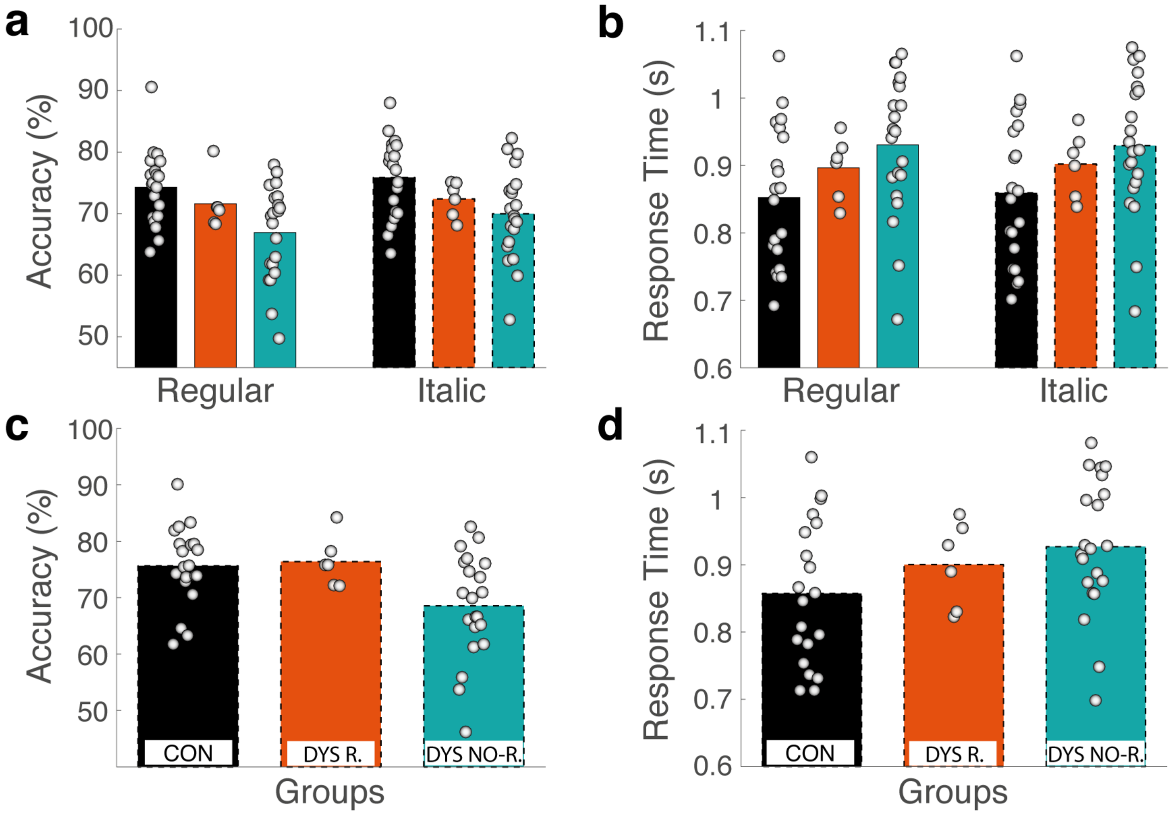


Figure 2.2. Behavioural performance and response time of all participants separated by group. Panels a and b illustrate group means for all trials collapsed across word length, whereas panels c and d present group means only for trials presenting short decision words in italic font. Dots denote each participant's individual mean across trials in the respective condition. Black bars depict

mean values for the control (CON), orange for the dyslexic recogniser (DYS R.), and green for the dyslexic non-recogniser (DYS NO-R.) group. **a)** Mean values for accuracy collapsed across word length. Bars surrounded by a solid outline represent trials in Arial regular font, a dashed outline represents Arial italic trials. **b)** Mean values for response time collapsed across word length for Arial regular and Arial italic trials. Bar outlines and colours as in panel a. **c)** Mean decision accuracy for short italicised decision words (≤ 6 letters). **d)** Mean response times for decisions on short italicised decision words.

2.4.2 EEG results

We performed pairwise comparisons of the control and dyslexic non-recogniser groups of all italic font decision words to identify the general effect of this specific font style irrespective of word length. This analysis revealed significant differences between 215 and 281 ms post-stimulus onset (M_{diff} = 0.9 μV; 95% $\mathrm{CI}_{\mathrm{MeanDiff}}$ [0.49, 1.53]; $g_{italic\ words}$ = 1.01; Figure 2.3a). The resulting ERP component differed significantly over right centrofrontal electrode sites (henceforth, centrofrontal component) as identified by our permutation analysis (Figure 2.3b).

To examine the precise perceptual effects of italic font without confounding effects of word length, we repeated the same between-group contrast but focused only on short italicised decision word trials instead (Figure 2.3d-f). This contrast yielded significant differences in activity within an even wider time window extending from 167 to 299 ms post-stimulus onset (Figure 2.3d). By focusing only on short italicised words, our permutation analysis uncovered an additional cluster of left occipitotemporal electrodes (henceforth, occipitotemporal component) whereby we observed a significant difference in ERP amplitude between dyslexic non-recognisers and controls earlier in time (i.e., 167 to 236 ms), compared to the later centrofrontal component (Figure 2.3d and 2.3e). The difference between groups in this additional occipitotemporal component peaked at 175 ms post-stimulus (M_{diff} = 1.48 μV; 95% $\mathrm{CI}_{\mathrm{MeanDiff}}$ [0.70, 2.33]; $g_{occipitotemporal}$ = 1.09; Figure 2.4a). We note for reference purposes that the profile of this occipitotemporal component (i.e., timing and peak amplitude) was similar between the two dyslexia subgroups (i.e., dyslexic non-recognisers and dyslexic recognisers) within the significant time window revealed by our permutation test (i.e., 167 to 236 ms; Figure 2.4a).

This analysis also captured the right centrofrontal component we identified in the original analysis with all word lengths. Figure 2.3e illustrates that this centrofrontal component started to differ significantly between groups at 209 ms post-stimulus, consistent with the original analysis. It is characterised by a difference in positive ERP peak amplitude between our main groups of interest around 250 ms post-stimulus over a cluster of right and central frontal electrodes (M_{diff} = 0.96 μV; 95% $\mathrm{CI}_{\mathrm{MeanDiff}}$ [0.45, 1.50]; $g_{centrofrontal}$ = 1.11; Figure 2.4b). This component showed similar deflection and group grand average peak timing for all three groups (Figure 2.4b). The two components overlapped between 209 and 236 ms post-stimulus onset but had different spatial topographies (Figure 2.3e).

Figures 2.3c and 2.3f display the full scalp distributions of both ERP components. These differed clearly between the dyslexic non-recogniser and control groups throughout the time window associated with our two components. The control group showed lateralisation of activity depicted by opposite polarity over posterior electrodes early on, between 209 and 221 ms, as opposed to bilaterally distributed activity shown by both dyslexia subgroups on all italic trials (Figure 2.3c). This lateralisation of activity started to emerge even slightly earlier than 209 ms for controls on short italic word trials (Figure 2.3f). On these trials, any lateralisation of activity was absent in both dyslexia groups at all time points of the two components. Overall, the centrofrontal component (227 to 299 ms) in controls exhibited stronger positive activity over central anterior and stronger negative activity over right and left temporal electrodes as illustrated by their scalp maps. In contrast, dyslexic non-recognisers did not exhibit strong positive activation over anterior electrodes.

In contrast to the two components presented above that occurred within the first 300 ms after the onset of italicised decision words, we did not find any significant between-group ERP differences for time windows later than 300 ms post-stimulus or for between-group contrasts of trials presenting Arial regular font.

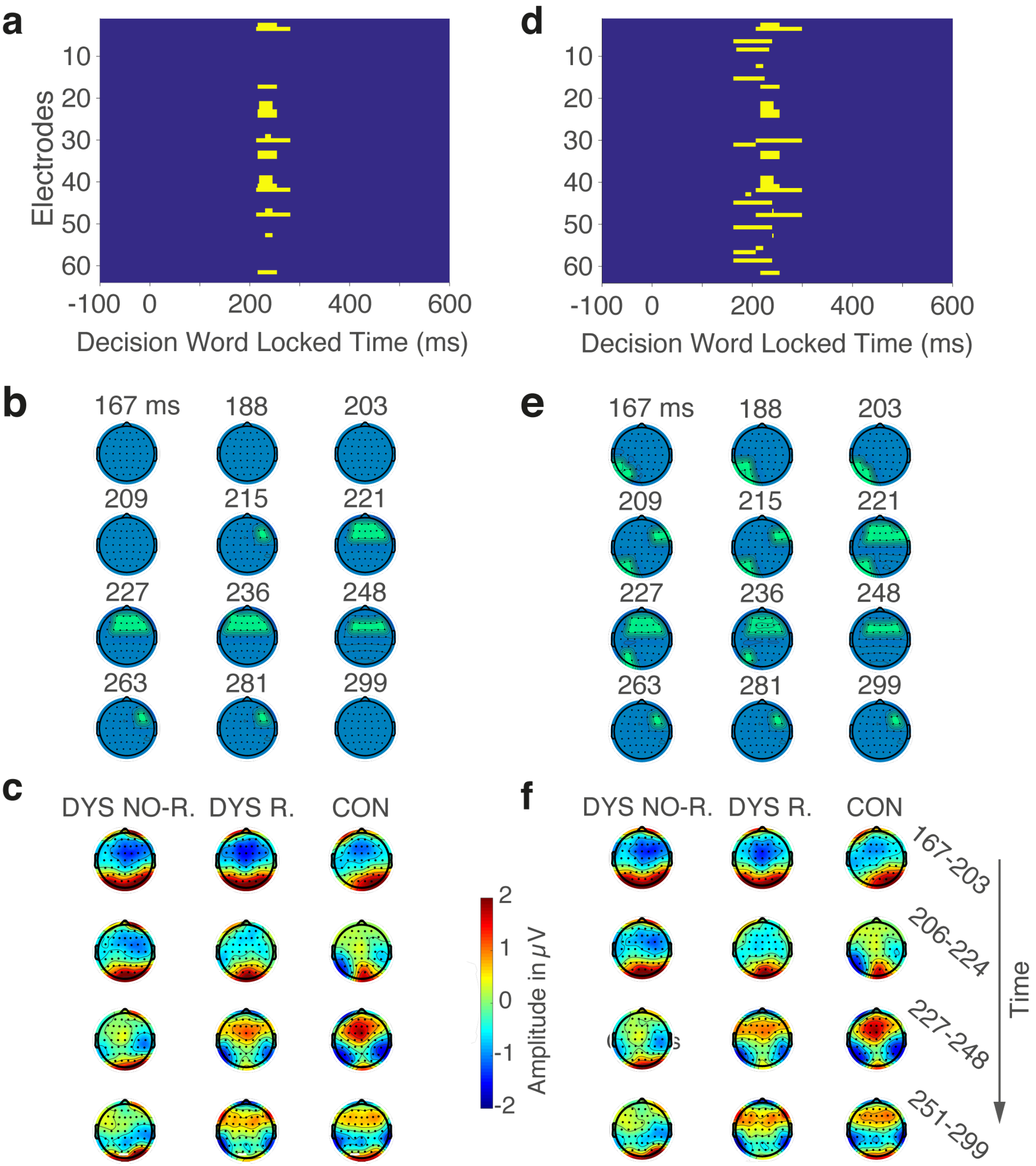


Figure 2.3. Temporal evolution and scalp distributions of ERP components. Panels a-c show ERP components for all italicised decision words independent of word length, whereas panels d-f illustrate the ERP components for trials presenting short decision words (≤ 6 letters) in italic font. Panels a, b, d and e depict significant ERP components for the main between-group contrast comparing the control to the dyslexic non-recogniser group on italic trials. **a)** Significant electrodes over time after cluster-based correction for multiple comparisons. Yellow indicates a significant electrode at a given time point. **b)** Evolution of significant ERP components over time and space at representative time points. Green denotes significant clusters of electrodes. **c)** Scalp distribution of activity averaged separately across participants of each group and time points corresponding to the same row in panel b and as specified in panel f. Groups are denoted as control (CON), dyslexic recogniser (DYS R.), and dyslexic non-recogniser (DYS NO-R.). **d)** Significant electrodes over time for italic short decision word trials after multiple comparisons correction. Yellow indicates a significant electrode at a given time point. **e)** Scalp distribution of significant electrodes at representative time points. Green denotes significant electrode clusters. **f)** Scalp distribution of activity averaged separately across participants of each group and time points corresponding to the same row in panel e. Group specification as in panel c.

2.4.2.1 Single subject peak amplitudes

To avoid masking intra-group variance by comparing ERP group grand averages, we examined the individual subject peak amplitudes of the two previously identified components that fell into their respective time windows for short italic decision words. We found that participants' peak amplitudes pointed consistently in the direction of their group's grand average, independent of the component (Figure 2.4c and 2.4d). Although dyslexic non-recognisers showed slightly larger variability in polarity of their peak amplitudes of the centrofrontal component (i.e., 8/21 dyslexic non-recognisers exhibited negative peak amplitudes), the majority of single subject peak amplitudes pointed in the direction of their group grand averages (Figure 2.4d). The consistency of the single subject peak amplitude polarity underlines that the observed group grand averages did not mask large variability within a group.

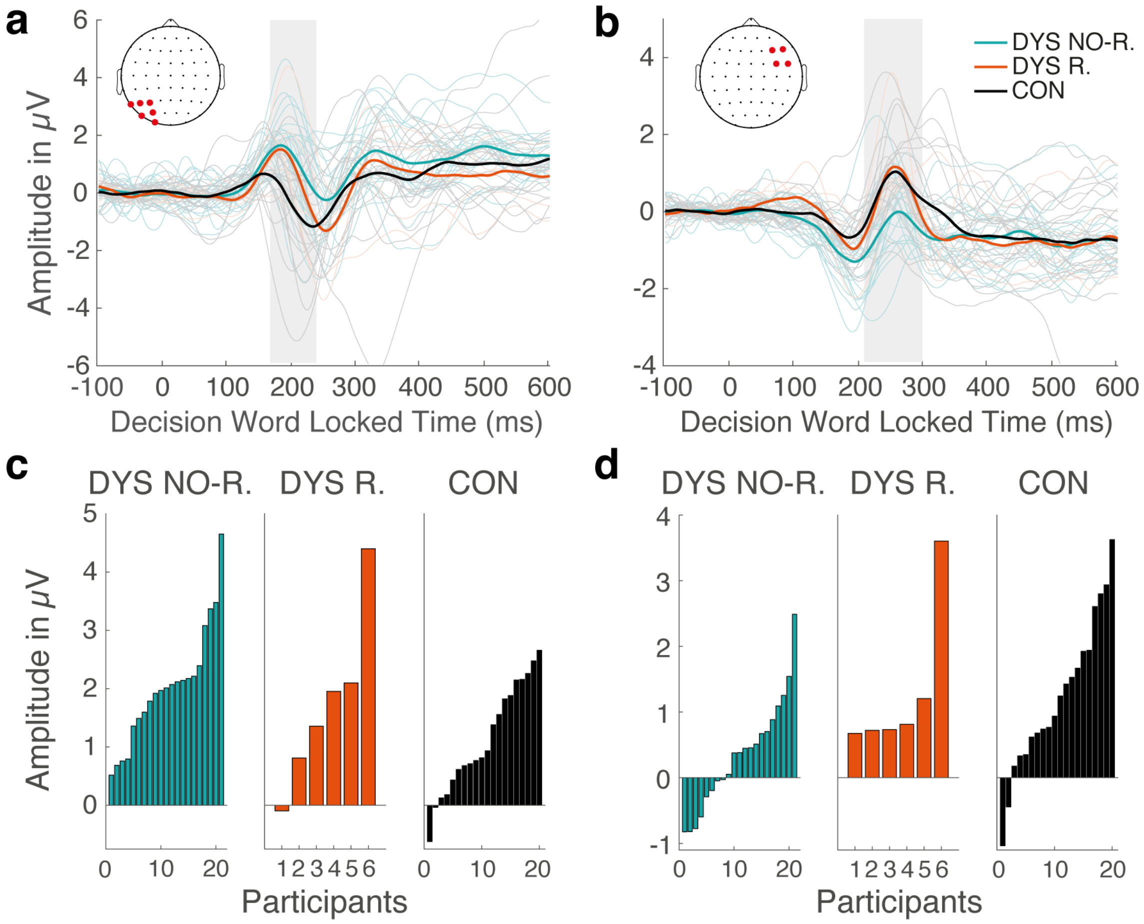


Figure 2.4. ERP group and individual participant grand averages and individual participants' component peak amplitudes. a) Shows ERP group grand averages (thick lines) and individual participant grand averages (thin, faded lines) averaged across electrodes of the significant left occipitotemporal cluster for short decision words in italic font. Averages for this cluster were computed across the following electrodes: P3, P5, P7, PO7, PO5, O1. Locations of these electrodes as shown in red on the corresponding scalp plot. **b)** Illustrates the same ERPs as panel a, but averages were computed across the four electrodes of the right frontal cluster that were consistent

over time. Electrodes of this cluster were: F4, F6, FC4, FC6. Electrode locations of this cluster as shown in red on the corresponding scalp plot. **c-d)** Depict individual participants' peak amplitudes sorted in ascending order by amplitude and separated by group and component (c, occipitotemporal component; d, centrofrontal component). Groups are denoted using the following colours in panel a-d: black for the control (CON), orange for the dyslexic recogniser (DYS R.), and green for the dyslexic non-recogniser (DYS NO-R.) group.

2.4.2.2 Linking activity between posterior and anterior neural components

Since there was partial temporal overlap between our two identified components, we complemented our ERP analysis with a single-trial regression to evaluate a potential link between the sources underlying the relevant occipitotemporal and centrofrontal components (Figure 2.3e). For every participant, we obtained standardised regression coefficients (ßs) from a single-trial regression predicting peak amplitude of the centrofrontal component based on the peak amplitude of the preceding occipitotemporal component (Figure 2.5a). We searched for a systematic correlation between our two component amplitudes by testing whether these ß regression coefficients came from a distribution with mean zero using a two-tailed t-test. This procedure resulted in negative ß coefficients for all participants independent of their group illustrating significant trial-by-trial functional coupling between the two identified neural components ($t_{46} = -23.82$, $p < .0001$; 95% CI [-0.47, -0.39]; $g_{\mathrm{link}} = 3.47$; Figure 2.5b). The negative direction of this relationship represents lower peak amplitude of the occipitotemporal component being coupled with a higher peak amplitude of the centrofrontal component on a single-trial basis. Thus, this link illustrates that the identified components might form a part of an interconnected cascade of neural processes relevant for lexical decisions on short italicised words in particular.

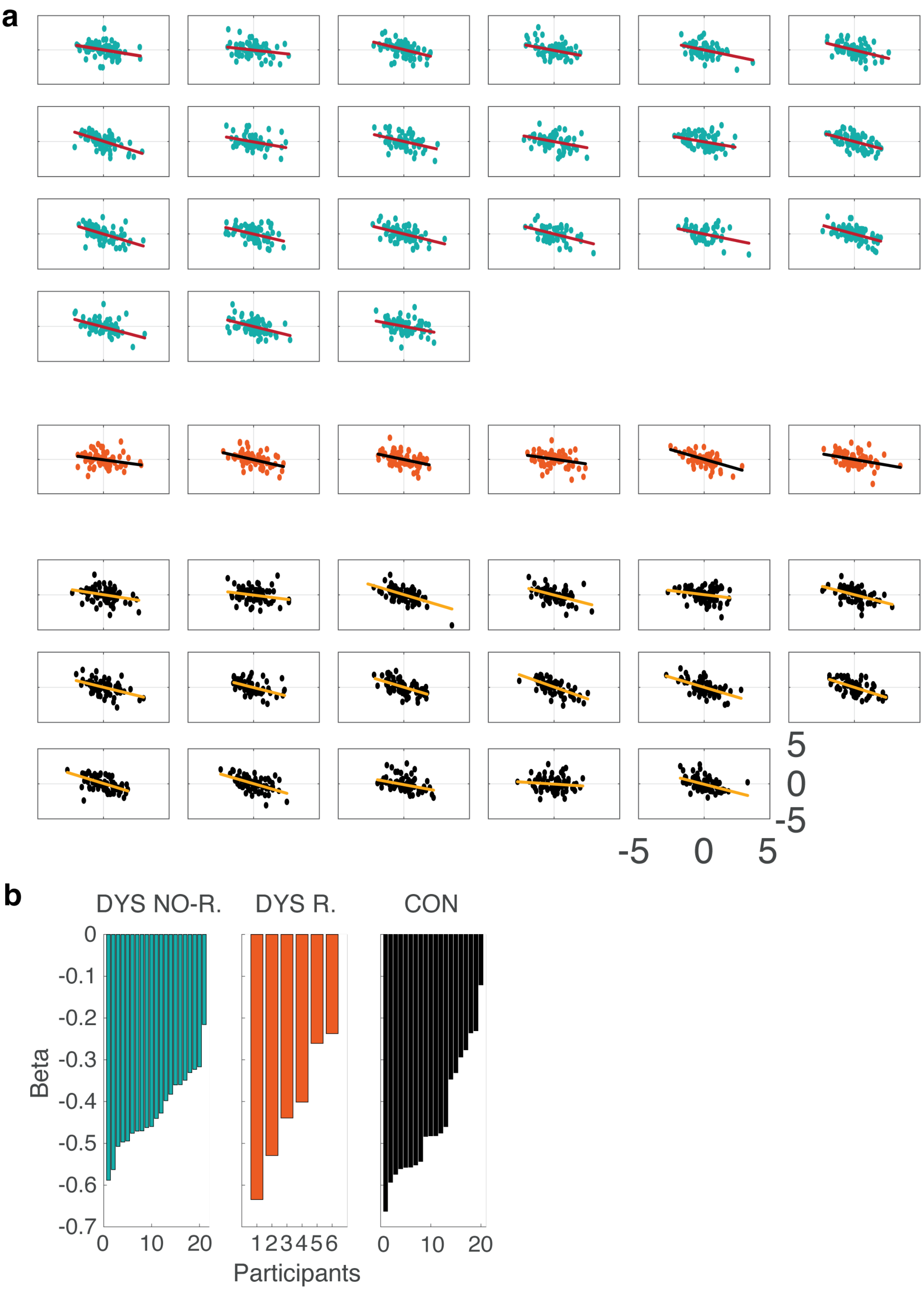


Figure 2.5. Single-trial peak amplitude regression. Results depicting the relationship between the left occipitotemporal and the right centrofrontal component. **a)** Single-trial peak amplitudes for the occipitotemporal and centrofrontal component by participant. One dot per trial. Coloured lines represent least-square lines. Groups are denoted by coloured dots and separated by space (from top: dyslexic non-recognisers in green, dyslexic recognisers in orange, and controls in black). **b)** Individual participants' β coefficients separated by group and sorted by magnitude. Group colours as in panel a.

2.4.2.3 Peak amplitudes and decision accuracy

To test the extent to which the two identified ERP components were further predictive of behavioural performance, we correlated each of the two component peak amplitudes with mean decision accuracy across all participants. We found an interesting dissociation in the way the two components were linked to performance. Specifically, we did not find a significant relationship between the occipitotemporal component's individual grand average peak amplitudes and mean accuracy across participants (r_{45} = -.16; p =.28; BF_{10} =.22; Figure 2.6a). In contrast, subjects who exhibited higher centrofrontal mean peak amplitude also showed better behavioural performance independent of their group (r_{45} =.33; p =.024; BF_{10} =.87; Figure 2.6b). Hence, the centrofrontal component represents one of the earliest processes during lexical decision making relevant for behavioural performance.

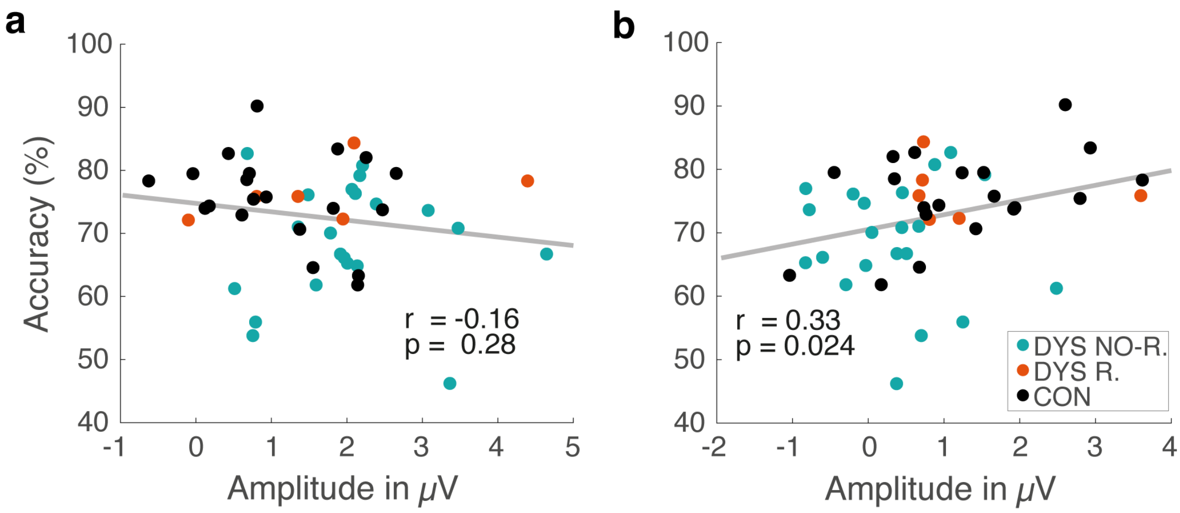


Figure 2.6. Correlation between individual participant mean peak amplitude and decision accuracy across all participants for short italic words separated by component. Colours of dots denote group affiliation. Groups: dyslexic non-recognisers in green, dyslexic recognisers in orange, and controls in black. Statistical results from robust bend correlations using 20% bending in both directions (i.e., X and Y) across all participants are denoted next to the grey least-squares fit line. **a)** Occipitotemporal component peak amplitudes, computed in the window between 151 and 251 ms post-stimulus, correlated with mean decision accuracy. **b)** Centrofontal component peak amplitudes, computed in the window between 200 and 300 ms post-stimulus, correlated with mean decision accuracy.

2.4.2.4 Peak amplitudes and response time

Dyslexics are well-known for responding slower on speeded decision tasks than controls due to processing speed deficits (Breznitz & Misra, 2003; McLean et al., 2011). Therefore, we intended to rule out the possibility that our identified neural components merely represented differences in response times between the two groups. We sorted all subjects by mean response time irrespective of group and plotted their individual ERP grand average activity for each of the two components separately. Both ERP component peaks were clearly observable locked to the stimulus and appearing within a 100 ms interval during and around the respective component's time window, rather than shifting in time in accordance with longer response times (Figure 2.7a and 2.7b). We quantified this observation using two robust correlations that evaluated the relationship between the participants' mean response time and their occipitotemporal and centrofrontal component peak times separately across all subjects. Neither the occipitotemporal component (r_{45} =.13; p =.37; BF_{10} =.14) nor the centrofrontal component (r_{45} =.06; p =.70; BF_{10} =.12) were correlated with response time across participants. Consequently, the observed early neural components could not simply be explained by longer response times of the dyslexic non-recognisers. This account further endorses the proposition that the ERPs of the dyslexic non-recognisers and controls differed mainly in component amplitude.

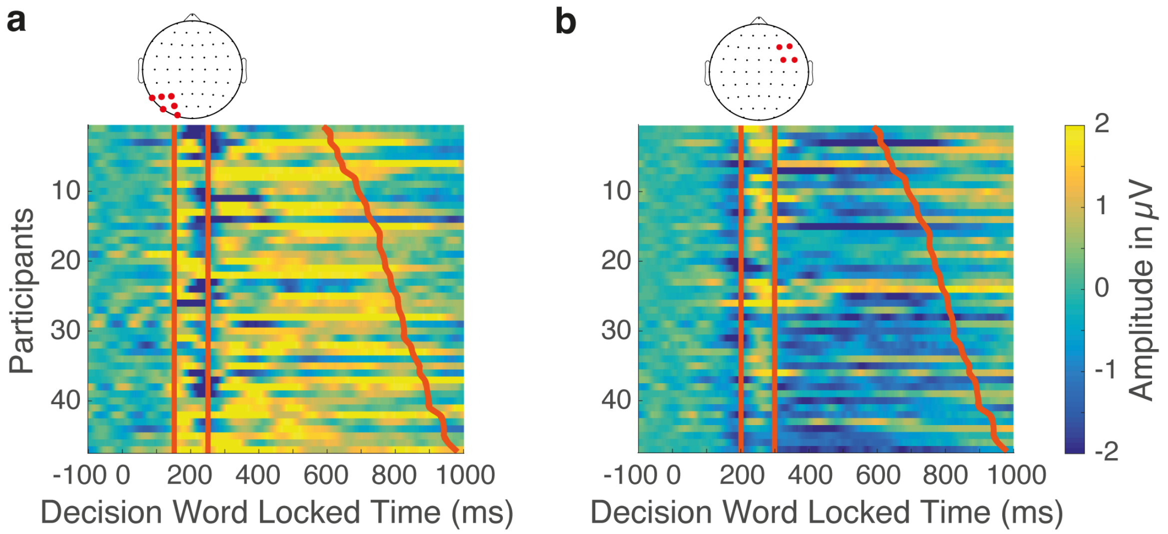


Figure 2.7. Individual participants' mean ERP amplitude in relation to their mean response time on italic short decision word trials. Vertical lines indicate the start and end of the 100 ms time window used for identifying peak amplitudes. Windows were 151 to 251 ms and 200 to 300 ms post-stimulus onset. Slanted orange lines depict mean response time. All participants were sorted in ascending order by response time independently of their group affiliation. **a)** Individual participant mean ERP amplitude averaged across the left occipitotemporal component's electrode cluster shown in red on the scalp plot above. **b)** Individual participant mean ERP amplitude averaged across the temporally most consistent right centrofrontal electrodes shown in red on the scalp plot above.

2.5 Discussion

In this study, we have provided evidence for adult dyslexics' impairments during a legal lexical decision making task when the text is presented in italic font. We linked behavioural impairments of dyslexics to two ERP components occurring within 300 ms post-stimulus onset that differed in amplitude between our groups. Crucially, we found a functional coupling between both components but only the second (later) centrofrontal component was more tightly linked to trial-by-trial changes in behavioural performance. Neither component shifted in time with participants' response times. These two ERP components illustrate the challenges that italic font poses for adult dyslexics' neural word analysis. The earlier occipitotemporal component substantiates the account that font affects the orthographic processing stages of lexical decision making, while changes in the later centrofrontal component are likely to reflect impairments in post-sensory processing more closely linked to the eventual decision outcome. Our results highlight the crucial role that font style plays within the word-recognition cascade.

2.5.1 Behavioural impairments

Dyslexics demonstrated worse behavioural performance across font styles. In light of their well-known general deficits with text comprehension (e.g., Elbro & Petersen, 2004), we show here that these impairments persist into adulthood despite decades of reading practice. In our task, decision accuracy was higher for italicised words irrespective of group or word length. This finding is in line with reports of harder to read fonts'—such as italics or Monotype Corsiva—ability to facilitate retention in non-dyslexics (Diemand-Yauman et al., 2010) and dyslexics (French et al., 2013). However, it stands in opposition to multiple reports of strong aversion against and worse performance on italicised font by dyslexics (Rello & Baeza-Yates, 2013, 2016). One plausible explanation for our finding is that overall participants might have allocated more attention (i.e., exogenous alerting or endogenous executive attention; Amso & Scerif, 2015) to the trials presenting italicised words as a consequence of their unfamiliar look, which could lead to increased salience in these trials. Salience is believed to be one of the key gatekeepers for attention allocation and bottom-up processing (Knudsen, 2007). In addition, the short time of each trial (~4 seconds), leading to temporarily limited task demands, might have allowed even dyslexics to compensate in part by allocating more attention during more salient trials. It seems that encountering disfluent fonts in small chunks as in our and French and colleagues' (2013) study does not necessarily pose a major problem for adolescent and adult dyslexics on the behavioural level. We argue that such improvements are most likely specific to tasks that only present short segments of words at a time and our specific sample of dyslexic university students. Based on dyslexics’ reported aversion against disfluent fonts, we can only speculate that the demands, and in turn (cognitive or ‘neural’) costs, would rise with increasing length of text passages in italicised or disfluent fonts.

Interestingly, the fact that only a small subset of dyslexic participants (22%) reported having recognised italic font during the experiment provides further evidence for dyslexics’ deficits with fast visual word recognition. However, the small size of this group, and the concomitant lack of statistical power, only allowed us to use this group for visualisation and reference purposes (relative to the other groups). A larger sample size would have allowed us to investigate intra-group-differences of the spectrum disorder dyslexia in detail, particularly concerning conscious font style recognition.

2.5.2 Changes in neural brain dynamics

2.5.2.1 Occipitotemporal component

Our neural results suggest that dyslexics process italicised text differently. The earliest differential ERP component we found started at 167 ms post-stimulus onset for trials presenting short italicised decision words. This component was located over a cluster of occipitotemporal electrodes. Its timing strongly suggests that it represents different early sensory processing of italicised orthographic word forms, particularly, since we only observed it when changes in font style itself exert a maximum impact on a word’s general shape (i.e., on short words). Visual word form perception is one of the first processes of fast and incremental visual word recognition in reading (Gaskell, 2007) whose orthographic analysis plays a crucial role in the word-recognition process (Lété & Pynte, 2003). In this respect, the efficiency and processing speed of perceiving the abstract letter and word identity is crucial for successful word recognition.

Importantly, effects of orthographic manipulations including words versus symbols (Appelbaum et al., 2009), transposed letters within a word (Grainger et al., 2006), different case (Spironelli & Angrilli, 2007), and font type (Chauncey et al., 2008) have been reported for an early latency range around 150 ms post-stimulus that is in line with our occipitotemporal component (Dien, 2009). Moreover, differential activity in the ventral stream, which hierarchically codes for letter strings (Vinckier et al., 2007), has been linked to deficits in two processes in dyslexia: neural adaptation (Perrachione et al., 2016) and efficient tuning to print (e.g., Kronschnabel, Schmid, Maurer, & Brandeis, 2013; Mahé et al., 2012). These two processes affect early components within 250 ms and normally evolve during childhood in non-dyslexics (Brem et al., 2010). In combination with higher ERP amplitude being a signal for increased processing demands (Otten & Rugg, 2005), dyslexics' higher occipitotemporal ERP amplitude suggests worse neural tuning and adaptation to print that persists into adulthood. Such sensory inefficiency may be a possible mediator of dyslexics' word-recognition impairments.

More support for this component's role in orthographic word form perception comes from studies linking activity in the VWFA, an area in left occipitotemporal cortex that plays a crucial role in word form recognition (e.g., McCandliss et al., 2003), to electrophysiological equivalents peaking around 170 ms (e.g., Brem et al., 2006). The VWFA commonly shows aberrant different BOLD activation patterns in dyslexia (Kronbichler et al., 2006; Shaywitz & Shaywitz, 2005; Shaywitz et al., 2003) and BOLD activity for unfamiliar words (Wimmer, Ludersdorfer, Richlan, & Kronbichler, 2016). Our component's occipitotemporal spatial distribution and its timing are consistent with these equivalents. However, methods with a better spatial resolution, such as fMRI, are needed to confirm this interpretation.

Taken together, these observations suggest that (1) dyslexics' exhibit deficits within the initial stages of orthographic processing, (2) italic font is sufficient to reveal dyslexics neural deficits at similar short latencies in relation to larger differences in font (i.e., Arial versus Gigi) that evoked comparable effects in non-dyslexics, and (3) adult dyslexics likely use a word's shape for decoding short words rapidly.

2.5.2.2 Centrofrontal component

Following the occipitotemporal component, we identified a centrofrontal component in both of our EEG analyses starting around 210 ms post-stimulus onset. Its appearance during the analysis of both short and long italicised words indicates that it is independent of word length, and therefore, captures a more general difference associated with the processing of a variety of italicised words in dyslexia. The observed link between this component and decision performance across all participants corroborates its importance for accurate lexical decision making. In the context of our task, which explicitly asked participants to indicate whether the decision word matched its preceding sentence, it seems plausible that this component signals a combination of post-sensory processing stages such as semantic congruency and phonological awareness as part of lexical access. These processes are not mutually exclusive. They can be associated with just one period as lexical access is inherently fast (Sereno et al., 1998) requiring the performance of crucial word identification steps within the time window of one saccade (i.e., ~275 ms without parafoveal preview; Sereno & Rayner, 2003). Semantics, often associated with the later N400 component, were also found to influence lexical decision making as early as 250 ms post-stimulus (Cavalli, Colé, et al., 2016).

Support for our interpretation is provided by a number of converging findings of a neural component peaking around 250 ms post-stimulus with positive topography over frontal electrodes that reflects effects of initial semantic matching of word forms or late stages of lexical access, termed recognition potential. Similar to our task, studies observing the recognition potential manipulated the congruency of terminal sentence words (Dien, Frishkoff, Cerbone, & Tucker, 2003; Martín-Loeches, Hinojosa, Casado, Muñoz, & Fernández-Frías, 2004) or the semantic properties of single words (Marí-Beffa, Valdés, Cullen, Catena, & Houghton, 2005; Martín-Loeches, Hinojosa, Fernández-Frías, & Rubia, 2001). Importantly, both the latency and amplitude of this component have been linked to reading ability on these similar tasks (Rudell & Hua, 1997).

More evidence for our centrofrontal component’s role in post-sensory processing comes from the fact that it appears independent of word length. Neural effects of word length, and therewith the physical stimulus make-up, have repeatedly been reported for an earlier time window around 100 ms post-stimulus onset (Assadollahi & Pulvermüller, 2001, 2003; Hauk, Davis, et al., 2006; Hauk & Pulvermüller, 2004). In agreement with these findings, modulation of the physical stimulus properties (i.e., word length and font) were captured by our earlier occipitotemporal, but not by our centrofrontal component in dyslexia. Further support for the centrofrontal component's role on post-sensory word identification stages comes from electrophysiological evidence of non-linguistic perceptual decision making tasks demonstrating that post-sensory neural activity is tightly linked to and a better predictor of the decision outcome than early sensory activity (Gherman & Philiastides, 2015, 2018; Philiastides et al., 2014; Philiastides & Sajda, 2006; Ratcliff et al., 2009). Congruent with the observed scalp activity profile such decision-relevant post-sensory signals have been located in frontal cortices (Filimon et al., 2013; Philiastides et al., 2014; Philiastides et al., 2011). Hence, this centrofrontal component could be part of the frontoparietal network associated with decision making.

2.5.3 Potential role of the frontoparietal network

Both of our components overlapped in time between 209 and 236 ms post-stimulus indicating a potential functional relationship between them. In fact, the peak amplitude of the occipitotemporal component was predictive of the subsequent centrofrontal component's peak amplitude on a single-trial basis across participants. This link illustrates that our identified components are part of a cascade of processes taking place in short succession during lexical decision making. As in previous non-linguistic decision making tasks, the information processing encoded in the early component is broadcasted onto downstream networks for subsequent post-sensory processing and decision making (Diaz, Queirazza, & Philiastides, 2017; Philiastides & Sajda, 2006; Ratcliff et al., 2009). Attention, in particular, can play a crucial modulatory role during this interplay (Philiastides et al., 2006) and help facilitate the propagation and enhancement of the most diagnostic stimulus features during visual word processing (Ruz & Nobre, 2008). In this context, Amso and Scerif (2015) proposed that connections between parietal and (pre-)frontal cortex may function as continuous loops controlling executive attention and decision making whereby these loops facilitate the transformation of the early visual processing into the relevant decision evidence along the ventral stream. In our task, such top-down influence would be reflected in an enhancement, that is lower ERP amplitude, of our occipitotemporal component as shown by our control group. In this respect, dyslexics' higher occipitotemporal ERP amplitude coupled with the centrofrontal component being linked to decision performance suggests that this network works less efficiently during word identification in adult dyslexia.

In contrast to the ERP components presented above, we did not find any significant between-group ERP differences for contrasts examining trials that presented Arial regular font. This finding suggests that, indeed, italic font affects fundamental orthographic properties of words such as word shape important during lexical decision making. If our results were reflecting general challenges of the adult dyslexic brain independent of font style, we should have observed similar neural differences for decision words presented in Arial regular font. Further, a lack of differences in later ERP components—such as the P300 and N400, commonly associated with working memory and obvious semantic mismatch on linguistic tasks (e.g., Helenius et al., 1998; Van Petten, 1995)—suggests that the italic font style led to the observed group-differences as opposed to different decision strategies based on other properties of our decision words (e.g. word class, expectancy, or semantic incongruency). However, we cannot rule out a mediating role of these properties as we included a variety of decision words. Hence, our results show cardinally different processing in adult dyslexia occurs within 300 ms after perceiving a word.

In summary, here we contributed to the literature by revealing that even small changes in font style, as embodied by italic font, are sufficient to elicit fundamentally different neural processing within the sensory and post-sensory stages of visual word decoding in adult dyslexia. These group-differences were captured by two distinct ERP components starting as early as 167 ms after the onset of a single italicised word. Here, it has become evident that font affects the rapid interplay of orthographic, lexical, and semantic processes during visual word-recognition, which is most likely modulated by attention. Our findings suggest refraining from using italic font in a variety of documents—especially legal contracts and education materials—in order to optimise word processing by dyslexics.

Chapter 3. The dyslexia font OpenDyslexic improves reading comprehension and facilitates visual processing of text in adult dyslexia

3.1 Summary

Proficient literacy skills and reading comprehension are crucial skills for participation and success in everyday life. One group that regularly falls short in demonstrating good reading skills are people with dyslexia. This group suffers from a range of well-characterised visual deficits. However, only recently designers started to develop affordable and easily implementable remedies that are supposed to reduce the visual symptoms of dyslexia such as specific dyslexia fonts. To date, empirical evidence about the efficacy of these fonts is contradictory, and their effects on adult dyslexics' eye movements and cognitive processing during longer reading tasks remains elusive. To bridge this gap, we measured the eye movements of adults with and without dyslexia during the reading of a set of standardised texts from the international reading speed texts (IReST; Trauzettel-Klosinski & Dietz, 2012) reading battery coupled with validated comprehension questions. These texts and questions were presented either in traditional Times New Roman or in the specific dyslexia font OpenDyslexic. Here, we found that OpenDyslexic led to improvements in reading comprehension in dyslexics and non-dyslexics. These improvements were larger for dyslexics. Contrarily, participants' reading speed was unaffected by OpenDyslexic. Our eye-tracking data showed increases in visual search intensity and visual ease on OpenDyslexic trials in the form of decreases in median fixation duration and fixation to saccade ratio as well as a smaller number of falsely programmed forward saccades among dyslexics. Our findings illustrate that OpenDyslexic results in a different visual reading strategy. These findings provide empirical evidence for the efficacy of OpenDyslexic in longer texts and suggest its use in everyday documents, education materials, and online sources.

3.2 Introduction

Reading is an everyday task that needs to be learned proficiently for one to be able to master chores independently and successfully in their daily lives. While most people develop efficient reading skills with relative ease and gain proficiency during the first years of elementary school, individuals suffering from the neurobiological learning disability dyslexia (Lyon et al., 2003), can be particularly challenged with gaining proficient literacy skills, even into adulthood.

Although dyslexics' impairments on reading tasks seem to be due to deficient phonological processing (Ramus, 2003; Saksida et al., 2016; Snowling, 1981; Snowling & Melby-Lervåg, 2016; Vellutino et al., 2004), an increasing body of evidence points towards impairments in the processing of non-linguistic stimuli (e.g., Schulte-Körne & Bruder, 2010; Stein & Walsh, 1997) that manifest in different neural activity (Norton et al., 2015; Shaywitz et al., 2006) and connectivity (Finn et al., 2014), and aberrant ocular movements (e.g., Fischer et al., 1993; Trauzettel-Klosinski et al., 2010). Even left-right asymmetry in the cone patterns on the retina may cause the visual symptoms observed in dyslexia (Le Floch & Ropars, 2017). These findings in combination with dyslexics frequently reporting distorted, blurred and reversed (or mirrored) vision of letters during reading led to the development of the magnocellular theory of dyslexia (Stein, 2001, 2014, 2018a, 2018b; Stein & Walsh, 1997). This theory postulates that abnormal development in the arrangement and connection of the magnocells, which play an essential role in the programming of eye movements and visual sequencing, may be the cause of the different eye movements found in dyslexia (Biscaldi et al., 2000; De Luca et al., 1999; Fischer & Weber, 1990; Fischer & Hartnegg, 2000; Hutzler & Wimmer, 2004; Prado et al., 2007; Starr & Rayner, 2001; Trauzettel-Klosinski et al., 2010; Vagge et al., 2015). Dyslexics have difficulties in moving their gaze smoothly along lines of written text (e.g., Prado et al., 2007), and make more eye movements with increasing text difficulty (Trauzettel-Klosinski et al., 2010). In this respect, saccades have been found to be impaired in dyslexia (Fischer & Weber, 1990; Fischer & Hartnegg, 2000; Pavlidis, 1981): specifically a higher number of express and shorter rightward saccades (De Luca et al., 1999; Trauzettel-Klosinski et al., 2010), more frequent regressions (Pavlidis, 1981; Trauzettel-Klosinski et al., 2010), and worse performance in the anti-saccade task (Biscaldi et al., 2000). Despite these evident differences in the frequency and number of saccades, dyslexics' saccade accuracy seems to remain intact (De Luca et al., 1999; Vagge et al., 2015). In addition, differences in fixations have also been found in dyslexia, namely increased loss of fixation/fixation instability (Vagge et al., 2015), longer fixation durations (De Luca et al., 1999; Hutzler & Wimmer, 2004; Masulli et al., 2018), more fixations (Hutzler & Wimmer, 2004; Vagge et al., 2015) with increasing differences for longer (De Luca et al., 1999; Hutzler & Wimmer, 2004) and less common words (Hutzler & Wimmer, 2004).

In an attempt to improve eye movements associated with reading in dyslexics, researchers started to investigate the effects of visual properties of text such as print size (O'Brien, Mansfield, & Legge, 2005), letter spacing (Dotan & Katzir, 2018; Hakvoort, van den Boer, Leenaars, Bos, & Tijms, 2017; Masulli et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012), background colour (Rello, Kanvinde, & Baeza-Yates, 2012), and font style (French et al., 2013; Kuster et al., 2018; Rello & Baeza-Yates, 2013, 2016) in dyslexia. Font characteristics can alter a word's appearance, independently of its linguistic characteristics, leading to performance improvements in reading time (Rello & Baeza-Yates, 2013, 2016) and comprehension (Diemand-Yauman et al., 2010; French et al., 2013) among dyslexics.

In an attempt to alleviate the visual symptoms of dyslexia, designers have developed dyslexia-friendly fonts that omit serifs, use increased inter- and intra-word spacing, and unique letter strokes. Manipulations of these properties have been reported to increase reading speed and reduce distortions in poor readers (e.g., Sjoblom et al., 2016; Wilkins et al., 2007). The two dyslexia fonts—OpenDyslexic (https://www.opendyslexic.org) and Dyslexie (https://www.dyslexiefont.com)—have been designed according to these property suggestions, but neither lead to stable improvements in reading duration (Kuster et al., 2018; Rello & Baeza-Yates, 2013, 2016), or accuracy (Kuster et al., 2018; Wery & Diliberto, 2017). However, Marinus and colleagues (2016) showed a slight increase in reading rate with Dyslexie, and Zikl and colleagues (2015) reported that some dyslexic children self-reported that the dyslexia font was more readable. Nevertheless, studies demonstrating quantifiable effects of dyslexia fonts that employ eye-tracking technology and standardised texts in English remain scarce. Eye-tracking technology provides detailed insights into the distribution of gaze and cognitive processes including attention during dynamic tasks such as reading. The various components of eye movements during reading including fixations, saccades, regressions, etc. allow researchers to make inferences about the allocation of attention and efficiency of the reading process, which is not obtainable from conventional behavioural measures such as reading duration, accuracy or comprehension alone. None of the aforementioned studies has provided detailed insights into the role of ocular movements beyond fixation measurements as underlying mechanisms of these findings for dyslexia fonts. Therefore, it remains elusive whether dyslexia fonts lead to better reading performance (i.e., higher reading accuracy and comprehension and faster reading speed) or whether they may help dyslexics' eyes to process text more efficiently (e.g., fewer re-readings of a word, termed regressions).

Here we sought to examine whether the dyslexia font OpenDyslexic leads to improvements in reading speed (i.e., less time to read a standardised paragraph) and comprehension (i.e., more correct answers on multiple-choice comprehension questions). Further, we investigated whether the dyslexia font leads to a decrease in reading-related eye movement errors when being contrasted with the commonly used traditional font Times New Roman. Based on previous literature, we hypothesised that reading texts in OpenDyslexic leads to (1) increases in dyslexics' reading comprehension, (2) decreases in reading duration, (3) a reduction in the number of fixations, average fixation duration, and reading-related eye movement errors such as the number of regressions and large shifts in the angle of forward saccades. Furthermore, (4) we expected stronger preference for OpenDyslexic among dyslexics.

To investigate these hypotheses, we asked adult dyslexic university students to read standardised texts from the IReST reading battery (Trauzettel-Klosinski & Dietz, 2012) in one of two fonts—OpenDyslexic or Times New Roman—while measuring their eye movements. A multiple-choice comprehension question, administered after reading each text, provided a measurement of reading comprehension.

3.3 Materials and methods

3.3.1 Participants

Participants. Here, we collected data from 73 participants: 38 controls without symptoms of dyslexia ($\text{male}_{\text{con}} = 4$, $\text{female}_{\text{con}} = 34$; $\mathit{Mean\ age}_{\text{con}} = 22.61$, $\mathit{SD}_{\text{con}} = 3.15$, $\mathit{Min}_{\text{con}} = 19$, $\mathit{Max}_{\text{con}} = 34$) and 35 dyslexics ($\text{male}_{\text{dys}} = 12$, $\text{female}_{\text{dys}} = 23$; $\mathit{Mean\ age}_{\text{dys}} = 23.54$, $\mathit{SD}_{\text{dys}} = 6.22$, $\mathit{Min}_{\text{dys}} = 18$, $\mathit{Max}_{\text{dys}} = 46$). To avoid including participants with dyslexia symptoms but without an official diagnosis in the control group, and to get a measure of dyslexia severity at the time of participation, all participants filled out the Adult Dyslexia Checklist (Smythe & Everatt, 2001). This checklist assessed aspects of literacy, language, word finding, and organisation skills. Items on this questionnaire require the respondent to rate the frequency of encountering certain ‘symptoms’ of dyslexia on a scale of 1-4 (i.e., rarely / occasionally / often / most of the time), which are associated with a varying number of points per item depending on their occurrence in dyslexia. A score of 45 or more points indicates mild to severe dyslexia symptoms. To ensure that control participants did not report dyslexia-like symptoms, we used a score of 40 points to delineate between those with no-dyslexic symptoms who were included and those with dyslexic characteristics. All dyslexic participants have previously obtained an official diagnosis of dyslexia as proof of their learning disability ($\mathit{Mean\ age}_{\text{diagnosis}} = 12.69$, $\mathit{SD}_{\text{diagnosis}} = 6.43$). All participants self-reported normal or corrected-to-normal vision, were at least 18 years of age, and were either current or former college or university students. They were paid $10 CAD or given course credit as compensation for their participation. All participants gave written informed consent prior to their testing session. The study was approved by the research ethics board at Concordia University, Montréal (Approval number: 30003975) and conducted adhering to the Canadian Tri-council Policy on ethical conduct for research involving humans (Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, & Social Sciences and Humanities Research Council of Canada, 2014).

We excluded six control participants from all analyses due to large inaccuracies during the calibration procedure (i.e., no eye with average error <.5° and max error <1.3°). Consequently, a total of 67 participants between the age of 18 and 46 ($\mathit{Mean\ age}_{\mathit{included}} = 22.99$, $\mathit{SD}_{\mathit{included}} = 4.87$) were included in all analyses. The control group consisted of 9 bilingual native English & French speakers, and 23 monolingual native English speakers. The dyslexia group consisted of 18 bilingual native English & French speakers, and 17 monolingual native English speakers.

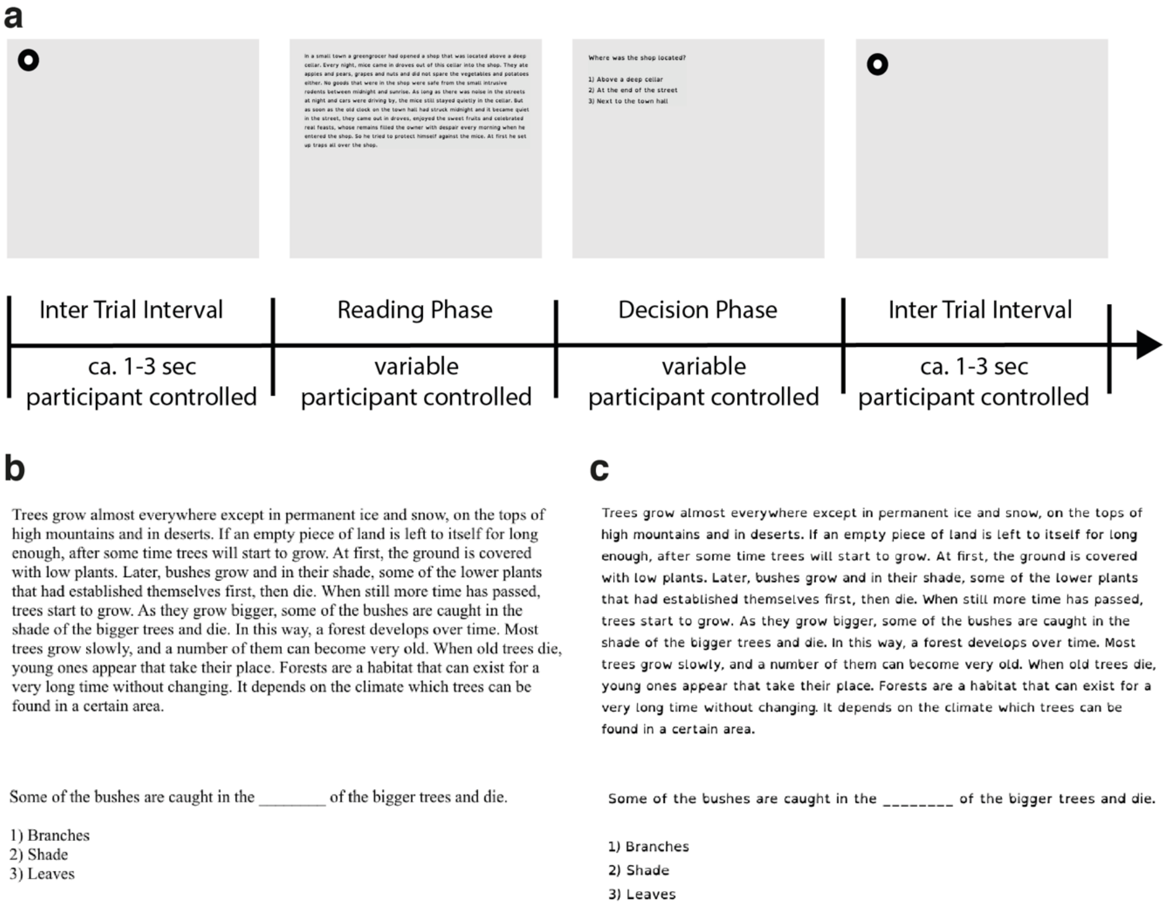
3.3.2 Stimuli, apparatus, and experimental procedure

Stimuli. We presented all participants with 10 standardised texts from the IReST reading battery (Trauzettel-Klosinski & Dietz, 2012; see Figure. 3.1 for examples). These texts have been standardised for certain properties such as the number of words, syllables, and characters, and the reading time in words per minute. Importantly, each text contains unique content. These properties guarantee the comparability across texts whilst preserving the novelty effect of every single text. Additionally, the IReST texts have previously been validated in a Canadian sample (Morrice, Hughes, Stark, Wittich, & Johnson, 2018). Each text was accompanied by one short multiple-choice question with three options of which one was correct. The question was presented immediately upon reading the text once. These questions were created and validated within a Canadian population (Morrice et al., 2018), and have been used in other reading studies (Morrice, Johnson, Marinier, & Wittich, 2017; Wittich, Jarry, Morrice, & Johnson, 2018). We chose a between-groups and within-items experimental design in which every participant was presented with all 10 IReST texts once. Five texts and their multiple-choice questions were displayed in the specific dyslexia font OpenDyslexic (https://www.opendyslexic.org), with the other 5 texts and their multiple-choice questions in traditional Times New Roman font. To equate for differences in physical text size, we varied the nominal font sizes using 20-point size for Times New Roman (Figure 3.1b) and 18-point size for OpenDyslexic trials (Figure 3.1c). Every text and its respective multiple-choice question were presented in the same font. To preserve novelty whilst being able to present all texts in all fonts we separated texts 1 through 5 and 6 through 10. Participants with odd participant ID numbers saw texts 1 through 5 in Times New Roman and 6 through 10 in OpenDyslexic font. Participants with even participant ID numbers saw texts and questions written in opposing fonts. We randomised the presentation order of these texts within-subjects (using the '*randperm*' function in MATLAB). One additional text with similar linguistic properties and a multiple-choice question were obtained from online sources and was presented as a practice trial in Arial regular font.

Apparatus. We presented stimuli and collected data using a Dell Quad-Core PC running Microsoft Windows 7. Participants viewed stimuli on a 20-inch linearised video monitor (View sonic G225fb 21” CRT, 1024 × 768-pixel resolution, 100-Hz refresh rate). We displayed texts in the upper half of the screen with 83.57 characters per line on average and left alignment. Binocular eye movements were recorded remotely and non-invasively at a sample rate of 1000 Hz using a video-based eye movement monitor (EyeLink 1000/2000, SR Research, Ottawa, Ontario). The EyeLink system was used in the Pupil-Corneal Reflection tracking mode, and we varied the eye movement monitor’s illumination between 50% and 100%. A chin rest was used to stabilise the head position and optimise tracking results at a distance of 70 cm from the screen.

Procedure. First, participants completed the Adult Dyslexia Checklist (Smythe & Everatt, 2001). Second, to examine participants’ processing speed, participants completed two short subtests from the Wechsler Abbreviated Scale of Intelligence test battery (Wechsler, 2008), specifically the Symbol Search and Coding subsections. Each test took about 2 minutes to complete. Third, the experimenter placed the participants chin on a chin rest and adjusted the infra-red illumination of the eye tracker to isolate the eye pupil to be tracked. Fourth, we performed a binocular calibration procedure by asking participants to follow a randomised series of 9 black dots on white background (using the SR EyeLink’s inbuilt 9-point calibration procedure with targets in the default locations). A validation procedure using the same 9 points in a randomised order confirmed the accuracy of the eye tracker’s calibration measurements. We chose to move on only after obtaining a calibration accuracy with an average error of $<.5^\circ$ of visual angle, and no point exceeding a maximum error of 1.3°. Once a participant had completed the calibration procedure successfully, they were instructed not to move their head for the remainder of the eye-tracking component of the experiment (approximately 15 mins). Upon reading the written instructions on the screen, if questions remained, the experimenter reiterated the key points of the instructions verbally. This was particularly important to ensure that dyslexic participants understood the instructions correctly.

Participants then read 10 texts from the IReST battery (Trauzettel-Klosinski & Dietz, 2012) silently in their head. Each text was presented separately, divided by a comprehension question that related to its preceding text (Figure 3.1a). Participants were instructed to read the text only one time and were interrupted by the experimenter if they attempted to re-read the text from the beginning. Before the presentation of each text, a drift correct fixation point (that is, a black circle), was presented in the top left-hand corner of the screen in order to orient participants eyes to the beginning of the first line of text. Participants had to fixate on the dot and press the space bar at the same time in order to proceed to the text. This fixation point was gaze-contingent such that the experiment would only proceed if the participant was fixating within 1° of the target when they pressed the space bar. Once participants finished reading each of the texts, they were instructed to press the space bar. At this point, a multiple-choice question about the preceding text with three response options of which one was correct was displayed in the top half of the screen. Participants indicated their answer to the question via a button press on the keyboard (i.e., number keys 1, 2, or 3). To familiarise participants with the entire procedure, they completed one practice trial presenting a text and question. Lastly, after reading all 10 texts, we administered a questionnaire concerning participants' experience with reading the texts, their preferences for the displayed fonts, as well as demographic information such as age and language background (see Appendix C for full questionnaire). In total, the entire experimental procedure lasted about 40 minutes.



In a small town a greengrocer had opened a shop that was located above a deep cellar. Every night, mice came in droves out of this cellar into the shop. They ate apples and pears, grapes and nuts and did not spare the vegetables and potatoes either. No goods that were in the shop were safe from the small intrusive rodents between midnight and sunrise. As long as there was noise in the streets at night and cars were driving by, the mice still stayed quietly in the cellar. But as soon as the old clock on the town hall had struck midnight and it became quiet in the street, they came out in droves, enjoyed the sweet fruits and celebrated real feasts, whose remains filled the owner with despair every morning when he entered the shop. So he tried to protect himself against the mice. At first he set up traps all over the shop.

Where was the shop located?

1) Above a deep cellar
2) At the end of the street
3) Next to the town hall

Trees grow almost everywhere except in permanent ice and snow, on the tops of high mountains and in deserts. If an empty piece of land is left to itself for long enough, after some time trees will start to grow. At first, the ground is covered with low plants. Later, bushes grow and in their shade, some of the lower plants that had established themselves first, then die. When still more time has passed, trees start to grow. As they grow bigger, some of the bushes are caught in the shade of the bigger trees and die. In this way, a forest develops over time. Most trees grow slowly, and a number of them can become very old. When old trees die, young ones appear that take their place. Forests are a habitat that can exist for a very long time without changing. It depends on the climate which trees can be found in a certain area.

Some of the bushes are caught in the ________ of the bigger trees and die.

1) Branches
2) Shade
3) Leaves

Trees grow almost everywhere except in permanent ice and snow, on the tops of high mountains and in deserts. If an empty piece of land is left to itself for long enough, after some time trees will start to grow. At first, the ground is covered with low plants. Later, bushes grow and in their shade, some of the lower plants that had established themselves first, then die. When still more time has passed, trees start to grow. As they grow bigger, some of the bushes are caught in the shade of the bigger trees and die. In this way, a forest develops over time. Most trees grow slowly, and a number of them can become very old. When old trees die, young ones appear that take their place. Forests are a habitat that can exist for a very long time without changing. It depends on the climate which trees can be found in a certain area.

Some of the bushes are caught in the ________ of the bigger trees and die.

1) Branches
2) Shade
3) Leaves

Figure 3.1. **Experimental design and example of stimuli**. **a)** The sequence of events of one trial. Upon fixating on a drift correction circle (the circle was smaller than depicted in a), which directed the participant's eyes to the location of the start of the text, participants read each text silently in their head once. Immediately after participants finished reading, they were asked to answer a short multiple-choice comprehension question relating to the content of the preceding text without time pressure. **b)** Example of one text and its comprehension question written in Times New Roman font. **c)** Example of the same text and its comprehension question as in panel b written in OpenDyslexic font.

3.3.3 Behavioural Analysis

To investigate the effect of dyslexia on reading comprehension and duration, and its relationship to cognitive processing speed, we used two GLMMs and several robust correlation analyses. Where appropriate, we also report the unbiased effect size (i.e., Hedges' g; henceforth *g*) and the 95% confidence interval around the effect size. For all our analyses, we collapsed across bilingual and monolingual participants within each group, since bilinguals performed at least equally well in the dyslexia (t_{33} = 1.198, *p* =.24, *g* =.396, 95% CI_g = [-.268, 1.072]; two-sample t-test) and the control group (t_{30} = -2.399, *p* =.02, *g* = -.92, 95% CI_g = [-1.743, -.13]; two-sample t-test) on reading comprehension. Hence, having a second mother tongue besides English did not impair participants' reading comprehension and allowed for this unification of participant subgroups.

Our GLMMs quantified our dependent variables, *reading duration* and *reading comprehension* as a function of the two categorical predictors: *font type* (i.e., OpenDyslexic and Times New Roman), *group* (i.e., dyslexics and controls), and their interaction separately on a single-trial level. We performed this analysis employing the *lme4* package (Bates et al., 2015) and the *bobyca* optimiser in RStudio (RStudioTeam, 2016). We specified a *gamma* model in the family argument of the *glmer* function for reading duration, a continuous variable, and a *binomial logit* model for reading comprehension, a categorical variable. Both GLMMs included the maximal random effects structure justified by the experimental design (Barr et al., 2013). They included all main effects and interactions of our two predictors, font type and group, as well as by-subject and by-item random intercepts and random slopes for all relevant main effects and interactions. We included random correlations for our model predicting reading comprehension but excluded random correlations for the model predicting reading duration. The 95% confidence intervals were calculated for all β estimates (using the '*broom*' package and '*Wald*' method in RStudio). We accounted for small imbalances in trial numbers of the predictors' levels by entering all predictors in mean-centred form (deviation coding). Then we checked all entered predictors for collinearity (using the '*cor*' function and model output in RStudio). Lastly, we used post-hoc likelihood-ratio X^2 model comparisons to quantify the predictive power and significance of all significant or trending effects (i.e., p <.1) revealed by the two GLMMs.

To examine potential effects of non-linguistic cognitive processing speed and the severity of reported dyslexia symptoms on behavioural performance, we correlated the standardised scores for processing speed, obtained from the Coding test, with reading duration and improvements in reading comprehension (i.e., $\text{accuracy}_{\text{OpenDyslexic}}$-$\text{accuracy}_{\text{Times New Roman}}$). We computed these correlations employing a series of robust bend correlations (Pernet et al., 2013), which used 20% bending in each direction, across all participants and for both groups separately. We only correlated scores of one processing speed measure (i.e., coding) with behavioural performance, since the standardised scores of the Symbol Search test did not differ significantly between groups (t_{65} =.399, p =.69, g = -.097, 95% CI_g = [-.382, .577]; two-sample t-test; Figure 3.3a). In addition, the

Coding test can be considered a test of visual working memory capacity; a skill that is known to be impaired in adult dyslexia (Beidas et al., 2013).

Lastly, we computed the proportion of participants of each group who preferred reading the presented texts and questions in OpenDyslexic font. Participants indicated their preference in writing as part of the questionnaire that was administered at the end of the procedure.

3.3.4 Eye movement analysis

Blinks, fixations, and saccades were recorded at a sample rate of 1000 Hz and stored for offline analysis. During offline analysis, we used inbuilt algorithms in DataViewer (version 3.1.97, SR Research, 2017, Ottawa, Ontario) for pre-processing of the aforementioned event types, performing reading-related interest area analysis and aggregating measures on a trial-by-trial basis. To avoid contaminating our eye movements analysis with reading unrelated events at the beginning and end of each trial, we defined an interest period in DataViewer that excluded the first and last 300 ms of each trial. In the case of a fixation spanning any of these two cut-off time points, the spanned fixation duration was trimmed. Additionally, we set the threshold of the duration of a valid fixation to > 50 ms, the fixation merging amplitude to 1°, the minimum saccade amplitude to 0.5°, and did not merge fixations separated by a blink. In fact, we removed fixations immediately before and after a blink saccade and excluded fixations beyond display bounds (i.e., the entire screen). All samples that were identified for exclusion on the grounds of any of the aforementioned criteria were excluded from all further analyses. Choosing these analysis parameters helps to remove outliers caused by random eye movements unrelated to reading. Furthermore, each word had an interest area including five pixels of padding around all sides of a word. We filled gaps between interest areas and chose a background RGB threshold of less than 350. All fixations were drift corrected by the drift value obtained at the start of each trial. Nevertheless, on trials where all fixations exhibited an obvious vertical offset across all lines of a text resulting in fixations lying on interest area boundaries, as examined by visual inspection, we manually adjusted all fixations of a given trial vertically (13.5% of all analysed trials). Importantly, we neither adjusted fixations horizontally nor moved single fixations separately.

The results of this pre-processing and initial offline analysis with DataViewer were then exported as .csv reports for further analysis in MATLAB (version 2016b, The MathWorks, 2016, Natick, Massachusetts) using custom scripts. The analysis in MATLAB included the computation of an aggregate number per trial of a variety of eye-tracking measures such as the number of regressions, fixation to saccade ratio, total scan path, ratio of visited interest areas, directional shifts of forward saccades. Further, we 'normalised' certain measures including the number of fixations, saccades, regression and runs, and the total scan path, which had initially been computed on a trial-by-trial basis by a trial's reading duration. The latter normalisation technique allowed us to account for potentially confounding effects of differences in reading duration between trials by calculating the aforementioned eye-tracking measures per 10-second segment. In addition, we estimated the reading speed in words per minute by dividing the words read during each trial by the trial's reading duration. This speed was estimated for trials read in less than one minute. Our offline analysis in MATLAB also involved calculating all measures split by group and font. Lastly, during offline analysis, we were forced to exclude all trials presenting text number 5 in Times New Roman font (4.9% of all analysed trials), since this text was displayed in a dissimilar font size compared to all the other texts presented in Times New Roman.

3.3.5 Statistical evaluation of eye movement data

To quantify the predictive power of all relevant eye-tracking measures (i.e., number of blinks, number of fixations, number of saccades, number of regressions, number of visited interest areas, number of runs, median fixation duration, maximum fixation duration, median saccade amplitude, number of directional shifts, fixation to saccade ratio, total scan path, and ratio of skipped words) on a single-trial basis on reading comprehension, reading duration, and font, we used separate GLMMs in RStudio (RStudioTeam, 2016). However, high values of collinearity of the aforementioned eye-tracking measures, indicated by pairwise correlations of up to *r* =.96, did not allow for using all these measures as separate predictors in our GLMM analysis. Instead, we performed principal component analysis (PCA) on normalised (i.e., z-scored) single-trial data (using the '*pca*' function in MATLAB 2016b) and used the component scores of the resulting three principal components, which each explained at least 10% of the variance of the entire data set and had an eigenvalue larger than 1, as predictors. PCA has been performed on eye-tracking data before in order to control for problems of collinearity and information redundancy in eye movement analyses (Bednarik, Kinnunen, Mihaila, & Fränti, 2005; Toker, Conati, Steichen, & Carenini, 2013).

We performed this GLMM analysis using the *lme4* package (Bates et al., 2015) and *bobyca* optimiser. We specified a *binomial logit* model for the models predicting font and reading comprehension as these were categorical dependent variables. We specified a *gamma* model for the model predicting reading duration—a continuous dependent variable. The two models that predicted reading comprehension and duration excluded random correlations, whereas the model predicting font included random correlations. In addition, we calculated 95% confidence intervals for all *β* estimates of our models (using the '*broom*' package and '*Wald*' method in RStudio). All three GLMMs included main effects of all three principal components as predictors as well as appropriate model specific by-subject and by-item random intercepts and random slopes for all relevant main effects and interactions. In addition, we drew upon our behavioural results for designing these GLMMs. For this reason, we included a main effect of the predictor group and its interactions with the three principal components in addition to the main effects of all principal components themselves in the model predicting reading duration. The model predicting reading comprehension included main effects for the two predictors, group and font, as well as their interactions with the three principal components in addition to the main effects of all principal components themselves. All predictors were entered in mean-centred form (deviation coding).

Furthermore, to quantify and compare the effect of font (i.e., OpenDyslexic-Times New Roman) in more detail without losing valuable information due to dimensionality reduction, we computed unbiased effect sizes (*g*) and their respective 95% confidence intervals in MATLAB (using the '*mes*' function of the Measures of Effect Size Toolbox by Hentschke and Stüttgen (2011) and its *exact analytical* method for determining confidence intervals) separately for each eye-tracking measure and group. We assumed a significant effect of font when the 95% confidence interval of a group's effect size did not include zero. In our design, positive effect sizes represented a higher number or ratio of the respective eye-tracking measure on OpenDyslexic compared to Times New Roman trials and vice versa. Subsequently, we estimated the probability density function corresponding to all eye-tracking measures that yielded a significant effect size for the within-group font comparison using kernel density estimation in MATLAB (using the '*raincloud_plot*' function by Allen, Poggiali, Whitaker, Marshall, and Kievit, 2018). In doing so, we created a probability density 'heat' map for all measures showing significant differences.

In addition, we evaluated differences in general eye movement coordination during reading between our two groups by contrasting radical angular shifts of forward saccades that could neither be classified as an inaccurate forward saccade nor inaccurate regression, termed directional shifts. Saccades with an angle between ± 45° and 135° qualified as directional shifts. We quantified these differences separately for each font using the two-sample Kuiper test (i.e., the circular analogue of the Kolmogorov-Smirnov test from the Circular Statistics Toolbox (Berens, 2009).

3.4 Results

3.4.1 Behavioural results

We constructed two separate generalised linear mixed effects models that analysed reading comprehension and reading duration as a function of our predictors: *font* (OpenDyslexic and Times New Roman), *group* (control and dyslexic), and their *font-by-group* interaction on a single-trial level.

Our first GLMM predicting reading comprehension, initially yielded no significant effects of font ($Z = -1.940$, $p = .052$), group ($Z = -1.326$, $p = .19$) or their interaction ($Z = 1.820$, $p = .069$) at an alpha level 5% (for details, see Table 3.1). However, post-hoc likelihood-ratio X^2 model comparisons demonstrated significant predictive power of the font main effect and font-by-group interaction on reading comprehension ($X^2(1) = 4.447$, $p = .035$, $X^2(1) = 4.5662$, $p = .0326$, respectively; Figure 3.2a).

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*Z*	*p*
Font	**-0.8995**	**-1.8081**	**0.0091**	**0.4636**	**-1.940**	**0.0524**
Group	-0.6478	-1.6052	0.3096	0.4885	-1.326	0.1848
Font * Group	**1.5611**	**-0.1205**	**3.2427**	**0.8580**	**1.820**	**0.0688**

Table 3.1. Generalised linear mixed effects model fixed effect parameter estimates for model predicting reading comprehension. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Further, we found that reading comprehension across fonts significantly correlated with the self-reported frequency of experiencing dyslexia symptoms, as assessed by the score on the Adult Dyslexia Checklist, only in the dyslexia group (r_{33} = -.36; p =.035, 95% CI_r = [-.621, -.019]; Figure 3.4b), but not in the control group (r_{30} = -.31; p =.08, 95% CI_r = [-.587, .085]; Figure 3.4c). The latter result illustrates that dyslexia is a spectrum learning disability whose varying frequency of experiencing related symptoms affects dyslexics' reading comprehension in general.

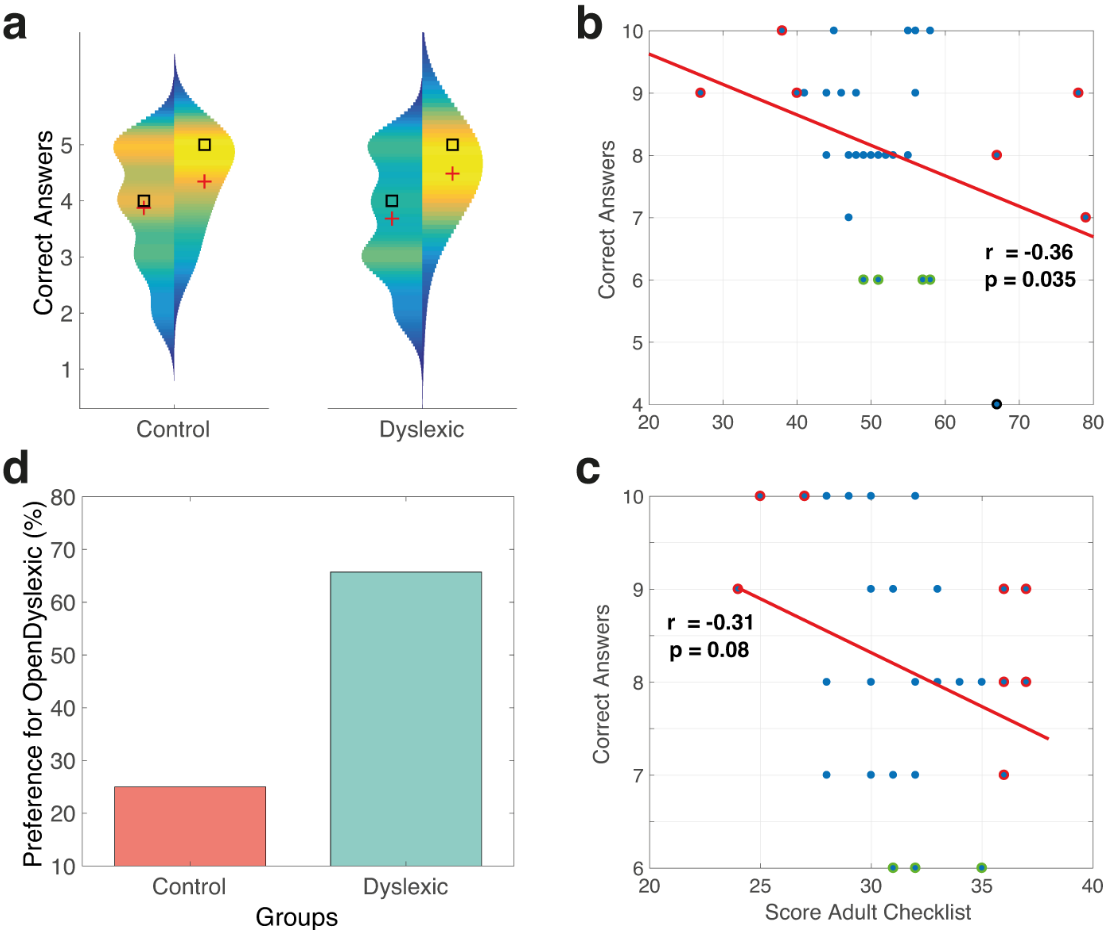


Figure 3.2. Reading comprehension and font preference. a) Reading comprehension (i.e., number of correct answers per font type) by font type and group. The left-hand side of each violin plot depicts trials presented in Times New Roman; the right-hand side depicts trials presented in OpenDyslexic font. Red crosses denote group means, and black squares denote group medians for

each font condition. **b)** Correlation of reading comprehension (i.e., number of correct answers across fonts) with self-reported dyslexia severity score from the Adult Checklist (higher scores indicate the experience of dyslexia symptoms more frequently) for the dyslexia group. Correlation coefficient (r) and p-value from robust bend correlation shown. Colours indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension 20% of data points were down-weighted. **c)** Correlation of reading comprehension with self-reported dyslexia severity score for the control group. **d)** The proportion of participants of each group who preferred reading the presented texts presented in OpenDyslexic over Times New Roman font.

Our second GLMM identified significant predictive power of the main effect of group on median reading duration with dyslexics showing slower reading speed ($t = -4.037$, $p <.0001$; Figure 3.3a; for details, see Table 3.2). This speed difference is underlined by dyslexics' lower words per minute reading rate ($Median_{\mathrm{CON}} = 247.19$, $Median_{\mathrm{DYS}} = 178.23$; Figure 3.3b). A post-hoc likelihood-ratio X^2 model comparison confirmed the main effect of group on reading duration ($X^2(1) = 13.931$, $p < .001$). However, unlike our results on reading comprehension, this model did not yield a significant improvement in reading duration with OpenDyslexic font ($t = 1.192$, $p =.23$) or a significant font-by-group interaction ($t = -0.701$, $p =.48$).

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*t*	*p*
Font	1.0909	-0.7026	2.8844	0.9151	1.192	0.233
Group	**-21.9459**	**-32.6019**	**-11.2899**	**5.4368**	**-4.037**	**< 0.0001**
Font * Group	-1.2754	-4.8413	2.2905	1.8194	-0.701	0.483

Table 3.2. Generalised linear mixed effects model fixed effect parameter estimates for model predicting reading duration. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Since the observed impairments in reading speed may as well be merely a result of dyslexics well-known deficits in cognitive processing speed (Beidas et al., 2013; Swanson & Ashbaker, 2000), we examined two types of non-linguistic cognitive processing speed, namely coding and symbol search speed (Wechsler, 2008), and their effects on reading duration. Dyslexics exhibited slower non-linguistic cognitive processing speed on the Coding test (a working memory test) ($t_{65} = 5.88$, $p <.0001$, $g = 1.422$, 95% $\mathrm{CI}_g = [.895, 1.973]$; two-sample t-test), but not on the Symbol Search test ($t_{65} =.399$, $p =.69$, $g = -.097$, 95% $\mathrm{CI}_g = [-.382, .577]$; two-sample t-test; Figure 3.3c). Coding speed was negatively correlated with reading duration across all participants ($r_{65} = -.51$; $p <.0001$, 95% $\mathrm{CI}_r = [-.680, -.300]$; Figure 3.3d) indicating that participants with better coding ability (i.e., faster processing speed) demonstrated shorter reading duration. This finding was predominantly a consequence of the significant negative correlation between coding and reading duration within the control group (r_{30} = -.39; p =.029, 95% CI$_r$ = [-.647, -.057]; Figure 3.3e), since this relationship was absent in our dyslexia group itself (r_{33} = -.08; p =.66, 95% CI$_r$ = [-.359, .282]; Figure 3.3f). Hence, coding processing speed seems to serve as an explanation for the difference in reading duration between our groups, but not among dyslexics themselves. However, coding speed was not linked to improvements in reading comprehension with OpenDyslexic font (i.e., accuracy$_{\text{OpenDyslexic}}$-accuracy$_{\text{Times New Roman}}$) across all participants (r_{65} = -.20; p =.10, 95% CI$_r$ = [-.405, .084]) nor across dyslexic participants (r_{33} = -.09; p =.63, 95% CI$_r$ = [-.422, .278]).

Additionally, we quantified the association between reading duration and the self-reported frequency of exhibiting dyslexia symptoms. Reading duration was positively correlated with self-reported dyslexia symptoms across all participants (r_{65} =.68; p <.0001, 95% CI$_r$ = [.545, .785]; Figure 3.3g). As expected, encountering dyslexia symptoms more frequently was linked to longer reading duration. Interestingly, we did not observe this relationship within the control (r_{30} = -.06; p =.75, 95% CI$_r$ = [-.459, .343]; Figure 3.3h) or dyslexia group itself (r_{33} = .21; p =.22, 95% CI$_r$ = [-.152, .522]; Figure 3.3i).

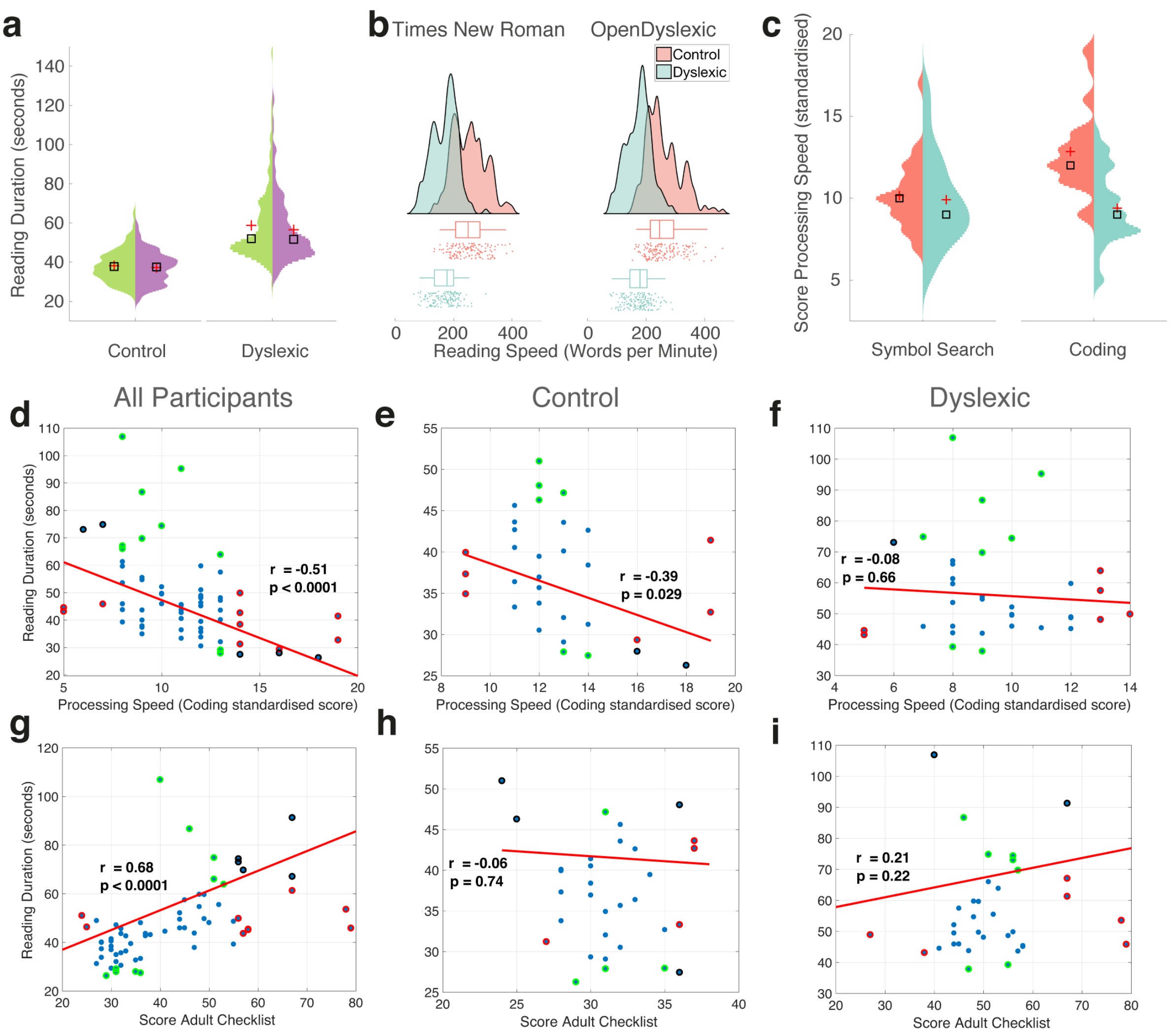


Figure 3.3. Reading duration, cognitive processing speed, and self-reported dyslexia severity. a) Median reading duration per trial by font and group. The left-hand side (i.e., green colour) of each violin plot depicts trials presented in Times New Roman; the right-hand side (i.e., purple colour) depicts trials presented in OpenDyslexic font. Red crosses denote group means and black squares denote group medians for each condition. **b)** Reading speed in words per minute (i.e., estimated speed if a trial's reading duration was shorter than one minute). **c)** Cognitive processing speed by font and group. Higher scored illustrate higher processing speed. The left-hand side of each violin plot depicts scores of the control group; the right-hand side depicts scores of the dyslexia group. Red crosses denote group means and black squares denote group medians. **d)** Bend correlation of reading duration with standardised Coding processing speed scores across all participants. Correlation coefficient (r) and p-value from robust bend correlation shown. Colours indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension 20% of data points were down-weighted. **e)** Bend correlation of median reading duration with standardised Coding processing speed scores for the control group. **f)** Bend correlation of median reading duration with standardised Coding processing speed scores for the dyslexia group. **g)** Bend correlation of reading duration with self-reported frequency of experiencing dyslexia symptoms across all participants. **h)** Bend correlation of reading duration with self-reported frequency of experiencing dyslexia symptoms for the control group. **i)** Bend correlation of reading duration with self-reported frequency of experiencing dyslexia symptoms for the dyslexia group.

We also asked participants about their preferred font at the end of the experiment. Sixty-six percent of dyslexic participants reported a preference for reading the IReST texts in OpenDyslexic font, whereas only 25% of control participants preferred reading the texts in this font (Figure 3.2d).

To subsume, OpenDyslexic facilitates reading comprehension across all participants with dyslexics exhibiting stronger benefits. On the contrary, dyslexics showed general deficits in reading speed that seemed to be linked to coding processing speed. Although most dyslexics preferred reading text in OpenDyslexic font, it did not help to increase their reading speed.

3.4.2 Eye movement results

In this study, our main focus was on investigating the effect of font on reading performance in dyslexia, and the explanatory power of reading-related eye movements. To reduce redundancy among our 12 eye-tracking measures during the analysis of reading-related eye movements, we identified three relevant principal components (henceforth, *components*) that explained 75.95% of the variance of all included eye-tracking measures. The first component predominantly represented measures of the total number of events per trial such as fixations, saccades, regressions, runs and the ratio of visited interest areas (henceforth, *number of events*). The second component represented the measures fixation to saccade ratio, scan path and number of blinks (henceforth, *visual search intensity*). The third component mainly represented median and maximum fixation duration as well as median saccade amplitude and the ratio of skipped words per trial (henceforth, *fixation duration*).

Our GLMM analysis used these three eye-tracking components (i.e., number of events, visual search intensity and fixation duration) as predictors, in addition to the predictors font and group. We found that none of the identified components nor their interaction with the predictors group or font showed significant power (i.e., at the nominal alpha level 5%) to predict reading comprehension on a single-trial basis (for details, see Table 3.3). Only the components visual search intensity ($Z = 1.876$, $p = .061$) and fixation duration ($Z = -1.763$, $p = .078$) yielded results trending towards this level of significance, with the model showing relatively low overall fit ($R^2 = .066$). However, post-hoc likelihood-ratio X^2 model comparisons showed that none of the predictors had significant power to predict reading comprehension.

Principal Component	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*Z*	*p*
Number of events	-0.0142	-0.173	0.144	0.0808	-0.176	0.8604
Visual search intensity	0.2425	-0.011	0.496	0.1292	1.876	0.0607
Fixation duration	-0.2416	-0.510	0.027	0.1370	-1.763	0.0779
Font	-0.0931	-0.680	0.494	0.2995	-0.311	0.7559
Group	-0.2583	-1.02	0.500	0.3869	-0.668	0.5044
Font * group	1.0045	-0.433	2.44	0.7333	1.370	0.1708
Font * number of events	0.0402	-0.240	0.321	0.1431	0.281	0.7786
Font * visual search intensity	0.1342	-0.294	0.562	0.2184	0.615	0.5388
Font * fixation duration	0.0123	-0.502	0.527	0.2626	0.047	0.9626
Group * number of events	0.1069	-0.221	0.435	0.1675	0.639	0.5231
Group * visual search intensity	0.3010	-0.202	0.804	0.2565	1.174	0.2405
Group * fixation duration	-0.1436	-0.839	0.552	0.3550	-0.405	0.6858

Table 3.3. Generalised linear mixed effects model predicting the reading comprehension of a trial as a function of principal components. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Contrarily, a second GLMM revealed that all three eye-tracking components, the predictor group, and the fixation duration-by-group and number of events-by-group interactions all showed significant power to predict reading duration (t = 27.37, p <.0001; t = 8.54, p <.0001; t = 13.21, p <.0001; t = -2.74, p =.006; t = -3.60, p =.0003, respectively; for details, see Table 3.4). Post-hoc likelihood-ratio X^2 model comparisons confirmed all main effects and the fixation duration-by-group interaction effect ($X^2(1)$ = 114.57, p < 0001; $X^2(1)$ = 37.866, p <.0001; $X^2(1)$ = 56.89, p <.0001; $X^2(1)$ = 11.82, p =.0006; $X^2(1)$ = 6.123, p =.0134, respectively). However, the number of events-by-group interaction was not confirmed by our model comparisons ($X^2(1)$ = 3.473, p =.0624). Thus, most interestingly, the results of this GLMM suggested that fixation duration increased to a larger extent with increasing reading duration in the dyslexia compared to the control group.

Further, it indicated that all eye-tracking components increased with longer reading duration across participants, and therewith corroborated the group difference in reading duration.

Principal Component	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*t*	*p*
Number of events	**4.818**	**4.47**	**5.16**	**0.1760**	**27.37**	**<.0001**
Visual search intensity	**1.6922**	**1.30**	**2.08**	**0.1981**	**8.54**	**<.0001**
Fixation duration	**2.7905**	**2.38**	**3.20**	**0.2112**	**13.21**	**<.0001**
Group	**-4.0598**	**-6.27**	**-1.85**	**1.1290**	**-3.60**	**<.0001**
Group * number of events	-0.7148	-1.42	-0.005	0.3622	-1.97	0.0484
Group * visual search intensity	-0.0418	-0.848	0.764	0.4110	-0.10	0.9191
Group * fixation duration	**-1.2286**	**-2.11**	**-0.350**	**0.4482**	**-2.74**	**0.0061**

Table 3.4. Generalised linear mixed effects model predicting the reading duration of a trial as a function of principal components and group. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Subsequently, we evaluated the power of our three eye-tracking components and the predictor group to predict the font of a trial. We observed significant predictive power of the main effects of all three components ($Z = 2.551$, $p = .0107$; $Z = -5.176$, $p < .0001$; $Z = 6.169$, $p < .0001$, respectively; Table 3.5), which were confirmed by post-hoc likelihood-ratio X^2 model comparisons ($X^2(1) = 9.1903$, $p = .0024$; $X^2(1) = 53.409$, $p < .0001$; $X^2(1) = 83.772$, $p < .0001$, respectively). The results of this GLMM indicated that the number of events and fixation duration decreased while the visual search intensity (i.e., total scan path and fixation to saccade ratio) increased on trials presented in OpenDyslexic font across participants.

Principal Component	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*Z*	*p*
Number of events	**0.5773**	**0.13**	**1.02**	**0.2263**	**2.551**	**0.0107**
Visual search intensity	**-2.4777**	**-3.42**	**-1.54**	**0.4787**	**-5.176**	**<0.001**
Fixation duration	**3.9219**	**2.68**	**5.17**	**0.6357**	**6.169**	**<0.001**
Group * number of events	-0.7330	-1.55	0.08	0.4165	-1.760	0.0784
Group * visual search intensity	-0.6995	-2.07	0.67	0.6969	-1.004	0.3155
Group * fixation duration	-0.1481	-1.82	1.52	0.8534	-0.174	0.8622

Table 3.5. Generalised linear mixed effects model predicting the font of a trial as a function of principal components. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

To investigate the effect of font on all eye-tracking measures in question in more detail without losing information due to dimensionality reduction, we calculated unbiased effect sizes (i.e., Hedges' g) of the effect of font for each eye-tracking measure and group separately. Dyslexics showed positive effect sizes, with 95% confidence intervals around the effect size that did not include zero (i.e., exclusion of zero indicates a significant effect) for a number of eye movement measures (Figure 3.5a; for details, see Table 3.6). These effects indicated larger median saccade amplitude (g_{Dys} =.91, g_{Con} =.81; Figure 3.4b), and a higher ratio of visited interest areas (g_{Dys} =.42, g_{Con} =.28; Figure 3.4d) with OpenDyslexic font in both groups (Figure 3.5a). In addition, our analysis yielded several significant negative effect sizes indicating shorter median fixation duration among both groups (g_{Dys} = -.54, g_{Con} = -.47; Figure 3.4a) as well as a smaller fixation to saccade ratio (g_{Dys} = -.28; Figure 3.4c) and a smaller ratio of skipped words per trial (g_{Dys} = -.44; Figure 3.4e) in the dyslexia group on OpenDyslexic trials. As visually assessed, these font effects were marginally larger in the dyslexia group (M_{Dys} =.565, M_{Con} =.51; absolute values; Figure 3.5a).

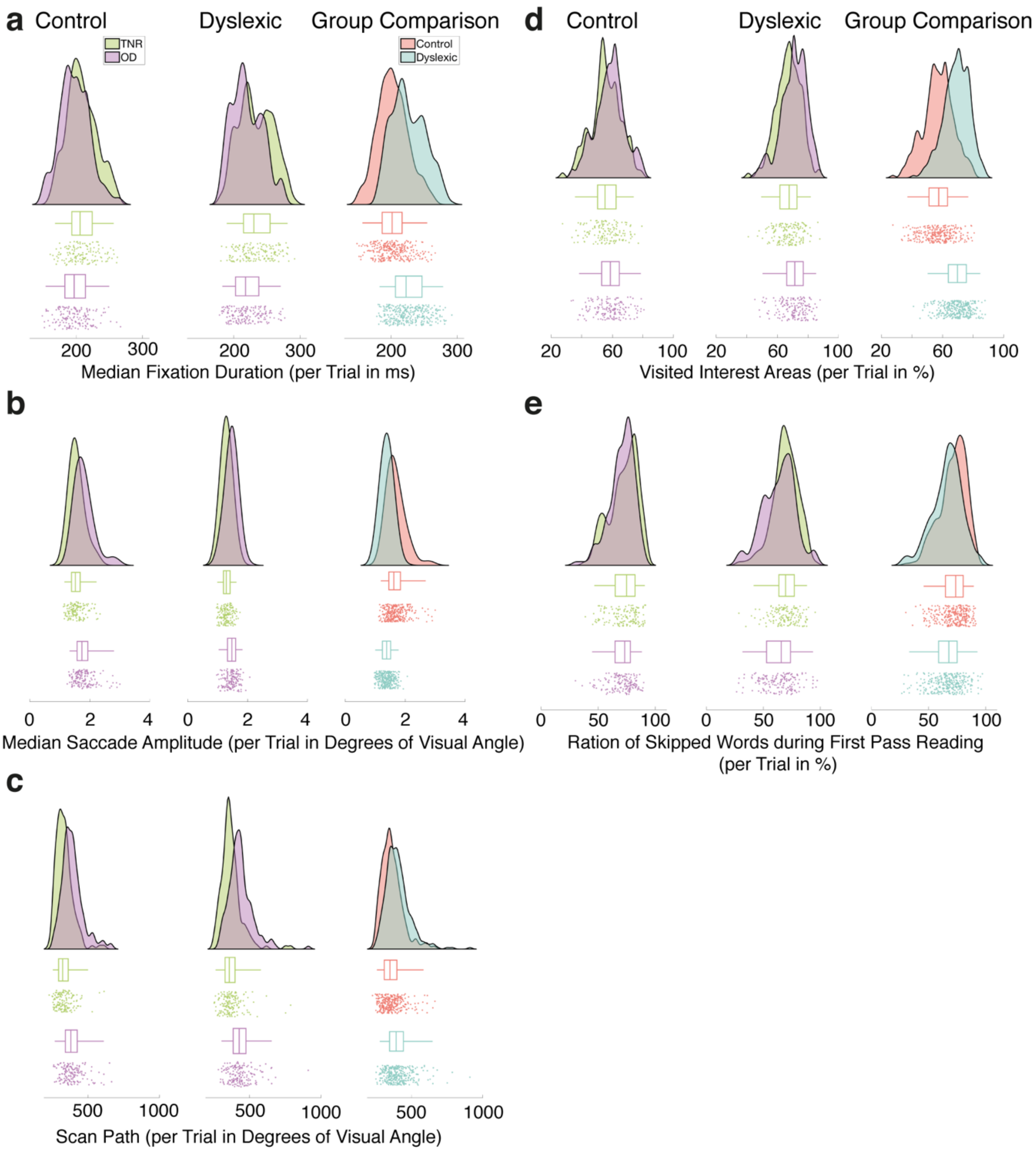


Figure 3.4. Eye-tracking measures per trial: fixation duration, saccade amplitude, scan path, skipped words, and visited interest areas. Plots display eye-tracking measures that showed significant within-group effects of font. The left two subpanels of each panel depict the font comparison by group, whereas the right subpanel depicts the group comparison collapsed across fonts. Scatterplots depict one average value per trial. **a)** Median fixation duration in milliseconds. **b)** Median saccade amplitude in degrees of visual angle. **c)** Scan path in degrees of visual angle. **d)** Ratio of visited interest areas in percent (i.e., the number of visited interest areas divided by the number of words of a trial). **e)** Ratio of skipped words during first pass reading in percent (i.e., all words that were skipped during first pass reading divided by the number of words of a trial).

On the contrary, we did not observe any significant effect sizes for measures representing the number of eye movement events per trial for either group (Figure 3.5a). However, after normalising the total number of eye movement events per trial by a trial's reading duration, we observed significant effect sizes in both groups for most measures representing the number of events (Figure 3.5b; for details, see Table 3.6). These effects indicated the occurrence of more events (i.e., number of fixations: g_{Dys} =.45, g_{Con} =.26, number of saccades: g_{Dys} =.6, g_{Con} =.52, and number of runs: g_{Dys} =.42, g_{Con} =.3) and a longer scan path on OpenDyslexic trials (g_{Dys} = 1.02, g_{Con} =.94; Figure 3.6a-e). Again, as visually assessed, all significant normalised effect sizes were larger in the dyslexia group (M_{Dys} =.623, M_{Con} =.505; Figure 3.5b). We did not find a significant effect of the number of regressions in either group (g_{Dys} = -.13, g_{Con} = -.1; Figure 3.5b).

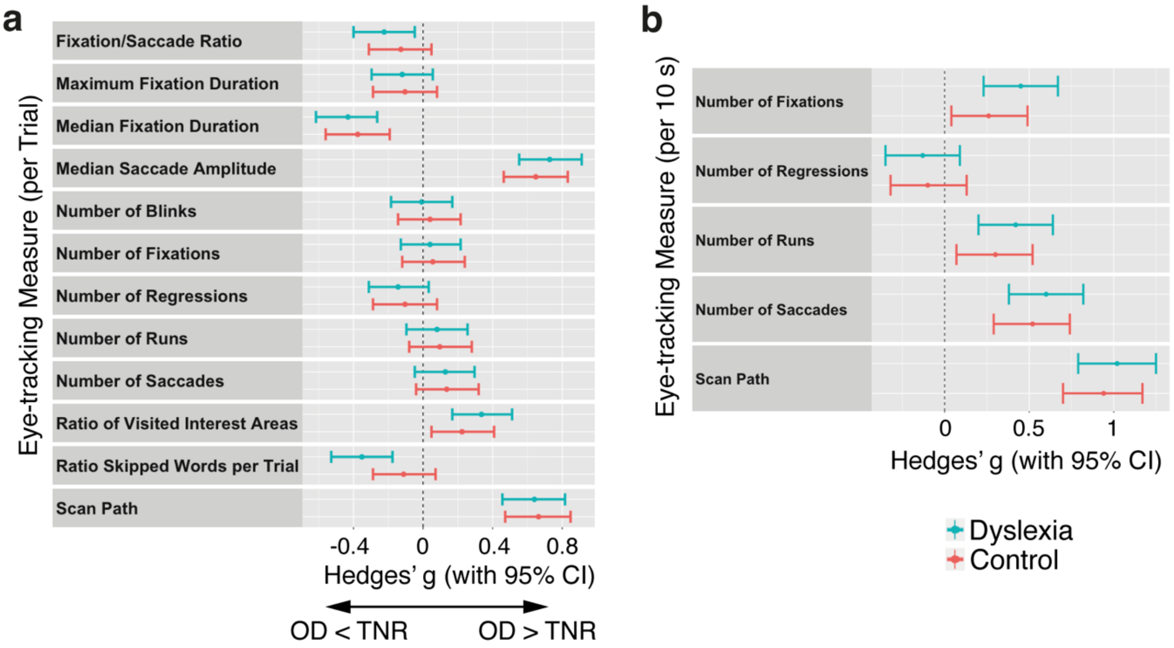


Figure 3.5. Effects sizes of the effect of font on various eye-tracking measures by group. Positive effect sizes (i.e., Hedges' g) illustrate a higher number of events or a larger ratio/amplitude on OpenDyslexic compared to Times New Roman trials. A negative effect size illustrates the opposite effect. Bars indicate the 95% confidence Interval for each effect size. Effect sizes were considered significant if the 95% confidence interval did not include zero. **a)** All eye-tracking measures included in the principal component analysis (i.e., one average value per trial). **b)** Selected eye-tracking measures normalised by a trial's reading duration and computed per 10 seconds. Please see Appendix B for detailed numbers corresponding to the effect sizes illustrated above.

Lastly, we quantified the tendency of forward saccades to deviate clearly from an accurate rightward forward movement or an accurate leftward regression by analysing the number and angles of saccades with an angle between ± 45° and ± 135°, termed directional shifts. Note, as part of this analysis, we excluded all other left-right saccades with an angle between 0° and ± 45° as well as 180° and ± 135°. In general, dyslexics exhibited a higher number of directional shifts on Times New Roman trials (t_{299} = 4.2624, p <.0001, g_{TNR} =.49, 95% CI_g = [.721, .262]; two-sample t-test), whereas we did not find such a significant difference in the number of directional shifts on OpenDyslexic trials (t_{332} = 1.5718, p =.1169, g_{OD} =.17, 95% CI_g = [-.043, .387]; two-sample t-test). Hence, deviations from normally expected left-right saccade patterns during reading occurred significantly more often among dyslexics only on Times New Roman but not on OpenDyslexic trials. These group-differences were corroborated by dyslexics' different angular pattern of directional shifts for both fonts ($k_{\mathrm{OD}} = 57{,}136$, $p_{\mathrm{OD}} =.001$; $k_{\mathrm{TNR}} = 40{,}852$, $p_{\mathrm{TNR}} =.001$, respectively). They expressed more directional shifts towards lower lines of text, while controls demonstrated the opposite pattern represented by more directional shifts towards upper lines ($M_{\mathrm{Dys\ OD}} = -65.56^{\circ}$, $SD_{\mathrm{Dys\ OD}} = 69.8^{\circ}$; $M_{\mathrm{Dys\ TNR}} = -59.99^{\circ}$, $SD_{\mathrm{Dys\ OD}} = 70.34^{\circ}$; $M_{\mathrm{Con\ OD}} = 75.97^{\circ}$, $SD_{\mathrm{Con\ OD}} = 68.76^{\circ}$; $M_{\mathrm{Con\ TNR}} = 74.11^{\circ}$, $SD_{\mathrm{Con\ TNR}} = 73.82^{\circ}$; Figure 3.6f). Corresponding to these group-differences, we found a negative effect of font on the number of directional shifts only within the dyslexia ($g_{\mathrm{Dys}} = -.23$, 95% $\mathrm{CI}_{g} = [-.45, -.016]$) but not the control group ($g_{\mathrm{Con}} =.12$, 95% $\mathrm{CI}_{g} = [-.103, .347]$), which indicated that OpenDyslexic helped to decrease the number of directional shifts among dyslexics.

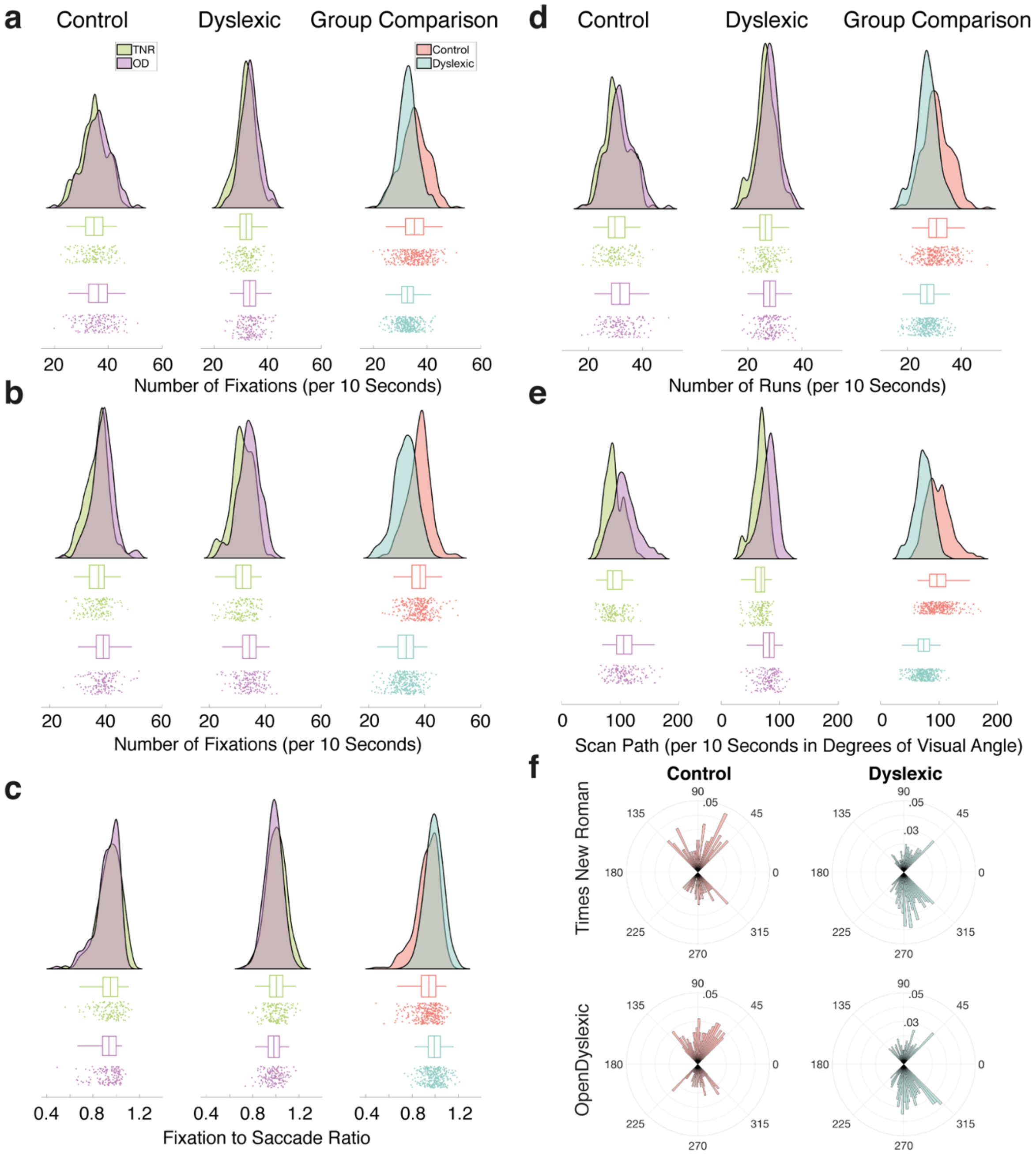


Figure 3.6. Eye-tracking measures per 10 seconds of reading duration: number of fixations, saccades, runs, fixation to saccade ratio, and scan path. Plots display eye-tracking measures that showed significant within-group effects of font. The left two subpanels of each panel depict the font comparison by group, whereas the right subpanel depicts the group comparison collapsed across fonts. Scatterplots display one value per trial normalised by 10 seconds of reading duration. **a)** Number of fixations. **b)** Number of saccades. **c)** Fixation to saccade ratio. **d)** Number of runs. **e)** Scan path in degrees of visual angle. **f)** Histograms of directional shifts by group and font across all trails. Only saccade angles between ± 45° and ±135° (displayed as 45/315° and 135/225°) qualified as directional shifts. 0° equals horizontal rightward direction of reading. All other saccades were excluded from this analysis.

3.5 Discussion

In this study, we investigated the effects of the specific dyslexia font OpenDyslexic on reading comprehension, reading duration, and visual processing strategy during the reading of standardised paragraphs of text IReST (Trauzettel-Klosinski & Dietz, 2012). Here, we found (1) better reading comprehension with OpenDyslexic across all participants (i.e., dyslexics and non-dyslexics) with larger benefits for dyslexics, (2) slower reading speed in the dyslexia group, which OpenDyslexic could not alleviate, (3) differences in a number of eye movement metrics as a function of the font a text was presented in (i.e., OpenDyslexic or Times New Roman), and (4) higher self-reported preference for OpenDyslexic among dyslexics.

Reading comprehension. Specifically, we observed improvements in reading comprehension with OpenDyslexic font across all participants, with larger improvements for dyslexics. In the literature reports of improvements in reading comprehension elicited by a dyslexia font are rare. Our finding gains importance due to the use of validated comprehension questions (Morrice et al., 2018), and paragraphs (i.e., ~150 words) of standardised texts (Trauzettel-Klosinski & Dietz, 2012), which contained more words than those used in most previous studies examining the impact of fonts on dyslexic readers (Kuster et al., 2018; Rello & Baeza-Yates, 2013, 2016; Wery & Diliberto, 2017). Previous studies have reported no improvements with dyslexia fonts (Kuster et al., 2018; Marinus et al., 2016; Rello & Baeza-Yates, 2013; Wery & Diliberto, 2017; Zikl et al., 2015), but have only measured reading accuracy and not reading comprehension using validated questions. Therefore, we cannot directly compare results. Reading accuracy is a less complex measure of reading success as it only measures whether a word is pronounced correctly but not whether its content has been encoded, understood and retained successfully. In this respect, our results provide empirical evidence for Wery and Diliberto's (2017) speculations of seeing positive effects of OpenDyslexic on reading comprehension due to the additional level of complexity examined by this measure. The observed improvements in reading comprehension demonstrate that such improvements are achievable in an adult population with years of reading practice, and which is familiar with reading text in Times New Roman font. This familiarity and learning effects may have even decreased the negative effects of Times New Roman, underlining the relevance of the observed improvements when using OpenDyslexic.

Psychophysiological mechanisms. The observed increase in reading comprehension among our dyslexic sample raises the question of potential mechanisms by which OpenDyslexic facilitates reading comprehension. Eye movements are well-suited to provide insights into such a mechanism. Here, we demonstrated a link between our three identified eye-tracking components and the font of a given trial. Specifically, we observed fewer events, higher visual search intensity, and shorter fixation durations on OpenDyslexic trials compared to Times New Roman trials across all participants. Also, the OpenDyslexic font led participants to visit more interest areas per trial. These differences suggest that OpenDyslexic eases general visual processing of text written in this font, whereby it facilitates efficient processing of the content. Particularly, the observed increase in the number of fixations while also seeing a decrease in median fixation duration and fixation to saccade ratio with OpenDyslexic provide evidence for this interpretation. The fixation to saccade ratio is a measure that is associated with the amount of information processing, where a lower ratio indicates less information processing and more search activity (Goldberg & Kotval, 1999). More evidence for increased visual ease comes from a higher number of saccades, the expression of larger saccades, and a longer scan path per 10 seconds of reading duration on OpenDyslexic trials. As previously shown, a font that is easier to process leads to fewer (Slattery & Rayner, 2010) and shorter fixations, and larger saccades (Rayner et al., 2006). In the present study, the observed larger saccade amplitudes may simply be a result of OpenDyslexic’s increased intra- and inter-word spacing (i.e., more white space between individual letters and words) that needed to be traversed by the readers’ eyes in order to read the same number of characters. However, this does not take away from the validity of the observed decreases in fixation duration and fixation to saccade ratio.

Furthermore, we found a larger number of directional saccade shifts (i.e., falsely programmed saccades, which are neither a clear rightward forward saccade nor a leftward regression) in our dyslexia group in the Times New Roman trials. Along the same lines, dyslexics exhibited a significant increase in the number of directional shifts when compared to non-dyslexics only on Times New Roman trials, whereas such a difference was absent on OpenDyslexic trials. Hence, these results suggest that a previously reported increased loss of fixation in dyslexia (Vagge et al., 2015) may be reduced by OpenDyslexic, or that the properties of OpenDyslexic simply help guide the dyslexic eye more successfully, allowing dyslexics to be better able to track the lines of text.

Together, these behavioural and eye movement results illustrate a font induced shift in participants' reading strategy, which is a likely consequence of OpenDyslexic's unique visual properties such as unique letter strokes and increased intra- and inter-word spacing. Particularly, the increased spacing of specific dyslexia fonts seems to be the driving mechanism behind their benefits (Marinus et al., 2016). Since serifs and close words surrounding a fixated word can function as effective distractors, particularly in dyslexia, increases in spacing coupled with the fonts' absent serifs may reduce the visual complexity of text. A reduction in visual complexity leads to lower levels of visual crowding—a negative consequence of visual complexity—that has previously been found in dyslexia (Callens et al., 2013; Gori & Facoetti, 2015). Also, since letter complexity is inversely related to letter identification efficiency (Pelli et al., 2006), OpenDyslexic's lower visual complexity may lead the dyslexic reader to focus more easily on the encoding of the fixated foveal text. Thereby it would allow for shorter processing times and easier parsing of a line or an entire paragraph of text. Easier parsing could also serve as explanation for the reduction in the number of directional shifts we observed. However, increases in spacing mean that less content (i.e., fewer characters) can be encoded per fixation resulting in more searching (i.e., a lower fixation to saccade ratio and more fixations) and more visited interest areas per trial. Our results are congruent with this devised theoretical account.

Reading speed. In the present study, dyslexics exhibited much slower reading speed independently of the font a text was presented in. Generally, slow (or slower) reading speed and a lack of reading fluency is a frequent finding in the adult dyslexia literature (e.g., Lefly & Pennington, 1991; Lyon et al., 2003; Shaywitz et al., 2003), which our result substantiates. Since reading speed has previously been associated with slower processing speed in dyslexics (Breznitz & Misra, 2003) and non-dyslexics (Lobier, Dubois, & Valdois, 2013), attributing the observed deficit to this factor would be obvious. However, we did not observe generally slower non-linguistic processing speed in our dyslexia group. In fact, dyslexics processing speed seems to be dependent on the type and level of processing speed tested. In this respect, dyslexics demonstrated slower processing speed on the Coding test—a test that assesses a high level of working memory capacity, whereas we did not find any difference on the Symbol Search test—a processing speed test requiring sequential visual matching only on a line-by-line basis. Here, we demonstrated the substantial role of working memory capacity for reading speed across the spectrum of university readers based on a correlation between slower coding processing speed and reading speed across all participants. Specifically, our results indicate that adult dyslexic university students suffer from slower non-linguistic processing speed only when high levels of visual working memory are required, but do not allow to assume a general non-linguistic processing speed deficit. Also, these results suggest that coding processing speed may play a part in dyslexics reading speed deficit.

Furthermore, we demonstrated a link between reading speed and prolonged median fixation duration in the dyslexia group, as revealed by a significant group-by-fixation duration interaction in our mixed effects model predicting reading duration. In general, longer fixations reflect an increased cognitive load; a relationship that has previously been reported in non-dyslexics for reading (Just & Carpenter, 1980) and visual search (de Greef, Lafeber, van Oostendorp, & Lindenberg, 2009). Consistent with the above findings, dyslexics' longer fixations may indicate their need to recruit more cognitive resources for decoding local entities of text (i.e., individual letters and overall word form).

In addition, longer median fixation durations provide evidence for a smaller perceptual span, since it has been shown that average fixation duration increases with decreasing size of the perceptual span during reading (Choi, Lowder, Ferreira, & Henderson, 2015), and a smaller perceptual span is linked to slower visual search speed in linear shaped arrays (Phillips & Edelman, 2008). A smaller perceptual span would result in the processing of fewer characters, and consequently less information, at once, whereby it may help to decode the fixated word. Reports of a smaller perceptual span in dyslexics (Rayner, Murphy, Henderson, & Pollatsek, 1989), and slower readers (Rayner et al., 2010) corroborate this interpretation in the context of the present study. Although we cannot conclusively answer here whether a smaller perceptual span is a direct result of increased cognitive load or merely a co-occurrence, our findings suggest that dyslexics' slower reading speed is a consequence of both factors. Future research could directly study the exact causal relationship between these factors in adult dyslexia.

The aforementioned mechanisms are plausible explanations for generally slower reading speed in dyslexia, but do not provide an explanation for the fact that neither the present nor previous studies have found substantial improvements in reading speed with the dyslexia fonts OpenDyslexic (Rello & Baeza-Yates, 2016; Wery & Diliberto, 2017; Zikl et al., 2015) or Dyslexie (Kuster et al., 2018; Marinus et al., 2016). Two specific dyslexia fonts that both have similar design properties (see Figure 1.1a). Based on our results, and in agreement with results and their interpretation from a study that compared two fonts with varying spacing (i.e., Consolas and Georgia) in non-dyslexics (Rayner et al., 2010), we propose a trade-off between fixation duration and fixation frequency as a mechanism that would lead to better reading comprehension albeit similar reading speed. Thus, in this framework, increased ease of processing would lead to faster reading speed. However, it would be outweighed by skipping fewer words, whereby more fixations on more words allow for improved reading comprehension.

Taken together, our results suggest that even though aberrant eye movements during reading are one facet of dyslexia, OpenDyslexic leads to a reduction in eye movement errors, and increases the ease in processing of text. Thus, it seems to reduce a dyslexic's cognitive load and facilitates reading comprehension.

Font preference. As expected, we observed a higher preference for OpenDyslexic in the dyslexia group (preference$_{\text{Dys}}$: 66%, preference$_{\text{Con}}$: 25%). Interestingly, previous studies have failed to find a preference for dyslexia fonts among dyslexics. These studies have reported a preference for Arial over Dyslexie and Times New Roman on the word level, and for Arial over Dyslexie (Kuster et al., 2018), and Verdana and Helvetica over OpenDyslexic on the sentence-level (Rello & Baeza-Yates, 2013, 2016). We consider two plausible explanations for these contradicting results. Firstly, the previous studies that did not report a preference for the tested dyslexia font included commonly used proportional sans-serif fonts (i.e., fonts with variable space between characters and without serifs) in their comparisons. These sans-serif fonts include Arial and Verdana, whose letters have been found to be more legible compared to fonts with serifs such as Times New Roman (Woods, Davis, & Scharff, 2005). Given that font familiarity can have beneficial effects for adult readers (Sanocki & Oden, 1991; Walker, 2008), it is plausible that including common easily legible fonts such as Arial and Verdana in font comparisons introduces a bias towards a preference for these more familiar fonts. Secondly, specific dyslexia fonts seem to aid reading predominantly through their wider spacing (Marinus et al., 2016). The resulting gains in visual ease are likely accumulating with increasing text length since font effects on eye movement behaviour represent small changes in subconscious processes. Therefore, studies presenting only single words or one sentence at a time (Kuster et al., 2018; Rello & Baeza-Yates, 2016) might not offer enough benefits to lead to conscious preference ratings in favour of dyslexia fonts. In these studies, OpenDyslexic may have seemed rather distracting to the unfamiliar reader outweighing potential conscious benefits. Therefore, presenting longer texts has presumably allowed for sufficient familiarisation with OpenDyslexic and the summation of small benefits leading to dyslexics' conscious preference for OpenDyslexic. Note, beyond these two plausible explanations, we also consider a placebo bias of participants' preference ratings a possibility due to the disclosure of the involvement of an easily by name identifiable dyslexia font (i.e., OpenDyslexic) prior to the experiment (Jamshidian, Hubbard, & Jewell, 2014). The inclusion of a third non-serif 'control' font or avoiding mentioning the dyslexia font's name throughout the recruitment and experiment could have abolished potentially confounding placebo effects on preference ratings.

Limitations. The design of the present study has given rise to four potential limitations: (1) bilingual participants could have been disadvantaged (i.e., native speakers of English and French) with respect to reading comprehension, (2) dyslexics might have become more fatigued by reading entire passages of text, (3) a lack of statistical power due to high model complexity might have not allowed to establish a direct link between eye-tracking components and reading comprehension, and (4) disclosing that a dyslexia font is being tested prior to participation while also using its real name (i.e., 'OpenDyslexic'), which reveals its specific purpose and focus on the dyslexia group.

First, we found that bilingualism did not impair reading comprehension. Quite the contrary, bilingual dyslexics did not perform worse than their fellow monolingual native English-speaking dyslexics, and bilingual non-dyslexics showed even better reading comprehension than their monolingual counterparts. This might be because participants were tested at an English-speaking university, and consequently are likely to have good to excellent English reading and comprehension skills. Second, to rule out potential effects of fatigue, we presented university students with only 10 texts of about 150 words that were designed for grade six reading comprehension level. The length of the presented texts was even shorter than that of most abstracts of scientific articles (i.e., ~250 words), which are common readings for university students. Therefore, text length and difficulty should not have posed considerable challenges for university students, even with dyslexia. In addition, participants were given the opportunity to take self-timed breaks between trials but only seldom considered this necessary. Also, the order and font of all texts were randomised across participants, and the main interest of our eye movement analysis was placed on the within-group effect of font. The strongest evidence against the fatigue effect is provided by the absent difference in reading durations that we observed in the dyslexia group. We could have tested the fatigue effect directly by splitting trials into two analysis bins based on their reading duration (i.e., slow and fast). However, due to the aforementioned reasons and the lack of any group-level effect on reading comprehension, we did not consider this necessary. Third, we were unable to establish a direct link between our identified eye-tracking components and the increases in reading comprehension on a single-trial basis. This lack of statistical significance may have been a consequence of the complexity of the chosen mixed effects model coupled with the relatively small number of error trials (~9% of all trials). Therefore, we suggest employing more concise models in future research that only include our identified eye-tracking components as predictors whilst excluding the predictors group, font, and relevant interactions. Fourth, disclosing openly in study recruitment materials that the purpose of this study was to test the efficacy of a dyslexia font, and explicitly mentioning the font's name, which comprises the word 'dyslexia', in the questionnaire that was used to obtain individual preference ratings of our two fonts may have increased the preference for OpenDyslexic among dyslexics and against it among non-dyslexics. If such a bias was introduced, it may have been a consequence of dyslexia's currently still negative connotation in society. In the future, we recommend to avoid naming any tested font explicitly to reduce the likelihood of introducing conscious and subconscious behavioural biases.

Conclusion. We observed better reading comprehension across all participants with even larger benefits among dyslexics as a result of reading entire paragraphs of text in the specific dyslexia font OpenDyslexic. However, OpenDyslexic did not lead to faster reading speed in any group, and dyslexics generally exhibited slower reading speed independently of font. In both groups, reading texts in OpenDyslexic resulted in an increase in the number of eye movement events but a decrease in median fixation duration. Additionally, dyslexics exhibited a lower fixation to saccade ratio and less directional shifts with OpenDyslexic. This pattern of results illustrates that OpenDyslexic changes the visual reading strategy, leading to more efficient processing of written content and increased visual ease. Crucially, since these improvements come without disadvantages in reading speed for anyone, our findings have broad implications for the presentation of educational materials, a variety of everyday documents and online texts. Being preferred by most dyslexics reinforces the positive effects and suggests wider use of the OpenDyslexic font.

Chapter 4. Temporal characterisation of audio-visual non-linguistic perceptual decision making in adult dyslexia.

4.1 Summary

Recent evidence has shown that adults with dyslexia exhibit obvious fundamental deficits spanning multiple sensory systems. Such deficits extend beyond the well-established linguistic difficulties when performing simple multisensory decision tasks such as integrating beeps and flashes. These findings suggest that deficits even start as early as the initial perceptual encoding of the sensory evidence. Particularly, dyslexics reading impairments are believed to be a consequence of deficient integration of congruent audio-visual information, a process required for the development of reading proficiency. However, it remains poorly understood whether dyslexic adults exhibit similar impairments when integrating audio-visual evidence in a non-linguistic perceptual decision task.

To address this question, we trained 37 dyslexics and 31 age-matched controls on separate speeded image (face versus car) and sound (speech versus car) categorisation tasks. Behavioural and EEG data were then collected using visual and audio-visual trials. Here, we exploited EEG components from our previous work in non-dyslexics as reference points to investigate the extent to which audio-visual integration affects early sensory evidence encoding ('early') or later decision-related stages ('late') in dyslexia using a linear multivariate discriminant analysis. This analysis classified stimulus- and response-locked EEG data between face versus car trials for each modality separately, and in turn, produced a temporal profile of the single-trial component amplitudes.

We found increased decision accuracy and slower response times during audio-visual trials for both groups. However, overall, dyslexics showed worse performance than controls. When comparing audio-visual to visual trials, we observed that while dyslexics exhibited an increase in the magnitude of an EEG component situated in-between the early and late processing stages, non-dyslexics, conversely, exhibited increased component amplitudes for a later post-sensory EEG component, consistent with a post-sensory influence of audio-visual integration. Our neural results suggest that adult dyslexics benefit from congruent

audio-visual evidence of noisy perceptual stimuli to a similar extent but adopt a different neural process to achieve these improvements.

4.2 Introduction

Imagine you are standing at a bus stop reading a longer eye-catching poster on a rainy day. Then you hear a muffled sound and must decide in an instant whether this sound signals the imminent arrival of your bus, which you have to wave down, or whether it is a friend calling for you. Our brains are presented with these types of noisy, fast-paced categorisation decisions numerous times every day. Such ubiquitous perceptual decisions seem to be easier when the human brain can draw back on multisensory evidence. A large body of literature shows that additional auditory evidence facilitates performance in the form of higher decision accuracy and shorter reaction times on a variety of audio-visual perceptual decision tasks in non-dyslexics (Chen et al., 2011; Gleiss & Kayser, 2014a; Kayser et al., 2017; Molholm et al., 2002; Sadaghiani et al., 2009; Sperdin et al., 2009; Werner & Noppeney, 2010).

In contrast, such a behavioural gain might not be achievable for individuals affected by the specific neurobiological learning disability dyslexia. Dyslexia is a developmental condition that has been found to manifest itself in impaired phonological processing, whereby efficient mapping of auditory speech sounds onto their corresponding visual letters is hampered (e.g., Pennington et al., 1990; Ramus, 2003; Wagner & Torgesen, 1987). These impairments have given rise to the eponymous phonological theory, which postulates those as the main cause of dyslexia (e.g., Snowling, 1980, 1981). Phonological awareness is a prerequisite for the development of proficient literacy skills. This is of particular importance in the context of this study, since developing phonological awareness requires the implicit and fast integration of audio-visual information across both modalities.

This traditional view associates dyslexia almost exclusively with deficits in language-related tasks (American Psychiatric Association, 2013; Lyon et al., 2003). However, a growing body of evidence calls this view into question by showing that children (Widmann et al., 2012) and adults (Blau et al., 2009; Francisco, Jesse, Groen, & McQueen, 2017; Hairston et al., 2005; Harrar et al., 2014; Jaffe-Dax et al., 2015) with dyslexia exhibit obvious fundamental deficits spanning multiple sensory systems. Such impairments occur even when performing simple audio-visual integration and temporal judgement tasks that do not require any linguistic processing for successful performance (for reviews, see Schulte-Körne & Bruder, 2010; Stein, 2018a, 2018b). Some studies even suggest that deficits affect the decision process as early as the initial perceptual encoding of the evidence (Jaffe-Dax et al., 2015; Mittag et al., 2012; Widmann et al., 2012). This growing body of evidence suggests that fundamental sensory impairments in audio-visual modalities and their cross-modal integration might as well be one factor for hampered development of linguistic proficiency in dyslexia. Despite the aforementioned findings, it remains elusive whether dyslexic adults also exhibit impairments when integrating audio-visual evidence during non-linguistic perceptual decisions discriminating between noisy real-world objects.

In the context of audio-visual perceptual decision making, the contribution of attention warrants a closer look given its substantial role during perceptual decision making (Heekeren et al., 2008) and multisensory integration (Talsma et al., 2010). Attention can be a mechanism for auxiliary multisensory enhancement (e.g., Fernández, Visser, Ventura-Campos, Ávila, & Soto-Faraco, 2015) and has been related to excitability changes in audio-visual decision making paradigms (Gleiss & Kayser, 2014a, 2014b; Kayser et al., 2017). Interestingly, many of the same systems associated with the neuronal architecture of perceptual decisions have also been associated with several feedforward and feedback processes of attention (Amso & Scerif, 2015). Not only do these brain systems underlie developmental differences, but they also engage the same areas and connections (i.e., mainly functional connections between the prefrontal and parietal cortices), which have previously been reported to show aberrant patterns of activity and connectivity in dyslexia (Finn et al., 2014; Shaywitz et al., 2006). In addition, dyslexics of all ages exhibit impairments in visual attention (Facoetti, Paganoni, Turatto, et al., 2000; Heiervang & Hugdahl, 2003; Vidyasagar & Pammer, 1999, 2010).

To probe a fundamental deficit in audio-visual gain exploitation in adult dyslexia in the absence of any linguistic task demands, we employed a two-alternative forced-choice task that used complex real-world stimuli, namely degraded images of faces and cars and noisy human speech and car-related sounds. Previous visual studies, using the same face versus car forced-choice task and single-trial classifier of the EEG data (Parra, Spence, Gerson, & Sajda, 2005; Sajda, Philiastides, & Parra, 2009), revealed two distinct temporal components that characterise the neural visual perceptual decision making process, referred to as early and late (Diaz et al., 2017; Philiastides & Sajda, 2006; Philiastides et al., 2006; Ratcliff et al., 2009). These occur around 170 and 300 ms post image presentation and represent the encoding of sensory evidence and post-sensory decision-related processing, respectively. Our single-trial information-mapping approach allowed us to develop a mechanistic account of the temporal neural components involved in audio-visual non-linguistic decision making. Here, we exploited these temporal components as reference points for formulating our hypotheses and evaluating potential audio-visual enhancements within the neural decision making process.

Our hypotheses for this study were two-fold. Firstly, based on existing literature, we expected to see classic—behavioural and neural—markers of decision-related processes and audio-visual integration in the non-dyslexic (control) group; namely improvements in task-related decision performance with added auditory evidence that are reflected in the modulation of post-sensory neural activity. Conversely, we hypothesised that dyslexics benefit less from additional auditory evidence on audio-visual trials in the form of worse decision accuracy and slower response times compared to control participants. Secondly, based on previous findings describing deficits in early stimulus encoding (Jaffe-Dax et al., 2015; Widmann et al., 2012) and deficits in attention (e.g., Beidas et al., 2013) in adult dyslexia, we also hypothesised to find discrepancies in early sensory and attention-related EEG components in this group, which would suggest a general difference in temporal processing (architecture) in adult dyslexia.

4.3 Materials and methods

4.3.1 Participants

Here, we tested 38 dyslexics ($male_{\text{dys}}$ = 18, $female_{\text{dys}}$ = 20) and 31 ($male_{\text{con}}$ = 15, $female_{\text{con}}$ = 16) age-matched controls ($Mean\ age_{\text{dys}}$ = 22.46, SD_{dys} = 4.46; $Mean\ age_{\text{con}}$ = 24.5, SD_{con} = 4.87) on a speeded (face versus car) categorisation tasks. All participating subjects were right-handed, native English-speaking adults who were attending university or had been in the past. All participants had normal or corrected-to-normal vision and reported no history of neurological disorders. Participants with dyslexia provided proof of their dyslexia in the form of an official diagnosis (*Mean age*$_{\text{diagnosis}}$ = 16.16, *SD*$_{\text{diagnosis}}$ = 5.71). Nevertheless, we tested all participants for their level of dyslexia-related issues using self-report scores from an adult checklist (Smythe & Everatt, 2001). Written informed consent was obtained from all participants in accordance with the guidelines of the Centre for Cognitive Neuroimaging at the University of Glasgow. All participants were paid £24 for taking part in both days of this experiment and £12 for attending only the first day. This study was approved by the ethics committee of the College of Science and Engineering at the University of Glasgow (CSE 300150102).

4.3.2 Stimuli and experimental procedure

Stimuli. We used a set of 15 face and 15 car greyscale images (image size 670x670 pixels), adapted from our previous experiments (Diaz et al., 2017; Philiastides & Sajda, 2006; Philiastides et al., 2006). Face images were selected from the face database of the Max Planck Institute of Biological Cybernetics (Troje & Bülthoff, 1996) and car images were sourced from the internet. Both image categories contained an equal number of frontal and side views (up to ± 45 degrees). All images were equated for spatial frequency, contrast and luminance, and had identical magnitude spectra (average magnitude spectrum of all images in the database). We manipulated the phase spectra of the images using the weighted mean phase technique (Dakin, Hess, Ledgeway, & Achtman, 2002), whereby we changed the amount of sensory evidence in the stimuli as characterised by their percentage phase coherence. Four levels of sensory visual evidence (27.5%, 30%, 32.5% and 35%) were used for this study in order to manipulate task difficulty (see Figure 4.1c for examples). These levels were based on our previous studies (Diaz et al., 2017; Philiastides et al., 2014; Philiastides & Sajda, 2006; Philiastides et al., 2006) as they are known to result in performance spanning the psychophysical threshold. We displayed all pictures on light grey background (RGB [128, 128, 128], in PsychoPy RGB [0, 0, 0]).

Auditory sounds functioned as cues in addition to the visually presented images. Cues were either human speech or car-related sounds obtained from online sources. They were sampled at a rate of 22.05 kHz and stored as .wav files. In

MATLAB (version 2015a, The MathWorks, 2015, Natick, Massachusetts), we added a 10 ms cosine on/off ramp to reduce the effects of sudden sound onsets and normalised all sounds. Subsequently, we reduced the intensity of these normalised sounds by lowering their amplitude by 80%. Sounds were embedded in Gaussian white noise and the relative amplitude of the sounds and noise was manipulated to create 17 different levels of relative noise-to-signal ratios (12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, 93.75%, 100%, 112.5%, 125%, 137.5%, 150%, 162.5%, 175%, 187.5% and 200%). The resulting noisy speech and car-related sounds were presented binaurally for 50 ms through Sennheiser stereo headphones HD 215.

The stimulus display was controlled by a Dell 64 bit-based machine (16 GB RAM) with an NVIDIA Quadro K620 (Santa Clara, CA) graphics card running Windows Professional 7 or Linux-x86_64 and PsychoPy presentation software (version 1.83.04; Peirce, 2009). All images were presented on an Asus ROG Swift PG278Q monitor (resolution, 2560x1440 pixels; 96x96 dots per inch; refresh rate set to, 120 Hz). Participants were seated 75 cm from the stimulus display, and each image subtended approximately 6x6 degrees of visual angle.

Task. We used an adapted audio-visual version of the widely used visual face versus car image categorisation task (e.g., Diaz et al., 2017; Philiastides & Sajda, 2007; Philiastides & Sajda, 2006; Philiastides et al., 2006). Our adapted two-alternative forced-choice task required participants to decide whether they saw an image of a face or a car on the screen. For half of the trials, participants were also given an additional auditory cue in the form of a sound that was congruent with the picture’s content. Audio-visual face trials were accompanied by a human speech sound, whereas audio-visual car trials were accompanied by car-related sounds, such as squeaking tyres or a slammed door. All pictures, and on audio-visual trials also sounds, were presented for 50 ms in the centre of the screen and to both ears, respectively. During audio-visual trials we presented pictures and sounds simultaneously. Participants were asked to indicate their decision via button press with their right hand on a standard keyboard as soon as they had formed a decision. The response deadline was set at 1.5 seconds. Participants were asked to indicate their decision as soon as they had formed it. This experimental paradigm required participants to attend a training and a testing session at the same time on two consecutive days.

On the first day, participants received behavioural training to familiarise themselves with the task (Figure 4.1a). They were asked to perform three separate simple categorisation tasks: (1) a visual image discrimination task (face versus car), (2) an auditory sound discrimination task (speech versus car) and (3) an audio-visual discrimination task (face/speech versus car). To facilitate adaptation to the task and moderate learning, participants were given visual feedback following each response on all three training tasks that lasted for 500 ms. We gave participants three types of feedback in the form of showing the following coloured written words in the centre of the screen: ‘Incorrect’ written in red and ‘Correct’ written in green for trials on which participants responded within the response deadline, and ‘Too slow’ written in blue when they exceeded the response deadline. Feedback was followed by an inter-trial interval that varied randomly between 1 and 1.5 seconds. During the visual training task, we used the same images and all four levels of visual coherence as on the second day (i.e., the testing day). During the auditory training task, we presented sounds to participants using eight different levels of relative noise-to-signal ratios (12.5%, 37.5%, 62.5%, 93.75%, 125%, 150%, 175%, and 200% of added noise). We estimated subject-specific noise levels supporting individual perithreshold performance (i.e., ~70% decision accuracy), including levels that might have fallen in between the eight noise-to-signal ratios used in this training task (from the larger set of 17). This design ensured that participants received similar relative levels of additional auditory information during audio-visual trials, whereby we accounted for inter-individual differences in auditory perception, independently of visual image difficulty.

In total, on the training day, we presented 480 trials for each of the visual and auditory discrimination training tasks split into four blocks of 120 trials with a 60 second rest period between blocks. However, we presented only 240 trials, split into two blocks, during the audio-visual training task. Taken together, all three training tasks lasted approximately 55 minutes on day one.

On the second day, the testing day, we collected behavioural and EEG data using visual (unisensory) and audio-visual (multisensory) trials (Figure 4.1b). Specifically, we used four levels of visual noise, but only one (subject-specific) auditory difficulty level, obtained at perithreshold performance during training.

Data presentation employed the same task timings as outlined above for the inter-trial interval, presentation duration, and decision deadline on both days. However, crucially, we did not give any feedback, and visual and audio-visual trials were presented in a random order during the testing day. By using only one auditory noise level per participant on the testing day, we kept the amount of additional provided auditory evidence constant across trials. This allowed us to evaluate the effects of auditory benefit at different levels of visual coherence as only the sensory evidence provided by the pictures varied from trial to trial.

Overall, on the second day, we presented 720 trials—divided equally between the two stimulus categories—in short blocks of 60 trials with 60-second breaks between blocks to allow for appropriate rest periods during the task. On the testing day, the entire experiment lasted approximately 45 minutes. Exclusively, data from the testing day were included in all subsequent behavioural and EEG data analyses.

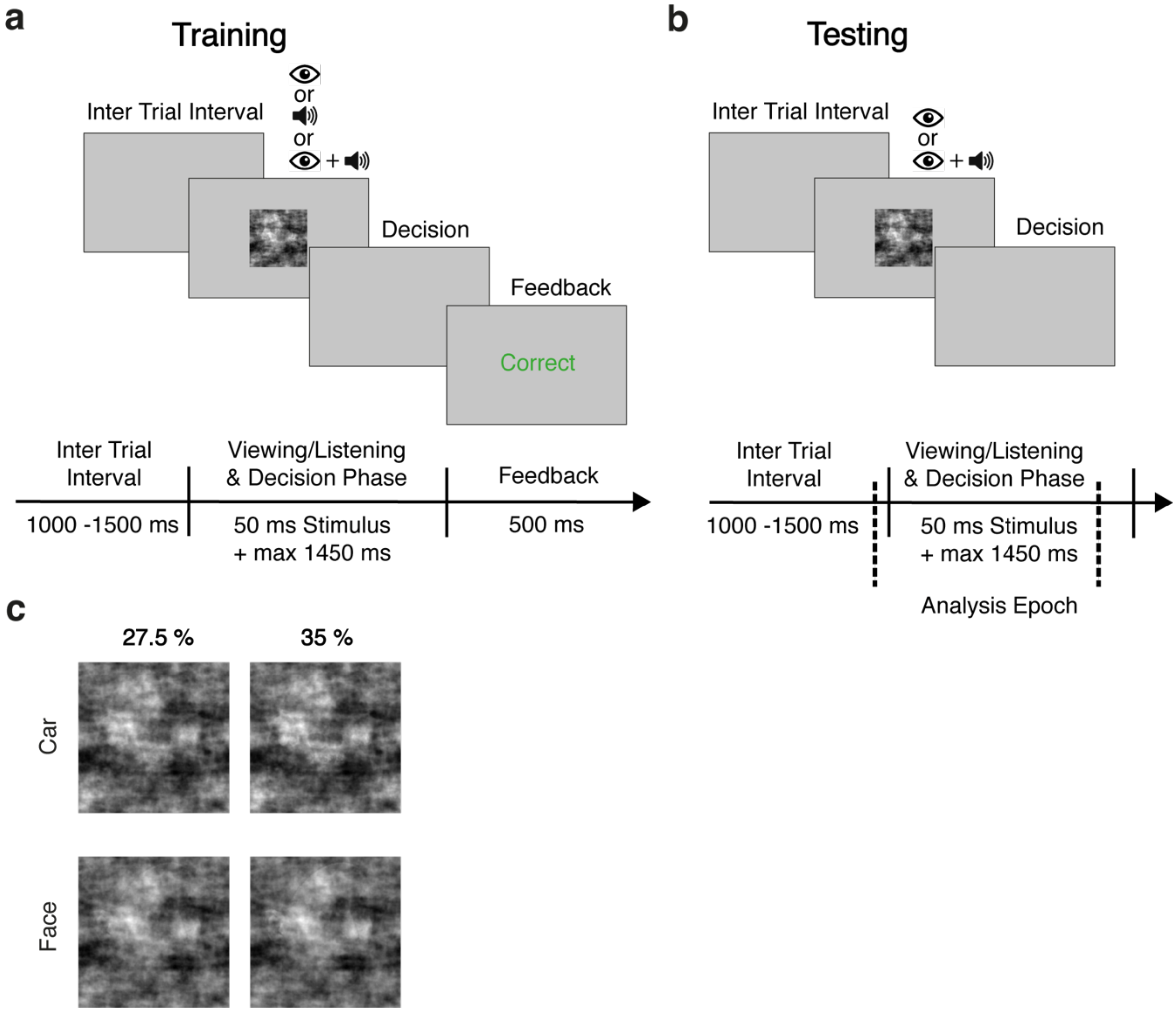


Figure 4.1. Experimental design and example of visual stimuli. a) Schematic representation of the experimental task illustrating the order of presented events for one trial on the training day. **b)** Order of the presented events for one trial on the testing day. Dashed lines indicate the chosen EEG analysis epoch. **c)** Examples of car (top) and face (bottom) images of the most difficult (least sensory evidence: 27.5% image phase coherence) and easiest (most sensory evidence: 35% image phase coherence) visual coherence level.

4.3.3 Behavioural analysis

To evaluate the additional benefit of auditory evidence for dyslexics and non-dyslexics we used a range of generalised linear mixed effects models (GLMMs) and robust correlation analysis. In a first step, we evaluated whether administered noise levels correlated with overall improvement in behavioural performance (i.e., $\text{accuracy}_{\text{audio-visual}}$-$\text{accuracy}_{\text{visual}}$) across participants for each group separately using a robust bend correlation analysis (Pernet et al., 2013). This analysis aimed at ruling out any biases that could have been introduced accidentally by the experimenters during noise level selection. We computed the mean accuracy across all trials of each visual coherence level for every modality and participant separately. Subsequently, we subtracted the resulting individual participant means for audio-visual trials from the means for visual trials resulting in the difference in performance due to additional auditory perceptual evidence (henceforth, multisensory performance benefit/improvement).

In a second step, our main behavioural analysis quantified behavioural performance (i.e., decision accuracy and response time) in the data collected during the testing day using two separate GLMMs. We performed this analysis using the *lme4* package (Bates et al., 2015) in RStudio (RStudioTeam, 2016) specifying a *binomial logit* model in the family argument of the *glmer* function for decision accuracy, a binary dependent variable, and a *gamma* model for response time, a continuous dependent variable while also selecting the *bobyca* optimiser. These two models used the maximal random effects structure justified by the design (Barr et al., 2013). Random correlations were included for the model predicting accuracy but excluded for the model predicting response time. Both models included all main effects and interactions of our three predictors group (control and dyslexic), modality (visual and audio-visual) and visual coherence (27.5%, 30%, 32.5% and 35%) as well as by-subject and by-item random slopes and random intercepts for all relevant main effects. The predictors group and modality were entered in mean-centred form (deviation coding) whereby we accounted for small imbalances in trial numbers between the predictors' levels. The visual coherence predictor was entered using mean-centred backward difference coding The dependent variable response time was entered in log-transformed form. We employed post-hoc likelihood-ratio X^2 model comparisons to quantify the predictive power, significance, and exact p-values of all main effects revealed by both GLMMs.

In a third step, to examine whether longer response times might have given some dyslexics an advantage in their decisions (as this group is known to show slower response times (McLean et al., 2011)), we evaluated the speed-accuracy trade-off (first described by Henmon, 1911; for a review, see Heitz, 2014) by using a robust bend correlation model (Pernet et al., 2013) computed separately across participants of each group. Here, we correlated participants' mean multisensory performance benefit with their median response time difference (i.e., median $RT_{audio\text{-}visual}$-median RT_{visual}) across visual coherences.

4.3.4 EEG data acquisition

Continuous EEG data was acquired in an electrostatically shielded and sound-attenuated room from a 64-channel EEG amplifier system (BrainAmps MR-Plus, Brain Products, Germany) with Ag/AgCl scalp electrodes placed according to the international 10-20 system on an EasyCap (Brain Products GmbH). In addition, all channels were referenced to the left mastoid during recording, and a chin electrode acted as ground. The input impedance of all channels was adjusted to <20kΩ. Data was sampled at a rate of 1000 Hz and underwent online (hardware) filtering by a 0.0016–250 Hz analogue band-pass filter. Trial specific information including experimental event codes and button responses were recorded simultaneously with the EEG data using PsychoPy (version 1.83.04; Peirce, 2009) and Brain Vision Recorder (BVR; Version 1.10, Brain Products, Germany). These data were collected and stored for offline analysis.

4.3.5 EEG data pre-processing

Offline data pre-processing was performed with MATLAB (version 2015a, The MathWorks, 2015, Natick, Massachusetts) by applying a software-based 0.5-40 Hz band-pass filter to remove slow DC drifts and higher frequencies (> 40 Hz). This cut-off was chosen as we were mainly interested in slower evoked responses that fall within the selected frequency range. These filters were applied non-causally (using MATLAB '*filtfilt*') to avoid phase-related distortions. Additionally, the EEG data were re-referenced to the average of all channels.

We removed eye movement artefacts such as blinks and saccades using data from an eye movement calibration task completed by participants before the main task. During this task, participants were instructed to blink repeatedly upon the appearance of a black fixation cross on light grey background in the centre of the screen before making several lateral and horizontal saccades according to the location of the fixation cross on the screen. Using principal component analysis, we identified linear EEG sensor weights associated with eye movement artefacts, which were then projected onto the broadband data from the main task and subtracted out (Parra et al., 2005). Further, all trials where participants exceeded the response time limit of 1.5 seconds, indicated a response in less than 300 ms after onset of the stimulus or exceeded the maximum amplitude of 150 µV during the trial were excluded from all subsequent analyses (0.7%, 0.4%, and 0.05% of all trials across participants, respectively)

4.3.6 EEG data analysis

In this study, we sought to investigate whether the neural substrates underlying our face versus car decisions were associated with early encoding of the sensory evidence, later decision-related processes, or more domain-general modulators including attention. To examine the temporal EEG components established in previous work (e.g., Philiastides & Sajda, 2006; Ratcliff et al., 2009), we used a linear multivariate single-trial discriminant analysis of our EEG data (Parra et al., 2002; Parra et al., 2005). Endogenous noise leading to trial-to-trial fluctuations of activity make it imperative to use single-trial information for disentangling the processes at play. This single-trial analysis used a linear multivariate classifier, combined with a sliding window approach employed in previous work (e.g., Gherman & Philiastides, 2015; Philiastides & Sajda, 2006), to discriminate between trials of the two image categories (i.e., face versus car) separately for visual and audio-visual trials. We chose to discriminate the image category and not the modality, since participants were asked to decide between the two image categories. Training the classifier to discriminate the two modalities (i.e., visual versus audio-visual) would have only provided us with information on where in time the additional auditory input is reflected in the EEG as opposed to disentangling the associated temporal decision processes themselves. Similarly, to ensure that we only discriminated between decision-relevant neural components of the face versus car decisions, without any distortion of the neural signatures that were simply introduced by stimulating an additional modality (i.e., auditory sounds), we ran the discriminant analysis separately for each modality.

Our multivariate approach distinguishes itself from the conventional univariate approach in that it allows for the integration of information from all 64 channels across multidimensional sensor space simultaneously. As a result, the signal-to-noise ratio is increased while single-trial information can be preserved, which is not the case in conventional univariate analysis. As part of our multivariate discrimination analysis, for each participant, we identified a projection of the multichannel EEG signal, $x_i(t)$, where i= [1…T] and T is the total number of a participant's valid trials, within a short time window that maximally discriminated between the face/speech and car stimulus categories. In separating the two stimulus categories, the discriminator was designed to map component amplitudes for one condition to negative values (here, cars) and those of the other condition to positive values (here, faces and speech). All time windows had a width of 60 ms and onset intervals every 10 ms. These windows were centred on and shifted from -100 to 1000 ms relative to stimulus onset on stimulus-locked data. Specifically, a 64-channel spatial weighting $w(\tau)$ was learned by means of logistic regression (Parra et al., 2005) that achieved maximal discrimination at each time window, arriving at the one-dimensional projection $y_i(\tau)$, for each trial i and a given window τ:

$$y(\tau) = w^T x(\tau) = \sum_{i=1}^{D} w_i x_i(\tau) \qquad (1)$$

Here, T refers to the transpose operator. We quantified the performance of our discriminator for each time window using the area under a receiver operating characteristic (ROC) curve (Green & Swets, 1966), referred to as A_z value, using a leave-one-out cross-validation procedure (Duda, Hart, & Stork, 2001). In addition, the linearity of the model allowed us to compute scalp projections of our discriminating components resulting from equation (1) by estimating a forward model (α) as shown in equation (2), which describes the electrical coupling of the discriminating component (y) that reflects most of the activity in x. In this model $y_i(\tau)$ is reorganised as vector $y(\tau)$, where each row of this vector corresponds to trial i. Further, $x_i(t)$ is organised as a matrix $x(\tau)$, where rows are channels and columns are trials, all for time window τ.

$$\alpha(\tau) = \frac{x(\tau)y(\tau)}{y(\tau)^T y(\tau)} \qquad (2)$$

Employing this approach, we first analysed our EEG data on a single subject-level, before comparing the resulting component amplitudes $y_i(\tau)$ between visual and audio-visual conditions in a second level group analysis. These component amplitudes reflect the quality of the category-selective information of the two discriminated conditions (here that is, face versus car). Since these component amplitudes were not directly obtained from a visual versus audio-visual discrimination analysis, we subtracted component amplitudes obtained for visual face trials (positive) from those for visual car trials (negative) first. The result of this subtraction indicated the magnitude of the neural difference between face and car trials for one modality. We repeated the subtraction of component amplitudes for audio-visual face/speech and car trials. This split into negative and positive component amplitudes for the two discriminated conditions is a result of the orthogonalisation procedure used by our multivariate approach.

We ran a second set of almost identical single-trial linear discrimination analyses that only differed insofar that it used response-locked as opposed to stimulus-locked data as input. In this case, a maximally discriminating spatial weighting was learned by shifting windows centred on the time range between -600 and 500 ms around the response time. All other parameters were kept constant. In both analyses, after averaging component amplitudes across each training window τ, the entire procedure resulted in continuous down-sampled traces of visual and audio-visual component amplitudes at 100 Hz, which we evaluated statistically.

Our previous EEG work in non-dyslexics revealed temporally distinct components encoding early sensory evidence (early) and later decision-related evidence (late) during visual perceptual decision making. Since aberrant processing has been found at many time points in adult dyslexia, here, contrary to earlier work (e.g., Diaz et al., 2017), we exploited the entire time course around the stimulus onset (-100 to 700) and response time (-600 to 300 ms) to investigate the extent to which additional auditory evidence is reflected in temporal components without focusing on specific early and late time bins. However, we constrained the reporting of our statistical analysis to time windows relevant for decision formation (i.e., 100 to 550 ms and -450 to 300 ms around stimulus onset, respectively).

Overall, these analyses allowed us to disentangle the temporal processing stages in relation to audio-visual non-linguistic perceptual decision making while also highlighting temporal neural components that may be associated with neural processes supporting dyslexics’ perceptual decision making such as attention.

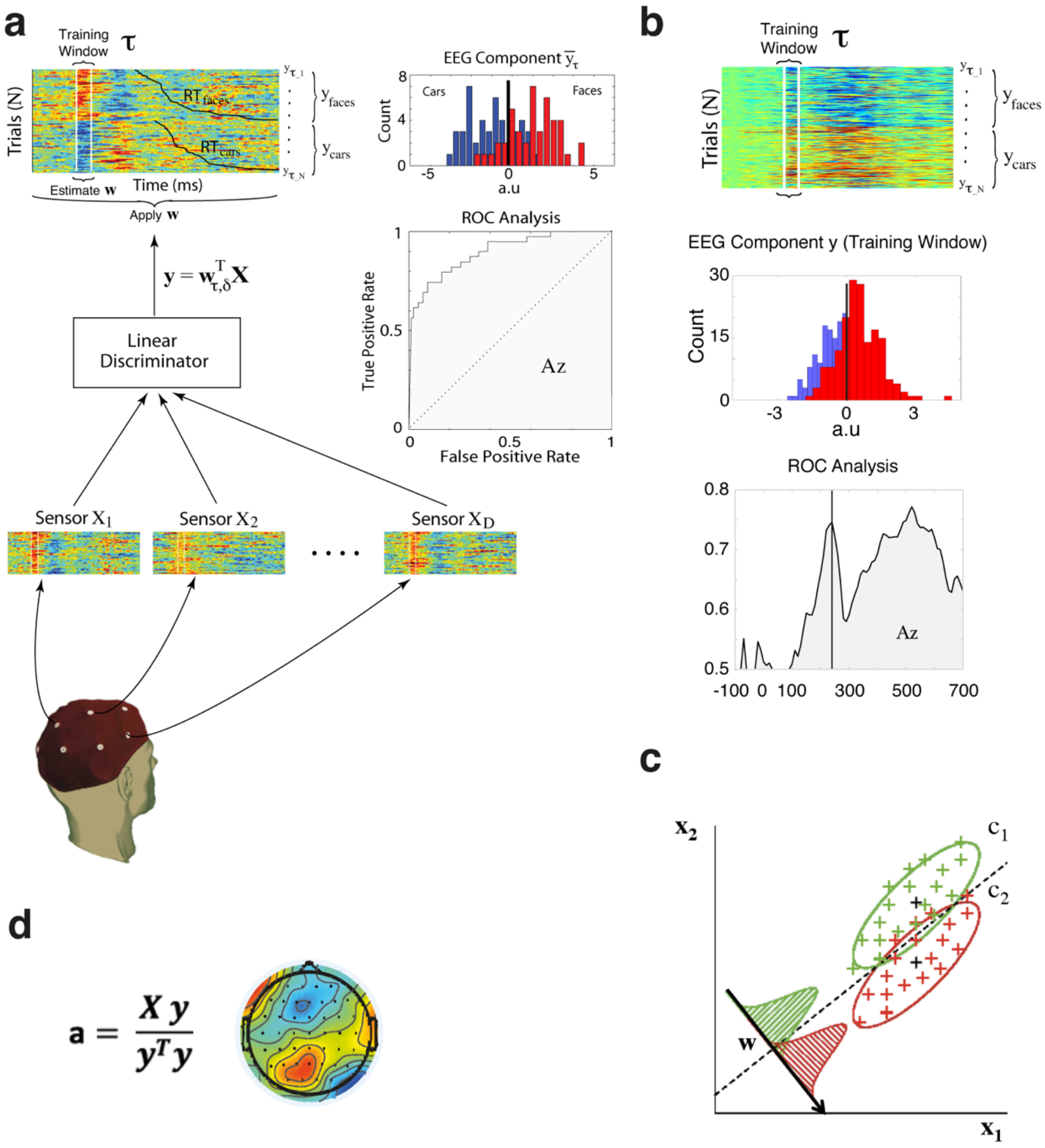


Figure 4.2. Summary of multivariate single-trial EEG discriminant analysis. a) Example of the steps involved in generating a discriminant component map as a result of discriminating two conditions, where w is the spatial weighting factor obtained for each training window τ. Here, this window was 60 ms in length and shifted in increments of 10 ms. **b)** Illustration of component amplitudes (*y*) and discriminator performance (A_z) over time for one exemplary participant. White vertical lines illustrate training window. Median EEG components (*y*) across 60 ms of the training window. Discriminator performance over time; vertical black line indicates the centre of the training window marked above. **c)** Example of two distributions (C1 and C2) with linear spatial weighting factor (w) that is maximally discriminating between the two distributions for one time window. **d)** Example of dorsal view of sensor projections of the so-called forward model a. Scalp projection illustrates the activity profile for the late component (i.e., mean activity dyslexia group).

4.3.7 Statistical evaluation of neural effects

To shed light on the fine-grained temporal evolution of brain dynamics that are a consequence of dyslexia, we chose to use the early and late components previously described by Diaz and colleagues (2017) as reference points while quantifying the entire time course around a decision (i.e., 100 to 700 ms for stimulus-locked and -600 to 300 ms for response-locked data). We tested for neural differences between visual and audio-visual trials within both groups (i.e., dyslexia and control) using three statistical analyses. Firstly, to check whether our discriminator performed above chance, we quantified differences between continuous visual and audio-visual mean performance of our discriminator (A_z-values) within each subject group over time, but separately for stimulus- and response-locked data. Secondly, to examine the quality of the evidence participants extracted from each modality condition, we quantified differences between stimulus-locked median component amplitudes (y) within each group separately. Lastly, to investigate the links between our neural and behavioural data, we correlated the difference between visual and audio-visual component amplitudes with behavioural multisensory performance benefit across all visual coherence levels but for each group separately. To investigate potential effects of stimulus difficulty in dyslexia, we repeated this correlation analysis for each specific visual coherence level separately across dyslexic participants.

We used a percentile bootstrap technique appropriate for comparing two dependent groups (using the ‘*pb2dg*’ function in MATLAB (Rousselet, Pernet, & Wilcox, 2017) with code obtained from the author’s Figshare repository: https://figshare.com/articles/Modern_graphical_methods_to_compare_two_groups_of_observations/4055970) to quantify the difference in discriminator performance and component amplitudes between both modality conditions at each sample/time point. By shuffling visual and audio-visual A_z-values or component amplitudes randomly within-subjects for each sample allowing for replacements, our bootstrapping procedure created random distributions of visual and audio-visual A_z-values or component amplitudes that resembled distributions expected by chance. This random assignation of trial labels was repeated 1,000 times. We used the resulting distributions’ 95th percentile as a data-driven Monte-Carlo threshold for comparisons with the difference in the original data. Subsequently, to avoid transient neural effects, we only accepted temporal clusters of at least two consecutive significant samples. This procedure corrects for multiple comparisons using cluster-based non-parametric permutation testing similar to Maris & Oostenveld (2007).

In addition, we employed a similar percentile bootstrap technique to confirm the results we obtained from our previous cluster-based analyses of A_z-values and component amplitudes. This confirmatory analysis used the bootstrapped median difference between visual and audio-visual A_z-values or component amplitudes of each sample. Here, random data was created by shuffling difference scores (i.e., audio-visual minus visual) within each group with replacement. We repeated this shuffling procedure 1,000 times for each sample whereby we created a random distribution of median difference scores before selecting the median of this bootstrap distribution for each sample. The resulting final distribution of random median difference scores represented the difference between visual and audio-visual A_z-values or component amplitudes expected by chance. Further, we computed the 95% confidence interval of the final random distribution of median difference scores from each sample's bootstrapped random distribution on a sample-by-sample basis. This confidence interval indicated whether our median difference between modality conditions was observed due to a true difference in the original data or could have been due to chance. We assumed a true difference in the original data when the confidence interval did not include zero. To ensure that neural effects were also traceable on a single subject-level without group-level measures of central tendency masking variability, we computed the proportion of participants who demonstrated a subject-level effect in line with the general group-level effect (that is, for example, higher audio-visual component amplitude for a given sample). We performed this confirmatory analysis using MATLAB code obtained from Rousselet and colleagues' (2017) Figshare repository (https://figshare.com/articles/Modern_graphical_methods_to_compare_two_groups_of_observations/4055970) and Rousselet, Foxe, & Bolam's (2016) Figshare repository (https://figshare.com/articles/A_few_simple_steps_to_improve_the_description_of_group_results_in_neuroscience/3806487).

To analyse a potential link between our neural and behavioural data over time, we employed robust bend correlations (using the '*bendcorr*' function in MATLAB as implemented in the robust correlation toolbox by Pernet et al., 2013). This part of our analysis correlated the behavioural multisensory performance benefit with the difference between median visual and audio-visual component amplitudes (i.e., $y\ \text{amplitude}_{\text{audio-visual}} - y\ \text{amplitude}_{\text{visual}}$) over time across all visual coherence levels and per visual coherence level separately. Bend correlations return correlation (*r*), *t*- and *p*-values after down-weighting bivariate outliers. In each dimension, we down-weighted 20% of all data points. One correlation coefficient (*r*), *t*- and *p*-value were obtained for each sample using alpha = 5% as the threshold for deciding on a sample's significance. Lastly, we also correlated the behavioural multisensory performance benefit with the difference between median visual and audio-visual component amplitudes, which we averaged across the time windows of our identified EEG components, across all visual coherence levels and per visual coherence level separately.

4.4 Results

4.4.1 Behavioural results

4.4.1.1 Decision accuracy and response times

Our behavioural analysis evaluated decision performance (i.e., decision accuracy) and response time separately as a function of the three predictors: group, modality, and visual coherence level using two GLMMs.

Our first GLMM yielded significant main effects of the predictors group and modality on accuracy across trials (for detail see Table 4.1; Figure 4.3a). Overall, dyslexic participants performed significantly worse than non-dyslexics ($Z = 2.589$, $p = .0096$). All participants performed better on trials that provided audio-visual evidence ($Z = -2.331$, $p = .0198$). These improvements in performance scaled with visual difficulty across all participants as visual noise decreased ($X^2(3) = 18.40$, $p < .001$). Although demonstrating overall worse decision accuracy, dyslexics performance increased to a similar extent during audio-visual trials (~5%; Figure 4.3b). In other words, we observed no difference between groups in multisensory performance benefit as indicated by the absence of a significant group-by-modality interaction ($Z = -0.547$, $p = .5847$). Similarly, we did not find any other significant interactions between the other predictors either (see Table 4.1).

We confirmed both main effects of group and modality using separate post-hoc likelihood-ratio X^2 model comparisons. In addition, we analysed the effect of visual coherence across all four levels of this predictor using a separate likelihood-ratio X^2 model comparison. Removing the main effect of the predictors group or modality from the model led to poorer fit of the respective model when compared to the full model, which included all predictors and their interaction terms ($X^2(1) = 6.40$, $p = .011$, $X^2(1) = 5.37$, $p = .021$, respectively). Removing all three main effects of the predictor visual coherence also decreased the model's fit compared to the full model whereby we identified a significant additional effect of image difficulty ($X^2(3) = 18.40$, $p <.001$).

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*Z*	*p*
Group	**0.2722**	**0.0662**	**0.4782**	**0.1052**	**2.589**	**0.0096**
Modality	**-0.2613**	**-0.4809**	**-0.0416**	**0.1121**	**-2.331**	**0.0198**
Visual coherence 30-27.5%	0.1764	-0.1227	0.4754	0.1526	1.155	0.2479
Visual coherence 32.5-30%	0.2652	-0.0358	0.5661	0.1536	1.727	0.0842
Visual coherence 35-32.5%	0.1841	-0.1181	0.4862	0.1542	1.194	0.2325
Group * modality	-0.0455	-0.2088	0.1178	0.0833	-0.547	0.5847
Group * vis. coh. 30-27.5%	0.0817	-0.0796	0.2432	0.0824	0.993	0.3209
Group * vis. coh. 32.5-30%	-0.0174	-0.1899	0.1551	0.0881	-0.198	0.8431
Group * vis. coh. 35-32.5%	0.0359	-0.1399	0.2118	0.0897	0.401	0.6887
Modality * visual coh. 30-27.5%	-0.0443	-0.6391	0.5503	0.3048	-0.145	0.8845
Modality * visual coh. 32.5-30%	0.1325	-0.4626	0.7276	0.3049	0.435	0.6639
Modality * visual coh. 35-32.5%	-0.1238	-0.7220	0.4748	0.3059	-0.405	0.6858
Group * modality * vis. coh. 30-27.5%	-0.0963	-0.4159	0.2231	0.1633	-0.590	0.5553
Group * modality * vis. coh. 32.5-30%	-0.0249	-0.3549	0.3051	0.1687	-0.148	0.8827
Group * modality * vis. coh. 35-32.5%	0.0109	-0.3306	0.3524	0.1745	0.062	0.9504

Table 4.1. Generalised linear mixed effects model fixed effect parameter estimates for model predicting decision accuracy. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Our second GLMM predicting median response time as a function of the same three predictors and interaction terms returned a main effect of *modality* that showed significant power to predict response times across all trials ($t = -4.15$, $p <.0001$;

for details see Table 4.2; Figure 4.3c). All participants responded slower on audio-visual trials (RT difference: ~50 ms). However, response times were not significantly affected by the visual coherence level of the stimulus ($t_{30\text{-}27.5\%}$ = -0.76, $p_{30\text{-}27.5\%}$ =.447; $t_{32.5\text{-}30\%}$ = -1.00, $p_{32.5\text{-}30\%}$ =.318; $t_{35\text{-}32.5\%}$ = -0.35, $p_{35\text{-}32.5\%}$ =.728) or group (t = -0.56, p =.572; Figure 4.3c and 4.3d). Additionally, we did not find any significant interactions explaining response time. A post-hoc likelihood-ratio X^2 model comparison confirmed the predictive power of our predictor modality on response time ($X^2(1) = 15.747$, p <.0001).

Parameter	*Estimate*	*CI 2.5%*	*CI 97.5%*	*SE*	*t*	*p*
Group	-0.0125	-0.0559	0.0309	0.0221	-0.56	0.572
Modality	**-0.0221**	**0.0326**	**-0.0117**	**0.0053**	**-4.15**	**<0.0001**
Visual coherence 30-27.5%	-0.0038	-0.0137	0.0060	0.0050	-0.76	0.447
Visual coherence 32.5-30%	-0.0052	-0.0155	0.0050	0.0052	-1.00	0.318
Visual coherence 35-32.5%	-0.0017	-0.0115	0.0080	0.0050	-0.35	0.728
Group * modality	0.0029	-0.0090	0.0148	0.0061	0.48	0.632
Group * visual coh. 30-27.5%	0.0029	-0.0040	0.0099	0.0036	0.83	0.408
Group * visual coh. 32.5-30%	0.0024	-0.0054	0.0101	0.0040	0.59	0.553
Group * visual coh. 35-32.5%	-0.0054	-0.0121	0.0014	0.0034	-1.56	0.119
Modality * vis. coh. 30-27.5%	-0.0000	-0.0186	0.0186	0.0095	0.00	1.000
Modality * vis. coh. 32.5-30%	0.0028	-0.0159	0.0214	0.0095	0.29	0.769
Modality * vis. coh. 35-32.5%	0.0004	-0.0183	0.0190	0.0095	0.04	0.967
Group * modality * vis. coh. 30-27.5%	0.0006	-0.0111	0.0122	0.0059	0.09	0.927
Group * modality * vis. coh. 32.5-30%	0.0020	-0.0097	0.0136	0.0059	0.33	0.739
Group * modality * vis. coh. 35-32.5%	-0.0021	-0.0138	0.0095	0.0059	-0.36	0.718

Table 4.2. Generalised linear mixed effects model fixed effect parameter estimates for model predicting response time. Fixed effect parameter estimates in log odds units. Effects with significant predictive power after post-hoc likelihood-ratio X^2 model comparisons in bold.

Lastly, since dyslexics often show better performance under less time pressure, we evaluated the well-known speed-accuracy trade-off by correlating the multisensory performance benefit with the difference in response times across visual coherence levels (i.e., audio-visual minus visual; Figure 4.3e and 4.3f) for each group separately. This robust correlation indicated a positive relationship showing higher multisensory performance benefit for dyslexic participants who responded more slowly on audio-visual trials (r_{35} =.25; p =.135; Figure 4.3e).

However, this relationship warrants cautious interpretation as it was not statistically significant (i.e., alpha <.05). In contrast, we found no correlation between our variables speed and accuracy in the control group (r_{29} =.12; p =.515; Figure 4.3f).

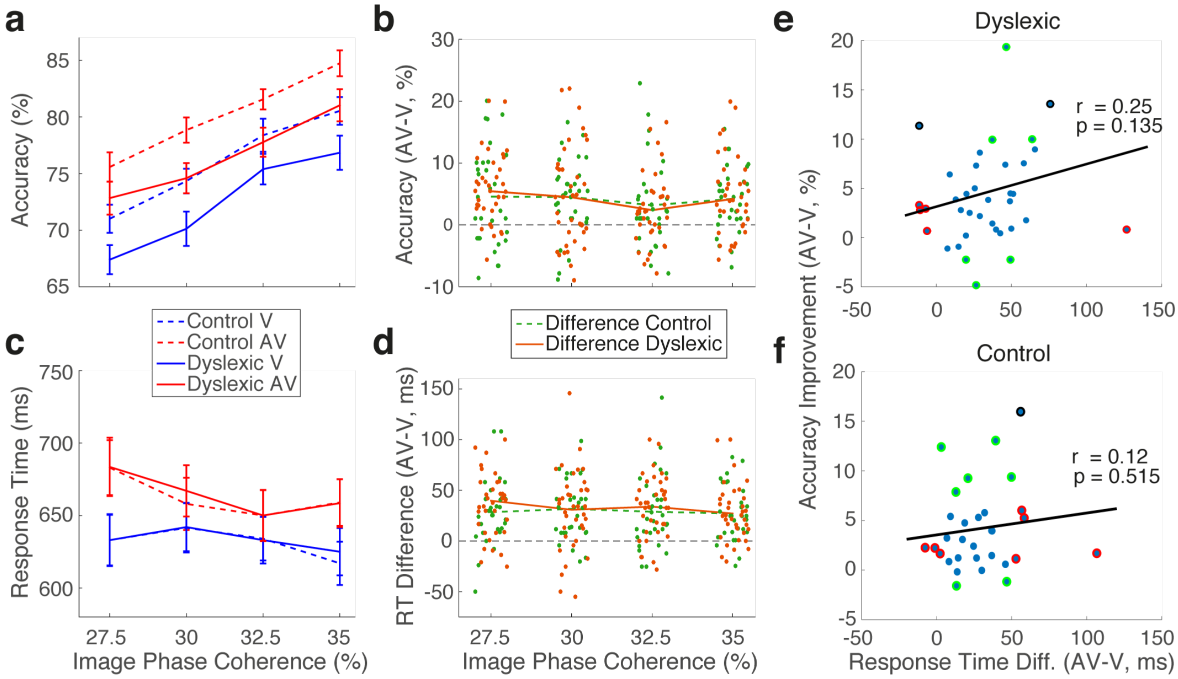


Figure 4.3. Decision accuracy, response time, and speed-accuracy trade-off. a) Decision performance by group, modality, and visual coherence level measured as mean accuracy in percent. Blue traces represent the visual and red traces the audio-visual condition. Dashed lines represent results for the control group and solid lines results for the dyslexia group. **b)** Audio-visual performance benefit by group and visual coherence level (i.e., audio-visual minus visual decision accuracy). **c)** Median response time by group, modality, and visual coherence level. Line and colour coding as in panel a. **d)** Difference in median response time between modalities by group and visual coherence (i.e., audio-visual minus visual median response time). **e)** Speed-accuracy trade-off for the dyslexia group correlating multisensory performance benefit with difference in median response time between modalities. Correlation coefficient (r) and p-value from robust bend correlation shown. Colours indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension 20% of all data points were down-weighted. **f)** Speed-accuracy trade-off for the control group. Colour coding as in panel e.

4.4.1.2 Decision accuracy and auditory noise level

During our auditory training task on day one, we selected one auditory difficulty level (i.e., noise level) from a range of different levels to account for inter-individual differences in auditory perception. We chose this noise level to be around a participant's perithreshold performance level (i.e., decision accuracy) of about 70%. To examine a potential effect of the chosen auditory noise level on audio-visual performance improvements, we correlated the mean multisensory performance benefit for each visual coherence level with the administered noise level of the sounds, separately across all participants of each group (Figure 4.4a and 4.4b). Figure 4.4a illustrates that dyslexic participants who received sounds with higher noise levels during testing seemed to benefit less from the additionally auditory evidence provided during audio-visual trials (r_{35} = -.34; *p* <.001). On the contrary, non-dyslexics did not benefit differently from the provided auditory evidence (r_{29} = -.10; *p* =.25; Figure 4.4b).

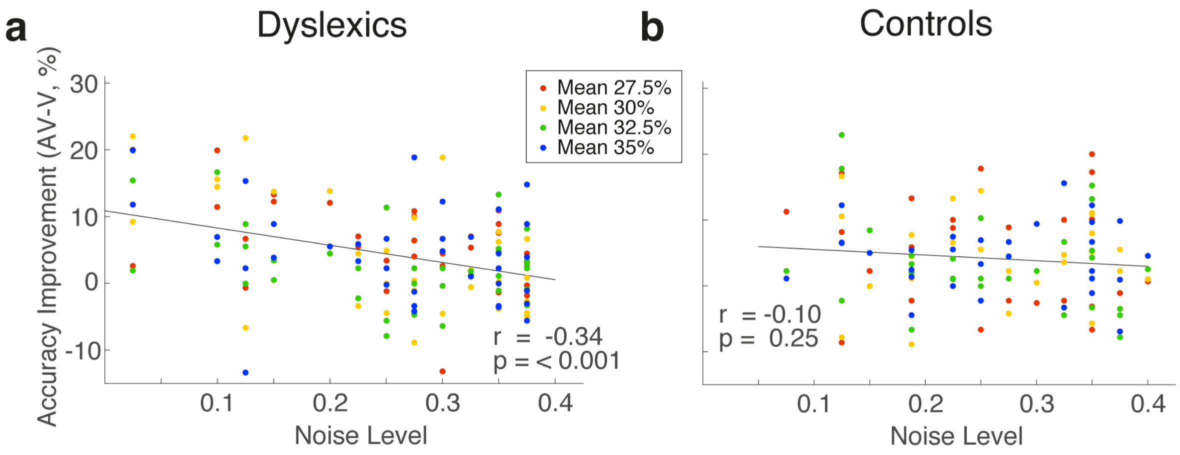


Figure 4.4. Correlation of auditory noise levels and multisensory performance benefit. Each data point shows the difference in mean decision accuracy between audio-visual and visual trials per participant and visual coherence level. As a result, four data points are displayed per participant where non-overlapping values allow for a distinction. Black lines represent the linear least-squares line across all data points. Correlation coefficients and p-values show results from robust bend correlations computed across all data points (i.e., all visual coherence levels) of each group by down-weighting 20% of all data points in each dimension. **a)** Dyslexia group with 37 participants. **b)** Control group with 31 participants.

4.4.2 EEG results

4.4.2.1 Stimulus-locked discriminator performance by modality

To identify differential activity during varying processing stages (e.g., early sensory, intermediate attention- and late decision-related processing) that are a result of influences of the additional auditory evidence on the visual evidence, we ran a stimulus-locked multivariate single-trial analysis discriminating between face and car stimuli. We observed gradually increasing component discriminator performance (A_z) for visual and audio-visual trials starting at 200 ms post-stimulus (Figure 4.5a). A cluster-based permutation analysis for dependent samples (see Materials and methods) revealed that, within the dyslexia group, face versus car discrimination was significantly higher for audio-visual than visual trials during two distinct time windows within our period of interest (i.e., 100-550 ms post-stimulus onset). These two time windows (henceforth, components) were (1) 270-350 ms and (2) 410-420 ms (Figure 4.5a). Both stimulus-locked components were observed clearly before the dyslexia group's median response time (i.e., 633 ms on visual, 663 ms on audio-visual, and 646 ms across all trials), and therefore, not confounded by motor signals stemming from the decision indicating button press.

We also performed a second confirmatory cluster-based permutation analysis, which quantified the median difference of our modalities' discriminator performance directly by checking whether it deviated significantly from zero as opposed to comparing the data values of each modality themselves. This analysis corroborated the previously identified two relevant components for dyslexics (Figure 4.5c). Specifically, this confirmatory analysis revealed a clear temporal overlap of the two significant components, which were identified in both, the original and confirmatory, statistical analyses (windows of overlap: 290-340 ms and 440-450 ms; henceforth, *intermediate* and *late* component, respectively; Figure 4.5c).

Furthermore, to illustrate that our significant differences in discriminator performance did not merely represent results on the group-level, which can mask large variability on the subject-level, we computed the proportion of participants who demonstrated the same effect that we observed when comparing group averages (i.e., higher discriminator performance on audio-visual compared to visual trials). This yielded the same pattern of results, with audio-visual discriminator performance being higher in 73% of individual data for dyslexics' intermediate and 67.5% for their late component (Figure 4.5e). Taken together, these converging results provide more evidence for a crucial role of these two temporal components during audio-visual perceptual decision making in adult dyslexia. They underline the consistency of the temporal neural processes represented by our two components across dyslexic participants.

We repeated the temporal cluster-based percentile bootstrap analyses for our control group, which revealed no significant differences in discriminator performance between visual and audio-visual trials when comparing both modality conditions directly (Figure 4.5b). Interestingly, contrary to the preceding result, the median difference percentile bootstrap analysis yielded one significant component ranging from 510 to 520 ms post-stimulus that we did not observe during the preceding percentile bootstrap analysis (henceforth, *late* component; Figure 4.5d). Overall, control participants exhibited more variability in their subject-level discriminator performance (Figure 4.5f). In this respect, 70% of control participants showed an effect similar to their modality group means (i.e., higher A_z-values for audio-visual trials) only briefly for the time window of their late component at 520 ms post-stimulus onset (Figure 4.5f).

For both groups, their late components fall into the time range that has previously been associated with late decision-related evidence (e.g., Philiastides & Sajda, 2006). Scalp topographies of these two late components were also similar to previous reports showing strong activation centred over posterior parietal electrodes (Figure 4.8a for dyslexics and 4.8b for controls). Conversely, activity in the time range of dyslexics' intermediate component has previously been associated with attention-related processes during perceptual decision making (Heekeren et al., 2008; Kayser et al., 2017). Its scalp topography depicted a mixture of activity profiles associated with previous reports of the early and late component (Figure 4.8a).

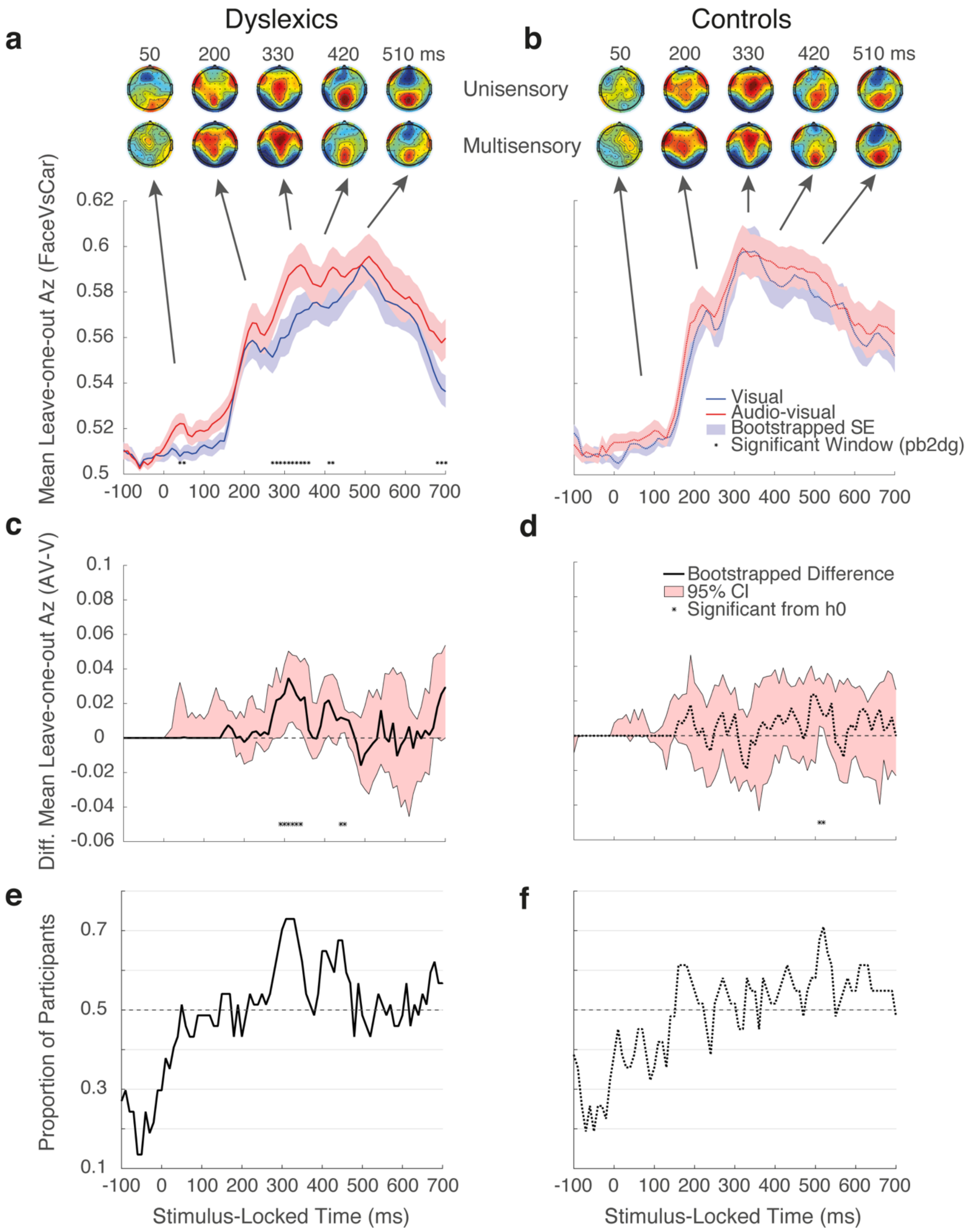


Figure 4.5. Comparison of stimulus-locked discriminator performance (A_z). a) Mean A_z discriminator performance after leave-one-out cross-validation for the dyslexia group. Statistical significance determined by percentile bootstrap method for dependent samples corrected for multiple comparisons by using a minimum number of two consecutive windows for a significant cluster. **b)** Mean A_z discriminator performance after leave-one-out cross-validation for the control group. Statistical evaluation as in a. **c)** Dyslexics bootstrapped median difference of mean A_z discriminator performance (audio-visual minus visual). Shaded area represents the 95% confidence interval of the median. Dashed line represents the null hypothesis (h0) that assumes no difference between discriminator performance for both modalities. A significant difference was a result of the confidence interval of two adjacent samples not including zero. **d)** Controls bootstrapped median difference of mean A_z discriminator performance (audio-visual minus visual). Statistics and details as in c. **e)** Proportion of participants of the dyslexia group over time who showed discriminator performance in the same direction of their group's means on the subject-level. A proportion of 1 represents all participants of one group. Dashed grey line indicates 50% level. **f)** Proportion of participants of the

control group over time who showed discriminator performance in the same direction of their group's means on the subject-level.

4.4.2.2 Stimulus-locked component amplitudes by modality

To investigate the changes in stimulus-related neural information in response to additional auditory evidence during perceptual decision making we compared the component amplitudes (*y*) of visual to those of audio-visual trials. These component amplitudes, originating from our analysis of stimulus-locked data, indicate the separation of the neural signals between trials of the two discriminated stimulus image categories (that is, face and car).

We expected amplified component amplitudes for the audio-visual condition, given that more sensory evidence was available during audio-visual trials, and our discriminator performed better on these trials. Indeed, for the dyslexia group, we found higher median component amplitudes in the audio-visual condition between 50 and 450 ms post-stimulus onset (Figure 4.6a). This difference was significant within two distinct temporal windows (1) 290-300 and 320-330 ms, and (2) 630-640 ms; as revealed by the temporal cluster-based percentile bootstrap analysis (Figure 4.6a). Equally, the percentile bootstrap analysis of median differences confirmed the previously identified temporal component (i.e., 300-330 ms; henceforth, *intermediate* component) in the dyslexia group (Figure 4.6c). This difference in component amplitudes in adult dyslexia around 300 ms post-stimulus was substantiated on the individual level by a large proportion of dyslexics (~70%) exhibiting higher component amplitudes for audio-visual trials around this time point (Figure 4.6e). The timing of the dyslexics' intermediate component was consistent across all stimulus-locked analyses of discriminator performance and component amplitudes.

On the other side, unlike our dyslexia group, the control group's component amplitudes did not show any significant difference between modality conditions (Figure 4.6b). Similarly, we did not find a significant component by analysing this group's bootstrapped median difference scores (i.e., after correcting for multiple comparisons; Figure 4.6d). Further, we found controls to show more temporal variability in component amplitudes in later time windows (i.e., >200 ms) across participants as illustrated by a smaller proportion of control participants showing a difference in the direction of their group's median difference (Figure 4.6f). This may as well result from later components shifting in time with perceived stimulus difficulty.

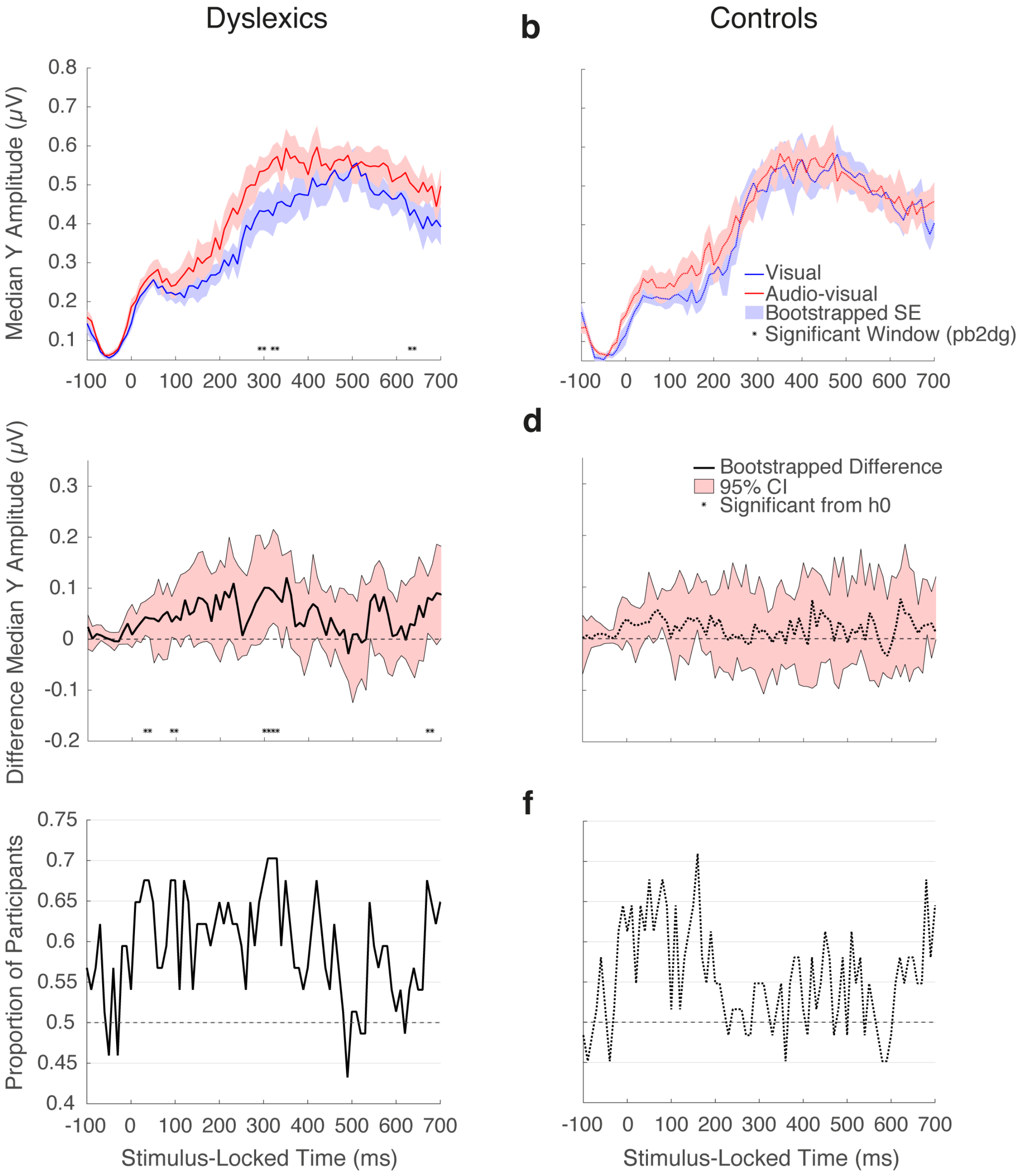


Figure 4.6. Comparison of stimulus-locked component amplitudes (*y*). a) Median component amplitudes y for the dyslexia group. Statistical significance determined by percentile bootstrap method for dependent samples corrected for multiple comparisons by using a minimum number of two consecutive windows for a cluster. **b)** Median component amplitudes y for the control group. Statistical evaluation as in panel a. **c)** Dyslexics bootstrapped median difference of median component amplitudes (audio-visual minus visual). The shaded area represents the 95% confidence interval of the median. Dashed line represents the null hypothesis (h0) that assumes no difference between discriminator performance for both modalities. A significant difference was a result of the confidence interval of two adjacent samples not including 0. **d)** Controls bootstrapped median difference of median component amplitudes (audio-visual minus visual). Statistics and details as in panel c. **e)** Proportion of participants of the dyslexia group over time who showed discriminator performance in the direction of their group's means on the subject-level. A proportion of 1 represents all participants of one group. Dashed grey line indicates 50% level. **f)** Proportion of participants of the control group over time who showed discriminator performance in the same direction of their group's means on the subject-level.

4.4.2.3 Response-locked discriminator performance (A_z) by modality

Our behavioural finding of slower response times on audio-visual trials across all participants suggested potential temporal inconsistencies of neural components between both modality conditions as the time from stimulus onset increased. Particularly, small differences between component amplitudes can be less traceable if they occur during later time windows in stimulus-locked data (i.e., later than 450 ms post-stimulus onset). However, a response-locked multivariate single-trial analysis provides a solution to this problem by offering better temporal alignment of neural components closer to the time of the response. In line with previous work (e.g., Diaz et al., 2017; Philiastides & Sajda, 2006; Ratcliff et al., 2009), we hypothesised that a later component close to the response time would show a difference between modality conditions in controls' neural data.

To examine this hypothesis, we repeated our single-trial discrimination analysis but locked the EEG data to the time of the response. Specifically, we investigated the period ranging from -450 to 300 ms around the time of the response button press, and quantified differences using the same percentile bootstrap analyses we employed in our previous analyses of stimulus-locked data.

The response-locked analysis reinforced our previous observation of overall better discriminator performance on audio-visual trials for dyslexics across almost the entire investigated time course (Figure 4.7a). Taken together, both cluster-based percentile bootstrap analyses revealed significantly better discriminator performance for one overlapping temporal component between 90 and 150 ms post-response in the dyslexia group (Figure 4.7a and 4.7c; henceforth, *post-response* component). More than 75% of dyslexic participants demonstrated better discriminator performance for audio-visual trials during this component's time windows after the button press, which substantiated this group-level effect on the subject-level (Figure 4.7e). On the contrary, control participants exhibited significantly better discriminator performance for audio-visual trials around -100 ms before their response as a result of both percentile bootstrap analyses (specifically, -150 to -50 ms; Figure 4.7b and d). The consistency of this group-level effect across participants of the control group was underlined by more than 65% of participants of this group showing better discriminator performance for audio-visual trials within the identified significant time windows before the response (Figure 4.7f).

Worth noting is that the difference in discriminator performance between the visual and audio-visual condition revealed distinct neural components, which occurred before the response in controls and after the response in dyslexics (dyslexics: 90-150 ms post-response; controls: -150 to -50 ms pre-response; Figure 4.7c and 4.7d). These results illustrate, as hypothesised, that later neural components close to the response differentiated visual from audio-visual perceptual decision making processes in non-dyslexics. These findings reinforce the notion that fundamental differences in temporal neural processes characterise audio-visual perceptual decision making in adult dyslexia.

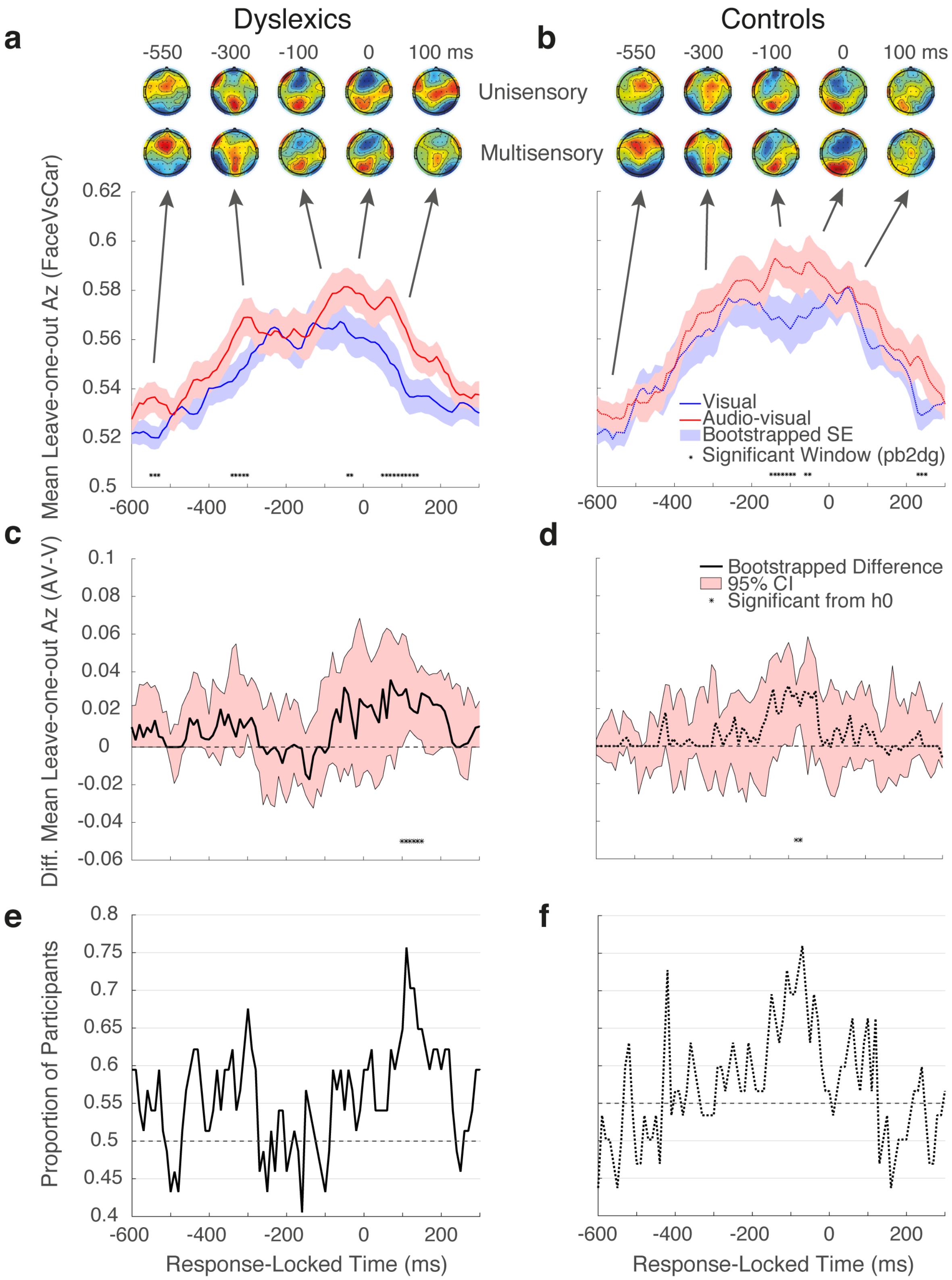


Figure 4.7. Comparison of response-locked discriminator performance (A_z). a) Mean A_z discriminator performance after leave-one-out cross-validation for the dyslexia group. Statistical significance determined by percentile bootstrap method for dependent samples corrected for multiple comparisons by using a minimum number of two consecutive windows for a cluster. **b)** Mean A_z discriminator performance after leave-one-out cross-validation for the control group. Statistical evaluation as in a. **c)** Dyslexics bootstrapped median difference of mean A_z discriminator performance (audio-visual minus visual). The shaded area represents the 95% confidence interval of the median. The dashed line represents the null hypothesis (h0) that assumes no difference between discriminator performance for both modalities. A significant difference was a result of the confidence interval of two adjacent samples not including 0. **d)** Controls bootstrapped median difference of mean A_z discriminator performance (audio-visual minus visual). Statistics and details

as in c. **e)** Proportion of participants of the dyslexia group over time who showed discriminator performance in the direction of their group's means on the subject-level. A proportion of 1 represents all participants of one group. Dashed grey line indicates 50% level. **f)** Proportion of participants of the control group over time who showed discriminator performance in the direction of their group's means on the subject-level.

4.4.2.4 Scalp topographies of stimulus- and response-locked components

To compare the activity profile of the neural components revealed by our separate preceding stimulus- and response-locked analyses, we examined scalp topographies at representative time points across the entire time course (Figure 4.8). Scalp topographies can provide insights into whether similar neural generators underlie the identified EEG components. As part of this analysis, we specifically compared scalp topographies of the intermediate and late components identified on stimulus-locked data with the pre- and post-response components found on response-locked data by means of visual inspection.

On the one side, scalp activity of dyslexics' intermediate component showed strong activation over right and left occipitotemporal electrodes and strong activation of opposite polarity over centrofrontal electrodes for both modalities (time point: 330 ms; Figure 4.8a). Dyslexics' late component was characterised by strong activity over centroparietal electrodes and strong activation of opposite polarity over anterior-frontal electrodes (time points: 420 and 510 ms; Figure 4.8a). The post-response component's scalp activity that resulted from our response-locked analysis resembled neither dyslexics intermediate nor late component's topography (time point: 100 ms; Figure 4.8a and 4.8c). On the other side, scalp activity of controls' late component showed the strongest activity centred on centroparietal electrodes, similar to their response-locked pre-response component (time points: 510 ms in Figure 4.8b and -100 ms in Figure 4.8d). This result suggests that the same neural generators underlie these two separately identified components of the control group. Both outlined topographies resemble the ones described by other authors for the late (e.g., Philiastides et al., 2014; Philiastides & Sajda, 2006) and CPP (Kelly & O'Connell, 2013; O'Connell et al., 2012) components that have been linked to post-sensory decision processes and perceptual learning gains (Diaz et al., 2017).

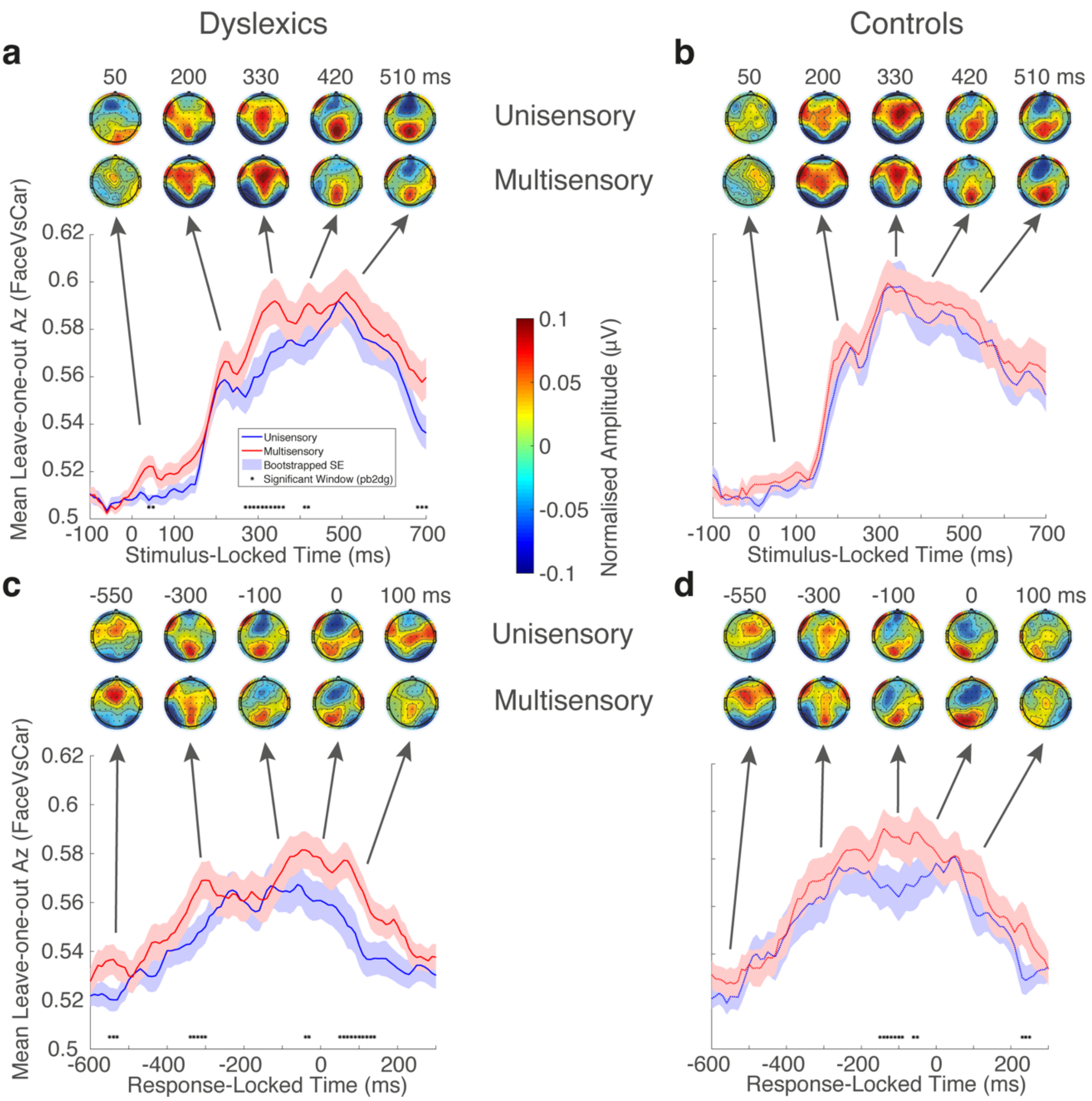


Figure 4.8. Scalp topographies and stimulus- and response-locked discriminator performance (A_z) at representative time points. a) Dyslexics' stimulus-locked discriminator performance (A_z) with representative scalp topographies. The top row of scalp topographies depicts the forward model for the visual condition. Bottom row depicts the forward model for the audio-visual condition. **b)** Controls' stimulus-locked discriminator performance with representative scalp topographies. Scalp topography arrangement as in panel a. **c)** Dyslexics' response-locked discriminator performance with representative scalp topographies. Scalp topography arrangement as in panel a. **d)** Controls' response-locked discriminator performance with representative scalp topographies. Scalp topography arrangement as in panel a.

4.4.2.5 Dyslexics' stimulus-locked component amplitudes by noise level

A potential concern was that we introduced a substantial bias into the data of the dyslexia group by falling short to select auditory noise levels around dyslexics' actual individual auditory perithreshold accuracy levels (i.e., equal available auditory sensory evidence across participants) on the training day. This could explain larger behavioural multisensory performance improvements on the testing day of participants who received sounds with lower noise levels (i.e., higher relative signal-to-noise ratios; Figure 4.4a) and might have also affected the neural components we identified on the group-level. To this end, we split the dyslexia group into two separate subgroups (stronger versus weaker auditory sensory evidence; Figure 4.9c) by splitting the range of noise levels we tested during training into two equally sized bins. Subsequently, we repeated our discrimination analysis of stimulus-locked data and extracted component amplitudes (***y***) for each of the two dyslexia subgroups separately.

The results of this analysis showed that the intermediate component, which we previously found for the entire dyslexia group, was also present in the dyslexia subgroup who had listened to weaker auditory sensory evidence (i.e., higher noise levels; 27 of 37 dyslexic participants; Figure 4.9b). Specifically, this intermediate component showed a significant difference around 300 ms post-stimulus onset for this subgroup (precisely 290–330 ms; Figure 4.9b) as a result of our cluster-based analysis of bootstrapped median difference scores. The timing of this component was identical to the timing of the intermediate component we identified when collapsing across all dyslexic participants (Figure 4.6c). For this subgroup who had listened to weaker auditory sensory evidence, we observed the group-level difference, namely higher component amplitudes for the audio-visual condition, on the subject-level in most participants of this subgroup (~70%; Figure 4.8e). On the contrary, we did not find a significant difference of this intermediate component or any other component after correcting for multiple comparisons during the time window of interest (i.e., 100-550 ms post-stimulus) in the dyslexia subgroup that was presented with stronger auditory sensory evidence (i.e., lower noise levels; 10 of 37 dyslexic participants; Figure 4.9a). These results provided further evidence for the notion that data from dyslexic participants who received stronger auditory sensory evidence did not drive the group-level difference represented by the stimulus-locked intermediate component. Thus, we can rule out an unbalanced noise level selection as a potential confounding factor for our neural results.

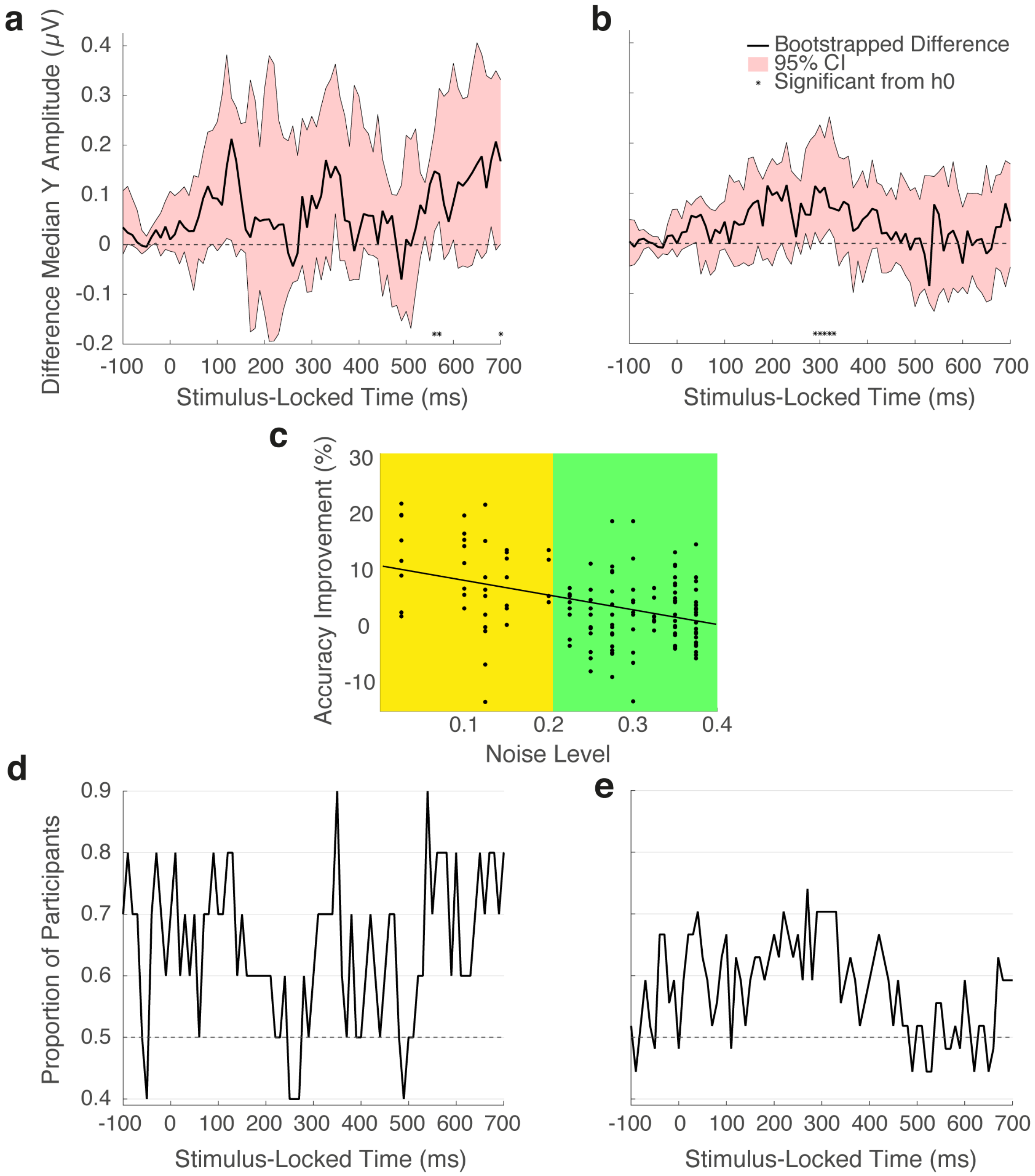


Figure 4.9. Stimulus-locked median difference of component amplitudes (*y*) by noise level. a) Dyslexics bootstrapped median difference of median component amplitudes (y) (audio-visual minus visual). The shaded area represents the 95% confidence interval of the median. The dashed grey line represents the null hypothesis (h0) that assumes no difference between component amplitudes for both modalities. A significant difference was a result of the confidence interval of two adjacent samples not including 0. **b)** Controls bootstrapped median difference of median component amplitudes (y) (audio-visual minus visual). Statistics and details as in a. **c)** Distribution of auditory noise level and multisensory performance improvement for the dyslexia group. Each data point shows the difference in mean decision accuracy between audio-visual and visual trials per participant and visual coherence level. As a result, four data points are displayed per participant where values are not overlapping. Yellow background highlights values of the dyslexic participants included in the dyslexia group who received sounds with less relative noise (n=10). Green background highlights values of dyslexic participants who received sounds with more relative noise (n=27). The black line represents the linear least-squares line across all data points. **d)** Proportion of participants of the dyslexia subgroup receiving stronger auditory sensory evidence over time who showed component amplitudes on the subject-level in the direction of the median difference of their entire subgroup. A proportion of 1 represents all participants of one subgroup. Dashed grey line indicates 50% level of the subgroup. **e)** Proportion of participants of dyslexia subgroup who received noisier sounds over

time showing component amplitudes in the direction of the median difference of their entire subgroup. Notation as in panel d.

4.4.2.6 Dyslexics' component amplitudes and decision accuracy

To investigate the extent to which changes in component amplitudes were linked to behavioural improvements, we correlated the difference between participants' visual and audio-visual median component amplitudes with their multisensory performance benefit in decision accuracy across participants of each group separately. We did not observe any significant relationship over time in the dyslexia group when collapsing across all visual coherence levels (Figure 4.10a). We did not find a significant correlation with behaviour when averaging the median component amplitudes across the time windows of dyslexics' intermediate neural component either (i.e., 290–330 ms post-stimulus onset; $r_{35} = -.06$; $p = .71$; $BF_{10} = .13$; Figure 4.10b). Similarly, in the control group, our correlation analysis did not yield a significant correlation for any time point post-stimulus onset (Figure 4.10c) nor their late component (i.e., 510–520 ms post-stimulus onset; $r_{29} = .09$; $p = .64$; $BF_{10} = .16$; Figure 4.10d). In sum, these results illustrate that neither dyslexics' intermediate component nor controls' late component could solely explain the multisensory benefit in choice performance.

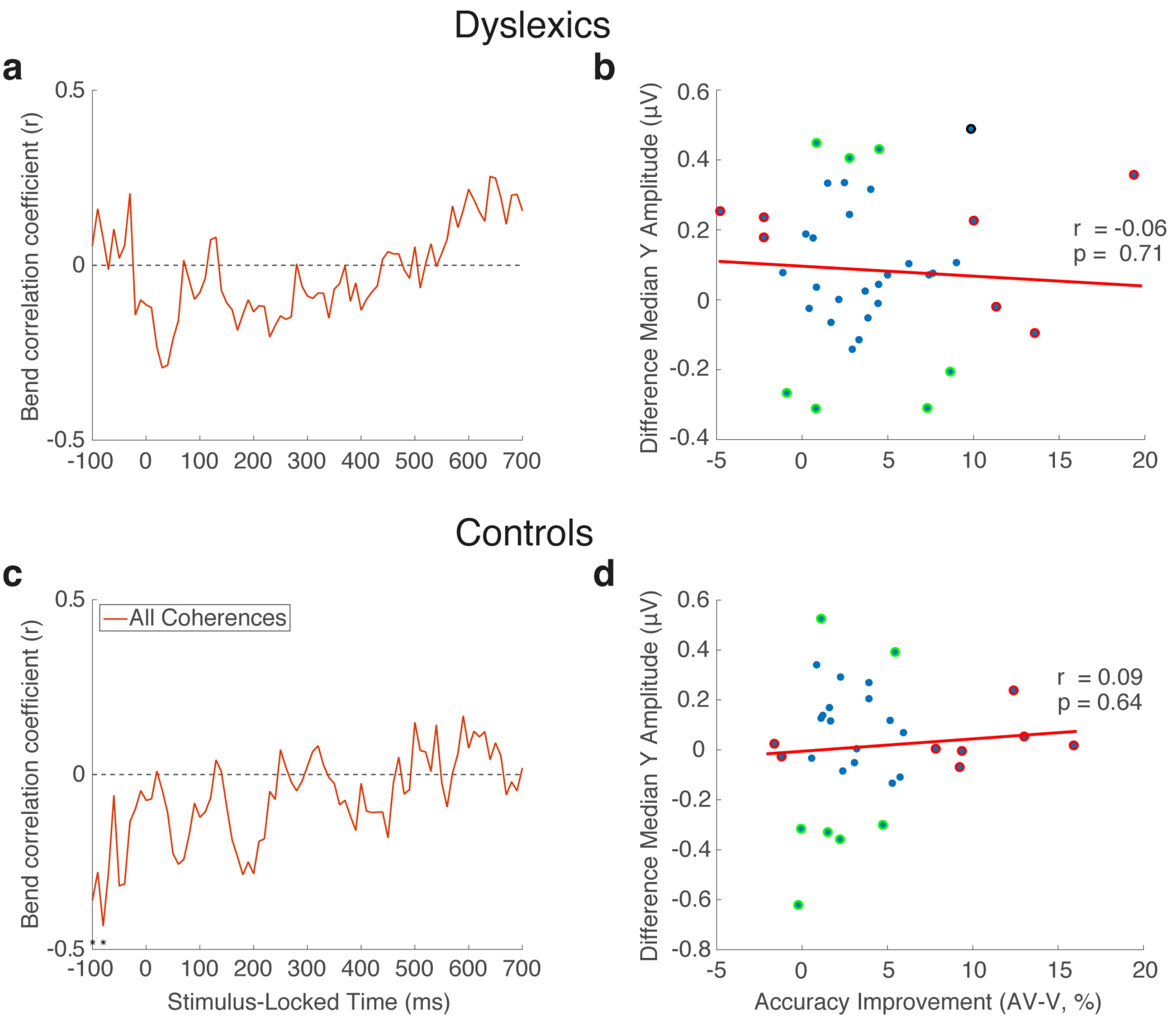


Figure 4.10. Correlations of stimulus-locked component amplitudes (*y*) with behavioural improvements across visual coherence levels. Panel a and b depict results of the dyslexia group, whereas panels c and d depict results of the control group. **a)** Correlation of the difference between audio-visual and visual median component amplitudes with behavioural multisensory performance improvement across coherences over time for the dyslexia group. Robust bend correlations were used for computing correlation coefficients. One correlation value per window. **b)** Correlation of the difference between audio-visual and visual median component amplitudes averaged across the time window of the stimulus-locked intermediate component (i.e., 290-330 ms post-stimulus) with behavioural multisensory performance improvement across coherences for the dyslexia group. Correlation coefficient (r) and p-value from robust bend correlation shown. Colours indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension 20% of all data points were down-weighted. **c)** Correlation of the difference between audio-visual and visual median component amplitudes with behavioural multisensory performance improvement across coherences over time for the control group. **d)** Correlation of the difference between audio-visual and visual median component amplitudes averaged across the time window of controls' stimulus-locked late component (i.e., 510-520 ms post-stimulus) with behavioural multisensory performance improvement across coherences for the control group. Colour coding as in panel b.

The absence of observable links between neural activity and behavioural results suggested two potential explanations. One possibility was that the component amplitudes of our intermediate EEG component varied with visual coherence level of the stimuli similar to the overall increase in behavioural decision accuracy with decreasing visual noise. Collapsing across all four visual coherence levels might have resulted in more variability of component amplitudes, which in turn, may have made their links to behavioural performance less traceable. To investigate this hypothesis in the dyslexia group, we repeated our robust correlation analyses but this time separately for each level of visual coherence. These analyses revealed differing strengths of the relationship between median component amplitudes and decision accuracy over time (Figure 4.11a-d). We found significant correlations for a few windows around the time of our previously identified intermediate EEG component (~300 ms) exclusively for trials presenting more difficult visual stimuli (i.e., 27.5% and 30% image phase coherence; Figure 4.11a and b).

Furthermore, we observed a significant relationship between component amplitudes averaged across the time windows of the intermediate neural component and decision accuracy for trials presenting images with 30% phase coherence (r_{35} = -0.33, p = 0.046; Figure 4.11f), but not for any of the other three coherence levels. Contrary to our expectations, this relationship had a negative sign indicating that dyslexic participants who exhibited higher visual than audio-visual component amplitudes during the intermediate component's time windows benefitted more from the additionally provided auditory evidence. All other correlations that we computed either over time (Figure 4.11c and 4.11d) or collapsed across the intermediate component's time window for the dyslexia group (Figure 4.11e, g and h), did not return significant results during relevant time windows (i.e., 130-550 ms post-stimulus). Overall, the results of this correlation analysis varied largely between visual coherence levels, which did not allow us to draw consistent conclusions.

All analyses considered, our results show that additional auditory evidence during audio-visual perceptual decision making increased decision performance of dyslexics and non-dyslexics while slowing down response times of both groups. However, dyslexics exhibited performance deficits on visual trials compared to non-dyslexics. These behavioural deficits were observed together with aberrant neural processing in the form of one neural EEG component occurring around 300 ms post-stimulus onset. This component neither represented the activity of the previously well-characterised early sensory nor late post-sensory neural decision components per se. Conversely, this intermediate component did not differ between modalities in the control group, illustrating differential neural processing in adult dyslexia.

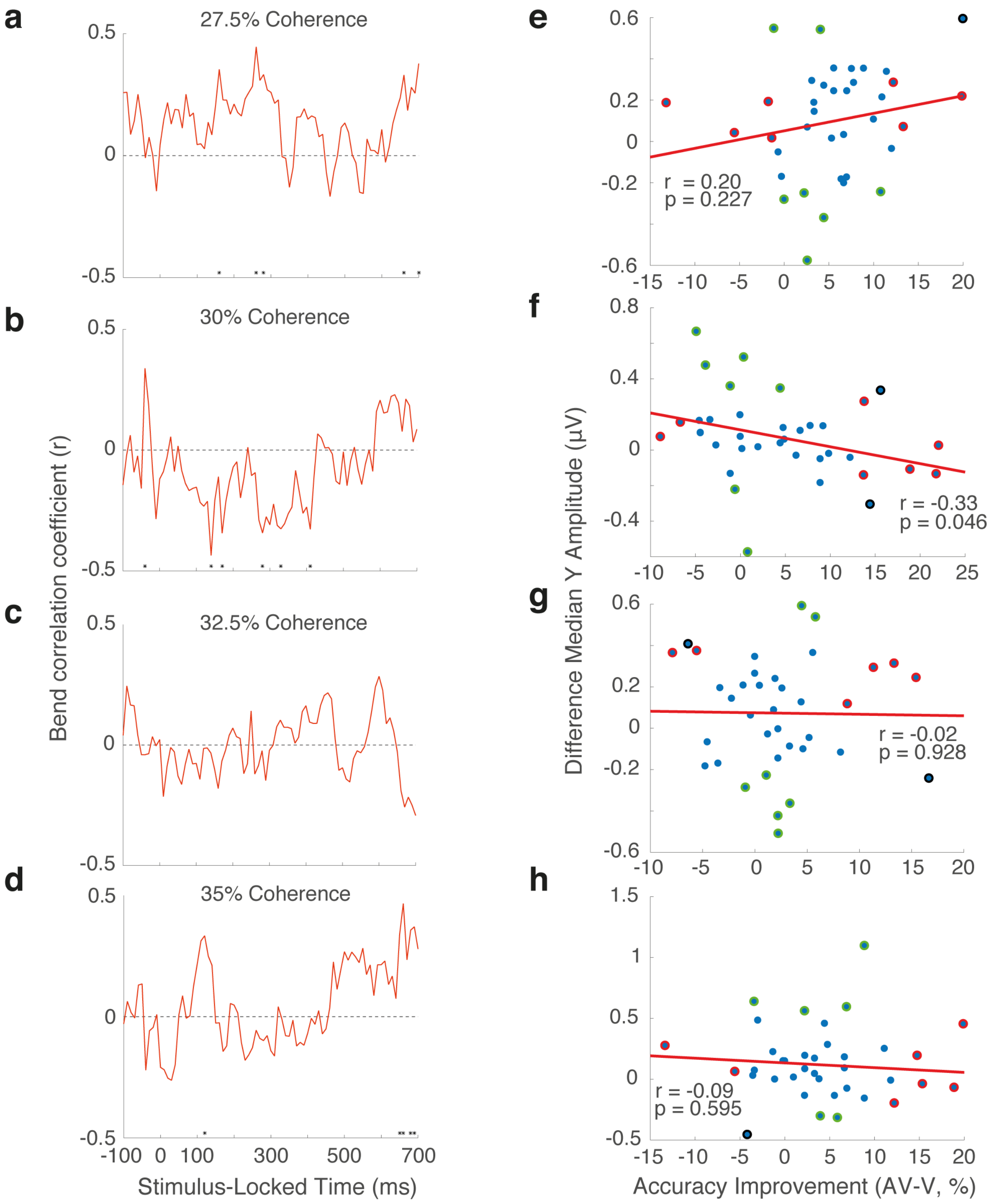


Figure 4.11. Correlation of dyslexics' stimulus-locked component amplitudes (*y*) with behavioural improvements per visual coherence level. a) Correlation of the difference between audio-visual and visual median component amplitudes with behavioural multisensory performance improvement for the 27.5% visual coherence level over time. Robust bend correlations were used for computing correlation coefficients (r) and p-values. One correlation value per window. **b)** Correlation as in panel a but for the 30% visual coherence level. **c)** Correlation as in panel a but for the 32.5% visual coherence level. **d)** Correlation as in panel a but for the 35% visual coherence level. **e)** Correlation of the difference between audio-visual and visual median component amplitudes averaged across the time window of the stimulus-locked intermediate component (i.e., 290-330 ms post-stimulus) with behavioural multisensory performance improvement for the 27.5% visual coherence level. Correlation coefficient (r) and p-value from robust bend correlation shown. Colours

indicate down-weighted data points: red for data in X, green for data in Y and black for data in X and Y. In each dimension 20% of all data points were down-weighted. **f)** Correlation of the component amplitudes, correlation values and colour coding as in panel e but for the 30% visual coherence level. **g)** Correlation of the component amplitudes, correlation values, and colour coding as in panel e but for the 32.5% visual coherence level. **h)** Correlation of the component amplitudes, correlation values and colour coding as in panel e but for the 35% visual coherence level.

4.5 Discussion

The main interest of this study was to use the electroencephalogram for characterising the temporal mechanisms underlying the influence of additional auditory evidence on neural representations of sensory and post-sensory visual evidence in adult dyslexia. Here, we have shown that differences during intermediate stages around 300 ms post-stimulus onset (i.e., between early sensory and later post-sensory decision-related processing stages) represent differential processing of audio-visual perceptual evidence in dyslexia. Specifically, we identified one ‘intermediate’ and one ‘late’ EEG component on stimulus-locked data, and one post-response component on response-locked data that differed between visual and audio-visual trials in the dyslexia group. Scalp topographies indicated that all three EEG components reflect the activity of different neural substrates. In the control group, neural differences between modalities were associated with one late component as identified by our stimulus- and response-locked analyses. Scalp topographies suggested that the EEG component identified by both analyses originated from the same neural substrates, and therefore, represent the same functional process indexing post-sensory decision-related processing (Diaz et al., 2017; Ratcliff et al., 2009).

Temporal EEG components. Significant differences during early encoding of the sensory evidence (i.e., < 250 ms post-stimulus) were absent in either group. Such differences would have suggested differential bottom-up sensory processing. This lack of significant early differences stands in opposition to a number of studies reporting enhancements of such early sensory neural components as a consequence of multisensory evidence in non-dyslexics (Boyle et al., 2017; Romei et al., 2007; Sperdin et al., 2009; Talsma et al., 2007), and deficits of dyslexics on simple non-linguistic integration tasks that start during early sensory encoding of the evidence (Mittag et al., 2012; Schulte-Körne et al., 1999; Widmann et al., 2012). Although these reports contradict the results presented in this study, they can be reconciled by taking a task’s demands into account. For instance, one could differentiate between tasks that present relatively simple and less noisy (i.e., less degraded) stimuli including features such as orientation, contrast, spatial frequency and pitch, and other tasks that require the holistic processing of noisy stimuli, which consist of a multitude of visual elements and auditory frequencies such as faces, cars, and speech.

In general, we found significant differences between visual and audio-visual trials in our EEG data exclusively during later time windows (i.e., > 290 ms post-stimulus onset) in both groups. These time points have previously been associated with post-sensory accumulation of decision evidence (e.g., Ratcliff et al., 2009), which is a vital part of the predictions of sequential sampling models (Ratcliff & Smith, 2010; Ratcliff, Smith, & McKoon, 2015; Smith & Ratcliff, 2004). The exact timing of all identified components suggests that the identified components represent post-sensory influences of combined audio-visual on visual representations. Differences occurred slightly earlier in time in the dyslexia group, which indicated influences of auxiliary processes on post-sensory processing of decision evidence.

In the dyslexia group, significant differences between visual and audio-visual component amplitudes started to emerge around 290 ms post-stimulus onset, represented by an intermediate EEG component. We termed it *intermediate*, since this component is temporally situated between the established *early* (indexing early sensory encoding of the evidence) and *late* components (indexing downstream decision-related processing), which have been repeatedly characterised in similar visual perceptual decision making tasks in non-dyslexics (Diaz et al., 2017; Philiastides et al., 2014; Philiastides & Sajda, 2006; Ratcliff et al., 2009). The intermediate component's timing allows it to be a good candidate for modulating downstream decision-related evidence accumulation as sensory evidence is passed through the cortices and entering the process of evidence accumulation. Fittingly, its scalp activity profile showed a mixture of the signatures of both previously characterised two components.

This scalp activity profile, namely strongest activation over centrofrontal electrode sites, is comparable to a component associated with the allocation of attention reported by Busse, Roberts, Crist, Weissman, & Woldorff (2005). Both its scalp topography and timing are in line with attention-related processes within the perceptual decision making cascade as proposed by Heekeren and colleagues

(2008). Such modulatory function of attention during audio-visual trials stands to reason since effects of attention on audio-visual integration with similar timing have previously been reported (Busse et al., 2005; Talsma & Woldorff, 2005). Further, largely overlapping networks have been associated with post-sensory decision processing and attention networks including temporoparietal and frontal cortices (Amso & Scerif, 2015). More evidence for the crucial role of attention in audio-visual perceptual decision making comes from its links to multisensory enhancements (Gleiss & Kayser, 2014a, 2014b; Kayser et al., 2017; Talsma et al., 2007). Our results point towards attention modulation taking the form of a top-down feedback process since attention has been proposed to act increasingly as a top-down modulator with increasing stimulus complexity in concurrent audio-visual stimulation (Talsma et al., 2010); which is similar to the stimulation we used in this study.

Specifically in the context of dyslexia, previous literature has found impairments in visual attention (e.g., Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Paganoni, Turatto, et al., 2000; Heiervang & Hugdahl, 2003; Lobier et al., 2012), and an aberrant cognitive profile including attention that persist into adulthood (Beidas et al., 2013), which are likely related to reading problems (Boden & Giaschi, 2007). In their review, Boden & Giaschi (2007) link these impairments in visual attention to the magnocellular system whose aberrant maturation has been postulated as one of the main underlying causes of dyslexia (e.g., Stein, 2001; Stein, 2018a, 2018b; Stein & Walsh, 1997). This system is specialised in the processing of fast transient stimuli of low contrast and low spatial frequencies (Merigan & Maunsell, 1993), and has been linked to reading (Laycock & Crewther, 2008) through it enabling rapid focusing of attention on the letter to be identified (Vidyasagar & Pammer, 2010). Congruent with this functional description, all images we used had relatively low contrast. These image properties coupled with our findings of lower component amplitudes and worse performance of our discriminator in the purely visual condition, albeit comparable component amplitudes for the audio-visual condition between-groups, suggest lower quality of the visual perceptual evidence in dyslexia. Concordant support for this interpretation is provided by our behavioural results showing a baseline deficit for dyslexics in the visual condition but intact audio-visual integration (i.e., similar improvements on audio-visual trials) across visual difficulty levels. This pattern of behavioural results was also found in dyslexic adults during audio-visual detection of short syllables in noisy backgrounds (Ramirez & Mann, 2005). Hence, the observed deficits in the visual condition may indicate functional deficits in dyslexics' magnocellular system.

Later in time, during time windows associated with the established late component (i.e., > 350 ms post-stimulus) that indexes downstream processing of decision-related evidence, we observed a small difference in discriminator performance between our modality conditions in both groups. In the dyslexia group, we found this difference exclusively in the stimulus-locked but not in the response-locked analysis. This suggests that, in adult dyslexia, our late component reflects post-sensory audio-visual influences on visual evidence accumulation, but to a smaller extent than this group's earlier post-sensory processes represented by the intermediate component. Contrarily, in the control group, only our response-locked discrimination analysis revealed a substantial effect of audio-visual influences on the quality of the neural evidence between -150 and -50 ms pre-response. This finding indicates that, in non-dyslexics, additional perceptual auditory evidence enhances the quality of the audio-visual neural evidence during post-sensory evidence accumulation stages near the response. The provision of additional auditory evidence resulted in the clearer separation of the stimulus-specific (i.e., face versus car) neural representations during these post-sensory processing stages. This interpretation is in agreement with previous accounts that have linked the quality of the neural evidence, represented by the component amplitudes of the Late component, to downstream decision-related processing in non-dyslexics (Philiastides & Sajda, 2006; Ratcliff et al., 2009), with predictive power of the decision outcome (Diaz et al., 2017). However, generally longer response times on audio-visual trials and the late component shifting in time with perceived stimulus difficulty (Diaz et al., 2017), serve as a plausible explanation for observing a substantial, significant difference in this component on the group-level only in response-locked data.

Another reason for the late component being better tractable in response-locked data might have been the relatively small amount of perceptual training participants engaged in for the audio-visual condition. As Diaz and colleagues (2017) demonstrated, component amplitudes of the late component increased and shifted earlier in time with perceptual learning. Providing only 15 minutes of training, as opposed to two hours in the latter study, and adding a second modality to the task, might have led to more inter-participant variance in perceived stimulus difficulty, whereby modality differences in stimulus-locked post-sensory components might have become less traceable.

Although dyslexics' neural components point towards a modulation of post-sensory decision processes by attention, conducting a spectral analysis with a focus on activity changes in the alpha- and beta-band (i.e., 8-12 and 14-20 Hz, respectively) could have provided us with more conclusive evidence for the specific role of attention in adult dyslexia on our task (Gleiss & Kayser, 2014a; Thut et al., 2006). Equally, adding a purely auditory control condition to the paradigm would have helped us to comprehensively answer whether the deficits we observed here are causally linked to domain-specific or domain-general perceptual impairments.

Behavioural differences. Alongside differences in neural processing, we observed general behavioural deficits in dyslexics' decision performance irrespective of modality and visual coherence level. Contrary to our hypothesis and previous findings of multisensory integration deficits (Hairston et al., 2005; Kast et al., 2011; Laasonen et al., 2002; Wallace & Stevenson, 2014; Widmann et al., 2012), dyslexics impairments were most prominent in the visual condition as the multisensory performance benefit itself was comparable to non-dyslexics. However, even after improving on audio-visual trials to a similar extent, dyslexics' decision performance on audio-visual trials did not surpass controls' decision performance on visual trials. In this respect, dyslexics also showed indications of a behavioural speed-accuracy trade-off (for a review of the concept, see Heitz, 2014) that might have helped them achieve these accuracy improvements. In other words, dyslexics who indicated their responses later in the audio-visual compared to the visual condition tended to improve more with audio-visual evidence. We did not observe such a relationship in non-dyslexics. Overall, contrary to our expectations, dyslexics did not exhibit slower response times on the group-level. Given reports of general deficits on visual speeded reaction-time tasks (e.g., Sigmundsson, 2005) and slower cognitive processing speed abilities in adult dyslexia (Beidas et al., 2013), this finding suggests that the observed increase in response time on audio-visual trials was not a result of a general cognitive processing speed deficit in our dyslexia group.

In this study, we have offered evidence for behavioural deficits and neural differences in adult dyslexia. However, the component amplitudes of our identified temporal components did not directly relate to the multisensory behavioural performance improvements. We can only conjecture about the reasons for this finding. Firstly, it is conceivable that correlation analyses using single-trial component amplitudes of our EEG components, as opposed to behavioural and neural trial averages, would allow us to establish a more mechanistic and robust link between neural processes and the behavioural decision outcome. Secondly, computational modelling using a drift diffusion-type model could offer valuable mechanistic insights as it would capture evidence coming from decision accuracy and response time, which makes it a more sensitive measure. Thirdly, we presume that the identified intermediate component is modulated by the cognitive process of attention. However, its absent link to the outcome of the decision may indicate that attention only plays an auxiliary role within the perceptual decision making cascade of events in dyslexia. This interpretation is in line with Schroeder and colleagues (2008) who concluded that the temporal sensitivity of multisensory enhancement effects discounts attention as the exclusive explanation of such enhancements.

Decision task. The face versus car decision task and EEG analysis employed in this study draw back on an extensive body of literature investigating the temporal neural decision components involved in non-linguistic visual perceptual decision making (e.g., Diaz et al., 2017; Philiastides & Sajda, 2006, 2007; Philiastides et al., 2006; Ratcliff et al., 2009). This literature provides precise indications of the involved neural components, their scalp topographies and interpretation, which we exploited as reference points in the study at hand. However, even though the temporal neural components expected in the context of this task are well known, some alterations and changes of the experimental design may improve discriminability of visual and audio-visual decision components in adult dyslexia. Firstly, an amended version of this task could include an orthogonal decision task such as colour discrimination of the images in the visual condition as previously used by Philiastides and colleagues (2007) or auditory tone-frequency discrimination. It is also conceivable to use an adapted version of the task during which a cue in the beginning of a trial indicates whether a decision is required on a given trial. A colour decision may activate different early decision components reflecting a perceptual event as reported by Philiastides and colleagues (2007) for non-dyslexics. Using a decision/no-decision design may allow for disentangling the neural components involved in a perceptual decision from components involved in mere perception of the stimuli. Adding such an orthogonal decision task to the paradigm would enable us to discriminate between trials with and those without a decision during the single-trial analysis, whereby differences in the timing and scalp profile of the decision components in dyslexia might become more evident. Secondly, another possibility would be to employ a different audio-visual task such as a random dot-motion task, which is known to activate the magnocellular system. Given the increasing evidence for deficits in the magnocellular system in dyslexia (Stein, 2001, 2018b, 2018a), the use of a motion discrimination task may allow shedding even more light on the specific differences in non-linguistic temporal perceptual decision components in adult dyslexia. This task could also avoid evoking early neural components by using a gradual instead of a sudden onset of the stimuli (O’Connell et al., 2012) and could be combined with a colour discrimination condition. Additionally and independently of the task, using a wider spectrum of sensory evidence (i.e., image phase coherence) might increase discriminability further and allow for establishing more reliable links between neural and behavioural data, since a wider spectrum has been shown to evoke different strengths of the decision components (e.g., Kelly & O’Connell, 2013; Philiastides & Sajda, 2006).

In summary, here we have demonstrated that adult dyslexics exhibit impairments on a purely non-linguistic audio-visual perceptual decision task that did not require the engagement of linguistic neural systems during decision formation. Dyslexics’ deficits were particularly striking in the visual condition as their decision accuracy improved to a similar extent when provided with additional auditory perceptual evidence compared to non-dyslexics. Specifically, one intermediate neural component for dyslexics, associated with initial attention-related post-sensory processing, and one late component for non-dyslexics, indexing post-sensory evidence accumulation, represented neural differences between modality conditions. The presented results suggest fundamentally different temporal processing of audio-visual non-linguistic evidence during perceptual decision making as an inherent part of dyslexia. The observed neural differences reinforce dyslexia’s neurobiological nature; while also making a substantial contribution to the literature by providing more evidence against the traditional view of dyslexia as an exclusively language based specific learning disorder.

Chapter 5. General discussion

5.1 Overview

Literacy, reading, and efficient visual word recognition are essential skills for independent life and success in many societies nowadays. Countless daily situations require fast word recognition and good reading comprehension ranging from ones as unremarkable as reading the list of ingredients on a food container, to completing educational assignments or making important contractual decisions.

Becoming a proficient reader depends highly on the process of print tuning (i.e., the adaptation to a novel script). This process is reflected in early ERP components such as the P1 and N1 (Brem et al., 2018; Maurer et al., 2006), which are also sensitive to the physical make-up and properties of words, such as font (Chauncey et al., 2008). However, since the neural dynamics associated with font style were entirely unknown in people with and without dyslexia, we relied on the temporal precision of EEG measurements to examine the effects of an italic font on temporal brain dynamics and reading comprehension in adult dyslexia (Chapter 2).

In Chapter 3, given numerous reports of visual dyslexia symptoms and dyslexics' struggle with certain font types, we aimed to develop an understanding of the physiological (i.e., visual eye movements) and cognitive mechanisms underlying the efficacy of specific dyslexia fonts. The design of these fonts incorporates multiple font properties that have been shown to enhance reading performance such as increases in spacing, letter size and roundness. Specifically, we used eye-tracking as a window into the human brain to investigate the effects of the dyslexia font OpenDyslexic on reading performance and eye movements in adults with dyslexia.

Although proficient reading is predominantly a visual process, learning to read is, in fact, an audio-visual process that builds heavily on the mapping of auditory speech sounds onto their visual letter representations. Developing the interrelated network of visual, auditory and heteromodal brain areas contributing to the skilled use of letter-speech sound associations takes years (Blau et al., 2010). Findings in non-dyslexics demonstrated that additional auditory perceptual evidence can modulate neural visual representations while enhancing behavioural decision performance using simple perceptual stimuli. Motivated by the long-standing theoretical debate about the aetiology of dyslexia (i.e., phonological linguistic high-level versus sensory perceptual low-level deficiencies), and building on these findings of perceptual, sensory differences, we probed a fundamental deficit in the neural integration of audio-visual perceptual evidence in the absence of any linguistic or phonological demands in dyslexia. To this end, we employed an established face versus car object categorisation task with noisy (i.e., degraded) real-world stimuli and a multivariate single-trial discriminant analysis of our EEG data (Chapter 4).

In short, this thesis sought to provide a mechanistic account of the neural and visual correlates of adult dyslexics' linguistic and non-linguistic perceptual decision making. We hypothesised that early sensory neural components would capture dyslexics' difficulties with (1) processing italicised font efficiently during visual word recognition, and (2) exploiting the benefits of additional auditory perceptual evidence during visual decisions in the absence of linguistic task demands. Finally, (3) we conjectured that the specific dyslexia font OpenDyslexic would ease visual processing demands leading to faster and more accurate processing of text as reflected in changes of certain eye movements.

5.2 Key findings

We demonstrated in this thesis that adult dyslexia manifests in deficient neural, visual (i.e., oculomotor control), and behavioural performance in a range of visual and audio-visual tasks. Across all studies, we found differences in temporal neural components at various early and later stages of the neural perceptual decision making process. Specifically, we revealed that even small perceptual alterations induced by a different font style (i.e., *italic* compared to regular font), which went undetected by most dyslexic participants, hampered the visual word recognition of the adult dyslexic reader with decades of reading practice. Such deficient visual reading processes could be alleviated in paragraph reading by using the specific dyslexia font OpenDyslexic, which led to more ease of processing, reduced cognitive load and enhanced reading comprehension. Visual deficits persisted even in the absence of any linguistic task demands, whereas audio-visual integration was found to be intact. This multifactorial combination of deficits in the visual domain highlights the vital role of aberrant visual perception in dyslexia.

The results from our lexical decision task show that neural differences in adult dyslexia start to emerge during early encoding of the sensory evidence in font-modulated visual word recognition. Specifically, we identified two distinct neural components that represented differential orthographic word form analysis (i.e., encoding of sensory evidence) within 170 ms after encountering a decision word, and initial steps of post-sensory processing of decision evidence around 250 ms (i.e., one occipitotemporal and one centrofrontal component, respectively). The timing of the earlier occipitotemporal component is in line with a study reporting congruency effects of font type around 150 ms after word presentation onset (Chauncey et al., 2008). Such early sensory components, occurring within 200 ms after word presentation onset, have repeatedly been associated with the processing of familiar scripts, font types, and holistic objects such as faces (Korinth, Sommer, & Breznitz, 2012; Maurer, Brandeis, & McCandliss, 2005; Pegado et al., 2014; Rousselet et al., 2008). Further, the two identified components were linked on a single-trial basis underlining that visual word recognition is based on a fast cascade of interconnected and incremental processes as proposed by previous literature (Bentin et al., 1999; Dien, 2009; Holcomb & Grainger, 2006; Rayner & Clifton, 2009; Sereno & Rayner, 2003). Similarly, in line with previous findings of bilateral EEG components and lower activity in the ventral stream in dyslexia, particularly in the VWFA (Hasko et al., 2012; Kronschnabel et al., 2013; Olulade, Flowers, Napoliello, & Eden, 2015; Shaywitz et al., 2002; Shaywitz et al., 2006), we observed a lack of left lateralisation of the early occipitotemporal component in the dyslexia group. Although adult dyslexic university students have years of training in reading and tend to have good vocabulary depth skills (Cavalli, Casalis, et al., 2016), these findings demonstrate that a small alteration of the font style can impede efficient neural processing during visual word recognition and lexical decision making. Our results suggest choosing font type and style carefully to optimise neural processing of text by everyone.

Strikingly, we found a post-sensory neural component with centrofrontal scalp activity profile peaking at somewhat similar latencies in both EEG studies (i.e., lexical decision making and audio-visual non-linguistic object categorisation). We observed this component during audio-visual object categorisation slightly later (i.e., around 300 ms compared to 250 ms post-stimulus onset), where it represented different quality of the neural perceptual evidence between visual and audio-visual trials. Important to note is that while the quality of the neural evidence and behavioural improvements on audio-visual trials were comparable between dyslexics and non-dyslexics, this component reflected diminished quality of the visual neural evidence for dyslexics. We observed this neural deficiency alongside a specific behavioural deficit in the visual condition.

These two EEG components complemented each other as they showed similar centrofrontal scalp topography, but were obtained using two different analyses (i.e., cluster-based ERP and single-trial multivariate discriminant analysis) and two fundamentally different tasks. Despite peaking at slightly different latencies, their comparable scalp topographies suggested that both components reflect differences in post-sensory decision-related neural activity at the beginning stages of evidence accumulation. This activity may represent loops of recurrent top-down modulated activity (Amso & Scerif, 2015) during access to the mental word lexicon or matching of the perceptual evidence for a face or car with stored representations of these objects. Our interpretation is supported by the across-subject link between the centrofrontal component and decision accuracy in our lexical decision task, as post-sensory decision components have been shown to be a better predictor of the outcome of a perceptual decision (e.g., Diaz et al., 2017; Ratcliff et al., 2009). This link to the decision outcome, its spatial topography, and the link to its preceding occipitotemporal component point to differences within the frontoparietal network implicated in decision making and attentional modulation (Amso & Scerif, 2015). In particular, the results from our multisensory non-linguistic perceptual decision task suggest the modulation of this post-sensory processing stage during audio-visual integration by attention (Heekeren et al., 2008). During this stage, attention has been proposed to take on an assistive role supporting multisensory enhancements in multisensory non-linguistic perceptual decision making (Schroeder et al., 2008).

Taken together, the consistency of the neural dynamics that characterise these two centrofrontal EEG components across the two different tasks endorses a fundamental difference at this stage of information processing in adult dyslexia. At the same time, the differences in these centrofrontal components' links to the decision outcome suggest that the noise level of stimuli and the nature of the task (i.e., linguistic or non-linguistic) plays an important role for unravelling the exact temporal processing stages of perceptual decision making in adult dyslexia.

In Chapter 3, we used eye-tracking as a psychophysiological window into the brain to clarify the role of oculomotor control in dyslexia and decipher the cognitive mechanisms underlying the efficacy of specific dyslexia fonts. We demonstrated that the specific dyslexia font OpenDyslexic helps to improve reading comprehension in dyslexics and non-dyslexics when using standardised texts as stimuli (IReST; Trauzettel-Klosinski & Dietz, 2012). Here, OpenDyslexic facilitated visual processing by increasing the average saccade amplitude while decreasing the average fixation duration. Generally, prolonged average fixation duration among dyslexics suggests higher cognitive load (Just & Carpenter, 1980) and the potential of a smaller perceptual span (Choi et al., 2015), which has previously been found for dyslexics (Rayner et al., 1989) and slower readers (Rayner et al., 2010). Also, dyslexics exhibited increased rates of falsely programmed saccades (i.e., directional shifts) only on trials presented in Times New Roman but not those in OpenDyslexic font. This finding is in line with studies reporting impairments in voluntary and involuntary saccade control (Biscaldi et al., 2000; Bucci et al., 2008, 2012), and points to aberrant oculomotor control in adult dyslexia. This strand of research has proposed a deficiency in visual attentional processing (Bucci et al., 2012; Fischer et al., 1993; Stein, 2014), and aberrancies in 'magnocellular' (M) nerve cells (e.g., Stein, 2014, 2018b). Although these directional shifts could also be a result of rushed saccades in order to compensate for slower reading, dyslexics' substantially longer reading duration renders this explanation unlikely. Our psychophysical results were complemented by the observation that the majority of dyslexics (66%) preferred OpenDyslexic over traditional Times New Roman font.

Since our results stand in opposition to several reports questioning the behavioural efficacy of specific dyslexia fonts (Kuster et al., 2018; Marinus et al., 2016; Rello & Baeza-Yates, 2013), they emphasise two points. First and foremost, our findings illustrate that physiological measurements such as eye movements capture the cognitive mechanisms elemental to the efficacy of dyslexia fonts (i.e., improved reading comprehension) better than behavioural measures do. Second, they endorse using standardised text stimuli for reading studies that present longer paragraphs of text to gain more control over the manipulation in question.

All results considered, we argue that Pringle Morgan's (1896) description of dyslexia as ‘congenital word blindness’ accurately highlighted one major symptom of dyslexia: deficits in visual perception. As shown in Chapters 2 and 3 of this thesis, small perceptual manipulations of written words, introduced by variations in font type and style, are sufficient to elicit differences in neural, visual, and cognitive processing during reading-based decision tasks. Explicitly, Chapter 3 revealed a dyslexia-specific pattern of eye movements, which illustrated dyslexics’ distinct psychophysiological reading strategy. These two studies measured reading comprehension as an index of perceptual decision making ability in sentence and paragraph reading, which requires the participant to comprehend and retain the read content for a short period before comparing it to the provided answers. As such, this measure offers high ecological validity and is inherently complex, which in turn, appears to reveal the subtle differences of dyslexia still present in adult university students. Further, the results presented in Chapter 4 provide evidence for a fundamental deficit in visual perception that appears to be independent of linguistic task demands. These findings add to the theoretical debate on the aetiology of dyslexia by giving merit to sensory dyslexia theories, such as the magnocellular theory (Stein, 2001, 2014, 2018a, 2018b; Stein & Walsh, 1997). This theory argues that magnocells ‘feed’ the cortex with visual information, which is the foundation for developing proficient phonological skills in a second step (Stein, 2018b). Following this view, visual sensory impairments would underlie commonly found phonological and word analysis impairments. However, since dyslexia is a spectrum disability with a number of possible symptoms and phenotypes, our findings do not allow for drawing conclusions that would discredit other dyslexia theories.

5.3 Limitations and future directions

Across all studies, we used a combination of complementary group-level, single-participant, and single-trial analyses. These analyses illustrated that dyslexia is a heterogeneous spectrum disorder resulting in a wide range of possible symptoms.

The large variability in Dyslexia Checklist scores (i.e., between ˜20 and ˜80 points in arbitrary units; Smythe & Everatt, 2001) across dyslexic participants who had all been given an official diagnosis of dyslexia underlined the heterogeneity of possible phenotypes. Such a large range may suggest that individuals with low scores have either successfully compensated for their initial deficits or obtained a diagnosis based on a few salient deficits that persisted but did not lead them to score highly on a checklist based on self-reports. This range might also be a result of our lenient participant inclusion criteria, which required participants to (1) be at least 18 years of age, (2) show proof of an official dyslexia diagnosis, and (3) have attended higher education at some point in their lives. It is conceivable that these inclusion criteria introduced additional variance as we did not specifically exclude dyslexic participants with comorbid disorders such as ADD or ADHD. Estimates of comorbidity of dyslexia with disorders such as ADHD range between 25% and 40% (Hahn et al., 2014; Schulte-Körne & Bruder, 2010). As such, comorbidity and potentially slightly varying cognitive profiles might have been one obstacle for establishing a reliable link between neural and behavioural data in our non-linguistic object categorisation study.

For these reasons, we cannot make inferences about ‘pure’ adult dyslexia, and only suggest modulatory as opposed to causal effects of attention on our tasks. However, dyslexia is by definition a complex specific learning disorder that seldom occurs in a pure form wherefore recruiting pure dyslexics could have introduced a different selection bias. Nevertheless, since the group-level differences presented in this thesis were obtained with high-functioning dyslexic university students, they suggest that similar if not even exacerbated deficits could be observed in a more general dyslexia sample. In future studies, it will be important to characterise dyslexia samples in more detail by using precise cognitive assessments, to be able to clarify the exact relationship between comorbidity, cognitive skills, various dyslexia symptoms, and neural differences during perceptual decision making in dyslexia.

Future research could also examine the effect of font type and style in the context of decision words controlled for word class. Reducing stimulus-induced variance to a minimum may amplify neural differences that result from the use of different fonts and could help to disentangle the processes represented by the post-sensory centrofrontal component we identified during lexical decision making. We consider these all potentially fruitful research issues. Their investigation will continue to illuminate the complex interplay between cognitive and physiological factors in adult dyslexia.

Finally, it is worth noting that while EEG offers precise temporal measurements of simultaneous activity of entire populations of neurons, it offers limited spatial resolution. This limitation did not allow us to disentangle the spatial neural substrates underlying the many processes happening in short succession or even in parallel during post-sensory processing stages of word recognition. Future work could explicitly attempt to disentangle these processes using modern simultaneous EEG/fMRI or MEG approaches, which provide better spatial resolution while preserving the temporal resolution of the EEG. Using this approach would also allow scientists to investigate the specific role of interhemispheric long-range connections in adult dyslexia as reported by Finn and colleagues (2014). For instance, connectivity analyses could shed light on the neural networks involved in compensation mechanisms activated by specific dyslexia fonts.

5.4 Conclusion

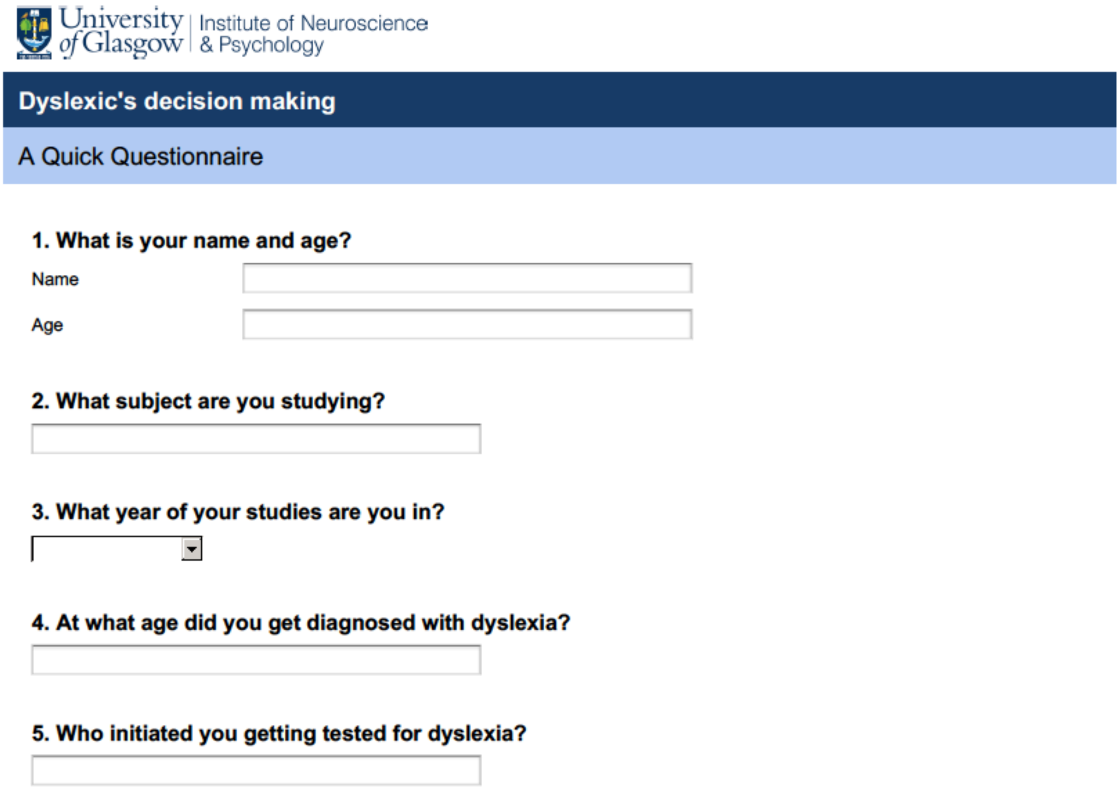
In summary, the empirical findings presented in this thesis suggest that adult dyslexics suffer from a fundamental visual perceptual deficit that goes beyond linguistic tasks, whereby they reinforce the neurobiological nature of dyslexia. They provide insights into the mechanisms underlying dyslexics' impaired perceptual decision making (i.e., reading comprehension, object categorisation and response time) across a variety of tasks. Specifically, we demonstrated that adult dyslexia is characterised by behavioural deficits in perceptual decision making performance that manifest in worse reading comprehension and slower response times. Adult dyslexics further exhibited differential neural activity at various stages during processing of visual stimuli. We found inefficient processing during early encoding of the sensory evidence over occipitotemporal electrodes within the neural word-recognition cascade as early as 170 ms post-stimulus onset. During the same font-based lexical decision task, we identified a second centrofrontal component slightly later in time (i.e., around 250 ms) that was linked to the outcome of the decision illustrating differences in post-sensory processing of decision evidence. More evidence for deficiencies during post-sensory processing around 300 ms post-stimulus onset was provided by findings of a centrofrontal component on an audio-visual non-linguistic object categorisation task. This component reflected worse quality of the neural perceptual evidence on visual trials. Both centrofrontal components emphasise the important role of post-sensory processes and auxiliary cognitive factors, including attention, during fast-paced perceptual decision making in adult dyslexia. Consistent with current beliefs, we showed that centrofrontal and parietal regions appear to play a vital role in processes relevant to the neural formation and behavioural outcome of a decision.

Remarkably, we also observed a different pattern of eye movements during reading that indicated deficits in oculomotor control and higher cognitive load during reading in adult dyslexia. However, we demonstrated that reading comprehension can be improved and cognitive load reduced by presenting written information in the dyslexia font OpenDyslexic.

Altogether, the results of this thesis characterise the neural and visual temporal correlates of font-based perceptual decision making during reading and show a fundamental deficit in visual non-linguistic decision making in adult dyslexia. These findings have the potential to serve as a cornerstone for future investigations of the neurobiological characteristics of dyslexia on applied real-world perceptual decision making tasks, and the development of affordable intervention programmes.

Appendices

Appendix A: Questionnaire administered to dyslexic participants after the lexical decision task (Chapter 2)



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Dyslexic's decision making

A Quick Questionnaire

1. What is your name and age?

Name

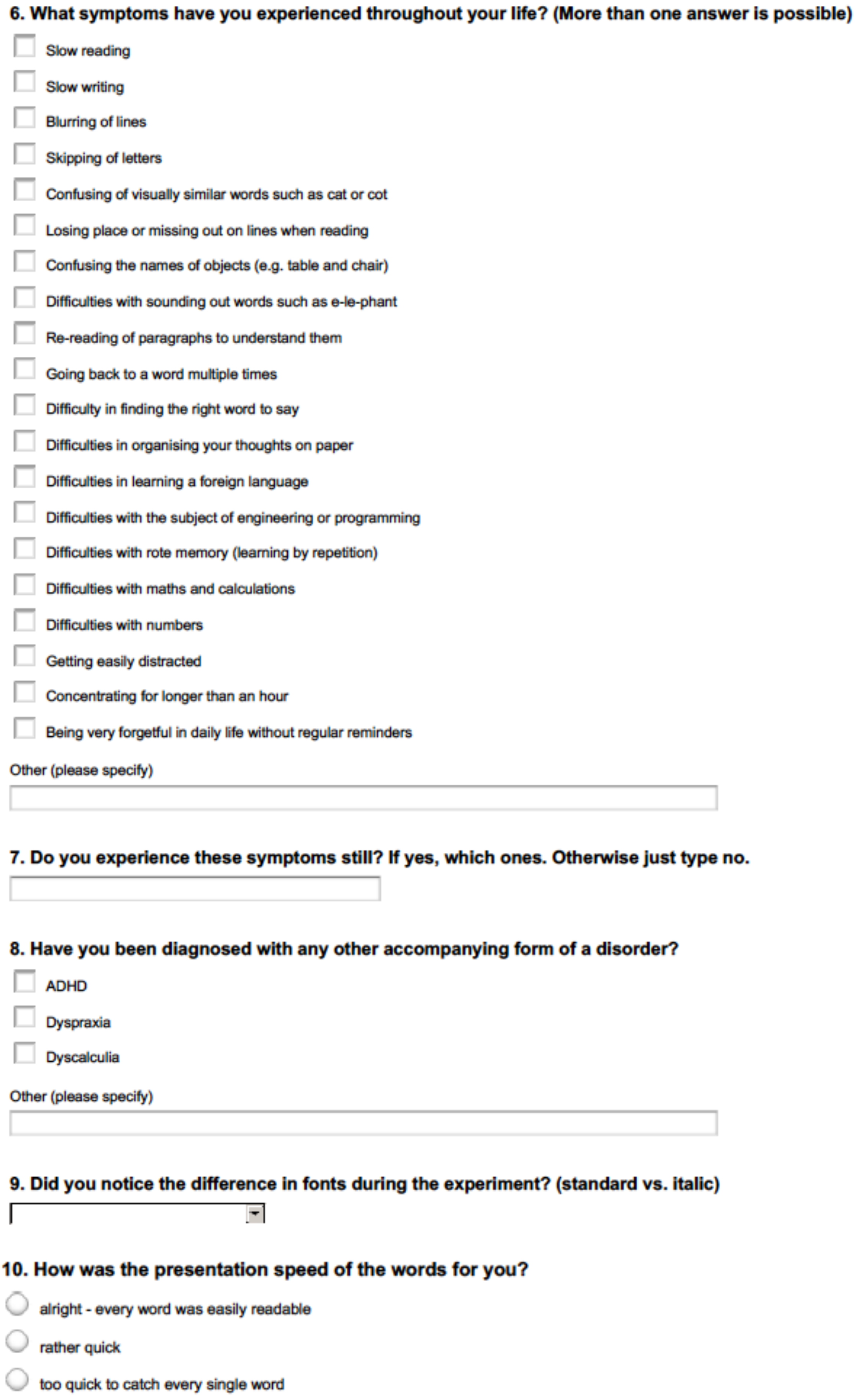
Age

2. What subject are you studying?

3. What year of your studies are you in?

4. At what age did you get diagnosed with dyslexia?

5. Who initiated you getting tested for dyslexia?



6. What symptoms have you experienced throughout your life? (More than one answer is possible)

- ☐ Slow reading
- ☐ Slow writing
- ☐ Blurring of lines
- ☐ Skipping of letters
- ☐ Confusing of visually similar words such as cat or cot
- ☐ Losing place or missing out on lines when reading
- ☐ Confusing the names of objects (e.g. table and chair)
- ☐ Difficulties with sounding out words such as e-le-phant
- ☐ Re-reading of paragraphs to understand them
- ☐ Going back to a word multiple times
- ☐ Difficulty in finding the right word to say
- ☐ Difficulties in organising your thoughts on paper
- ☐ Difficulties in learning a foreign language
- ☐ Difficulties with the subject of engineering or programming
- ☐ Difficulties with rote memory (learning by repetition)
- ☐ Difficulties with maths and calculations
- ☐ Difficulties with numbers
- ☐ Getting easily distracted
- ☐ Concentrating for longer than an hour
- ☐ Being very forgetful in daily life without regular reminders

Other (please specify)

7. Do you experience these symptoms still? If yes, which ones. Otherwise just type no.

8. Have you been diagnosed with any other accompanying form of a disorder?

- ☐ ADHD
- ☐ Dyspraxia
- ☐ Dyscalculia

Other (please specify)

9. Did you notice the difference in fonts during the experiment? (standard vs. italic)

10. How was the presentation speed of the words for you?

- ○ alright - every word was easily readable
- ○ rather quick
- ○ too quick to catch every single word

Appendix B: Detailed effect sizes of the effect of font on eye-tracking measures (Figure 3.5)

Eye-tracking measure	*Effect size dyslexic*	*95% CI dyslexic*	*Effect size control*	*95% CI control*
Number of blinks	-.01	-.23, .21	.05	-.18, .27
Number of fixations	.05	-.16, .27	.07	-.15, .3
Number of saccades	.16	-.06, .37	.17	-.05, .4
Number of regressions	-.18	-.39, .04	-.13	-.36, .1
Number of runs	.1	-.12, .32	.12	-.1, .35
Fixation/saccade ratio	**-.28**	**-.5, -.06**	**-.16**	**-.39, .06**
Maximum fixation duration	-.15	-.37, .07	-.13	-.36, .1
Median fixation duration	**-.54**	**-.33, -.77**	**-.47**	**-.24, -.7**
Median saccade amplitude	**.91**	**.69, 1.14**	**.81**	**.58, 1.04**
Scan path	**.8**	**.57, 1.02**	**.83**	**.59, 1.06**
Ratio of visited interest areas	**.42**	**.21, .64**	**.28**	**.06, .51**
Ratio skipped words per trial	**-.44**	**-.66, -.22**	-.14	-.36, .09
Number of fixations (10 sec.)	**.45**	**.23, .67**	**.26**	**.04, .49**
Number of saccades (10 sec.)	**.6**	**.38, .82**	**.52**	**.29, .74**
Number of regressions (10 sec.)	-.13	-.35, .09	-.1	-.32, .13
Number of runs (10 sec.)	**.42**	**.2, .64**	**.3**	**.07, .52**
Scan path (10 sec.)	**1.02**	**.79, 1.25**	**.94**	**.7, 1.17**

Significant effects in bold font. An effect was considered significant when the confidence interval did not include zero.

Appendix C: Questionnaire administered to participants after the eye-tracking experiment (Chapter 3)

Welcome page

UNIVERSITÉ Concordia UNIVERSITY

Thank you for participating in this eye-tracking study. We would like to ask you a couple of questions about the experiment and yourself.

Questions only to be answered by the experimenter

I. Subject ID: #
II. Tracked eye
    a. Left
    b. Right
    c. Both
III. Dominant eye
    a. Left
    b. Right
    c. None

Questions to be answered by the participants

1) How comfortable did reading OpenDyslexic feel to your eyes?
   This is OpenDyslexic
    a. 7-point Likert scale

2) How comfortable did reading Times New Roman feel to your eyes?
   This is Times New Roman
    a. 7-point Likert scale

3) Which of the two font types you encountered during the experiment do you prefer?
    a. OpenDyslexic
    b. Times New Roman

4) Overall, did you find the paragraphs presented difficult to understand?
    a. 7-point Likert scale

5) Overall, did you find the comprehension questions difficult to answer?
    a. 7-point Likert scale

6) Did you feel stressed at any point throughout the experiment?
    a. Yes
    b. Yes, a little at times
    c. No, not at all
7) Please rate your stress level during the experiment.
    a. 7-point Likert scale
8) Do you suffer from visual stress occasionally?

Visual stress refers to a condition characterised by the inability to see comfortably and without distortion when looking at a still standing stimulus, e.g. text. Symptoms are visual fatigue, perceived excessive light sensitivity, headaches from exposure to disturbing visual patterns and several kinds of perceptual distortion such as blurring, fading, or flickering of the visual stimulus. (Uccula et al., 2014)

   a. Yes, almost daily
   b. Sometimes
   c. No, not at all
   d. Only when reading

9) Do you like to read fiction?
   a. 7-point Likert scale

10) Do you like to read academic journal articles?
   a. 7-point Likert scale

11) Would you describe yourself as a regular reader?

By regular we mean reading text heavy formats such as academic journal articles, fiction or non-fiction books multiple times a week.

   a. Yes
   b. No

12) Overall, did you find the paragraphs presented easy to understand?
   a. 7-point Likert scale

13) Overall, did you find the comprehension questions easy to answer?
   a. 7-point Likert scale

Demographics

14) How old are you?

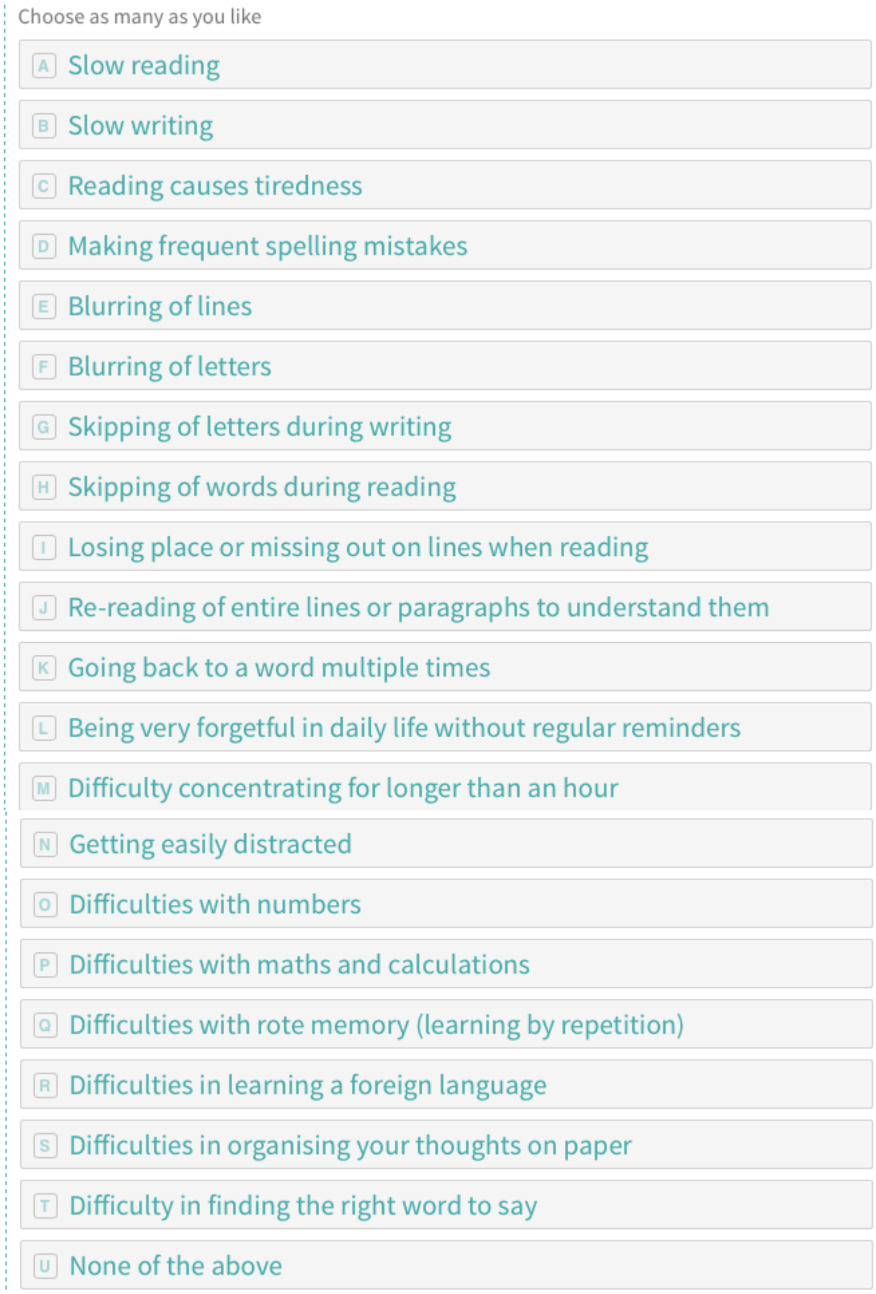
15) What is the current or former field/subject of your studies?

16) What year of your studies are you in?
   a. 1st
   b. 2nd
   c. 3rd
   d. 4th
   e. 1st Master
   f. 2nd Master
   g. PhD
   h. Alumni

17) Have you been given an official diagnosis of dyslexia at some point in your life?
   a. Yes
   b. No

18) If you have been given an official diagnosis of dyslexia, at what age was this diagnosis given?

19)Do you encounter any of the following problems today?



Choose as many as you like

- A Slow reading
- B Slow writing
- C Reading causes tiredness
- D Making frequent spelling mistakes
- E Blurring of lines
- F Blurring of letters
- G Skipping of letters during writing
- H Skipping of words during reading
- I Losing place or missing out on lines when reading
- J Re-reading of entire lines or paragraphs to understand them
- K Going back to a word multiple times
- L Being very forgetful in daily life without regular reminders
- M Difficulty concentrating for longer than an hour
- N Getting easily distracted
- O Difficulties with numbers
- P Difficulties with maths and calculations
- Q Difficulties with rote memory (learning by repetition)
- R Difficulties in learning a foreign language
- S Difficulties in organising your thoughts on paper
- T Difficulty in finding the right word to say
- U None of the above

20) What is your native language?
   a. English
   b. French
   c. Bilingual

21) Which language do you use more often?
   a. English
   b. French
   c. I use both interchangeably to the same extent

22) How many languages do you speak fluently including your native language?
   a. 1
   b. 2
   c. 3

   d. 4 or more

23) How many foreign languages have you been formally taught in school or university?
   a. 1
   b. 2
   c. 3
   d. 4 or more

24) What country are you a citizen of?
   a. Canada
   b. United States of America
   c. Other

25) If you selected other, please specify your country of citizenship. Otherwise ignore this question.

26) If you selected other, please specify how long you have been living in Canada for. Otherwise ignore this question.
Please fill in a number in months (1 year = 12 months)

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