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Altered patterns of directed connectivity within the reading network of dyslexic children and their relation to reading dysfluency

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ABSTRACT

Reading is a complex cognitive skill subserved by a distributed network of visual and language-related regions. Disruptions of connectivity within this network have been associated with developmental dyslexia but their relation to individual differences in the severity of reading problems remains unclear. Here we investigate whether dysfunctional connectivity scales with the level of reading dysfluency by examining EEG recordings during visual word and false font processing in 9-year-old typically reading children (TR) and two groups of dyslexic children: severely dysfluent (SDD) and moderately dysfluent (MDD) dyslexics. Results indicated weaker occipital to inferior-temporal connectivity for words in both dyslexic groups relative to TRs. Furthermore, SDDs exhibited stronger connectivity from left central to right inferior-temporal and occipital sites for words relative to TRs, and for false fonts relative to both MDDs and TRs. Importantly, reading fluency was positively related with forward and negatively with backward connectivity. Our results suggest disrupted visual processing of words in both dyslexic groups, together with a compensatory recruitment of right posterior brain regions especially in the SDDs during word and false font processing. Functional connectivity in the brain's reading network may thus depend on the level of reading dysfluency beyond group differences between dyslexic and typical readers.

1. Introduction

Although reading is a complex cognitive function, 90–95% of all children master it without notable problems. However, children suffering from developmental dyslexia never attain fluent reading skills despite adequate intellectual abilities and educational opportunities (Blomert, 2005; Lyon et al., 2003). Among the reading-related deficits of developmental dyslexia, reading dysfluency poses the most pronounced and long lasting hurdle (Shaywitz et al., 2008), especially in relatively transparent orthographies, such as Dutch or German (Blomert, 2011; Wimmer and Schurz, 2010). At the same time, dyslexics show substantial inter-individual variability in their level of reading (dys)fluency (Katzir et al., 2008; Leinonen et al., 2001). One of the neurobiological signatures of dyslexia is an abnormal pattern of functional and/or anatomical connectivity within the brain's reading network (Geschwind, 1965; Paulesu et al., 1996; Vandermosten et al., 2012; Wimmer and Schurz, 2010). Impaired connectivity could disrupt decoding or orthographic–phonological integration at word (Wimmer and Schurz, 2010), syllable and/or phoneme level (Blomert, 2011), causing slower and less accurate reading in dyslexics. In the present study we investigate whether atypical neural connectivity scales with differences in the level of reading (dys)fluency in dyslexic children.

Abbreviations: DTF, directed transfer function; TR, typical readers; MDD, moderately dysfluent dyslexic readers; SDD, severely dysfluent dyslexic readers.

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Reading depends on efficient processing in large scale neural networks combining information of multiple and distinct processes in different brain regions. In particular, reading is subserved by brain networks for spoken language and visual processing that become closely linked over the first years of reading development (Hannagan et al., 2015; Schlaggar and McCandliss, 2007). Communication or connectivity between these regions may be mediated by the phase relation of cortical oscillations (Engel et al., 2001; Varela et al., 2001). In humans, these oscillations are typically measured at different scalp locations using electro-encephalography (EEG) or magneto-encephalography (MEG). There are several methods to determine EEG/MEG-based functional non-directed or directed connectivity. One of the first proposed measures of functional connectivity refers to EEG coherence, which provides the correlation between cortical oscillations across channels (Varela et al., 2001). More recently, directed connectivity measures have been developed, which provide additional information on the directionality of connectivity across channels. In the present study, we apply the directed transfer function (DTF) method. DTF is based on multivariate autoregressive models and Granger causality (Granger, 1969; Kamiński and Blinowska, 1991).

Directed connectivity measures have been successfully used to investigate the oscillatory dynamics of the reading network in typically reading adults (Bedo et al., 2014; Kujala et al., 2007; Woodhead et al., 2014). For example, the MEG study of Kujala et al. (2007) investigated directed connectivity by coherence-based detection of interconnected nodes in brain source space. This method enabled them to demonstrate that the processing of words in a rapid serial visual presentation (RSVP) paradigm involves long-range communication via alpha band (8–14 Hz), and in about half of the subjects also via beta band (15–30 Hz) activity. More specifically, their results showed activation propagation from posterior to anterior areas with the inferior occipito-temporal cortex and cerebellum as the main driving nodes, as well as more local frontal connectivity in areas related with visual recognition and working memory (Kujala et al., 2007). Furthermore, an EEG study applying phase synchrony and transfer entropy to analyze connectivity between independent components, reported ventral occipito-temporal cortex (vOT) as a central hub for word reading, with theta (3–7 Hz) and gamma (30–50 Hz) band connectivity between vOT and both early visual and language-processing areas (Bedo et al., 2014).

Several EEG/MEG studies investigated connectivity in the reading network of typically reading and dyslexic children or adults during rest and reading/attention related tasks. These studies have reported a mixed pattern of group differences, as reflected by connectivity, coherence, spectral power and network configuration measures (Arns et al., 2007; Dhar et al., 2010; Dimitriadis et al., 2013; Fraga González et al., 2016a; Frye et al., 2012, 2010; Leisman, 2002; Ligges et al., 2010; Milne et al., 2003; Stokić et al., 2011). In broad outline, however, these studies revealed altered EEG/MEG connectivity in dyslexic readers, including a general tendency for altered posterior-to-frontal connectivity (e.g. Arns et al., 2007; Milne et al., 2003) and a relatively stronger reliance on right hemisphere regions (e.g. Arns et al., 2007; Ligges et al., 2010).

The central aim of the present study is to investigate whether directed connectivity during reading scales with the level of dysfluency in dyslexic children. We investigate patterns of directed connectivity in the reading network in typically reading (n = 20) and two groups of dyslexic children: moderately dysfluent dyslexic (n = 18) and severely dysfluent dyslexic (n = 16) readers. The same groups of children were previously shown to exhibit different patterns of neural integration of letters and speech sounds as represented by mismatch negativity (MMN, 100–250 ms) and late negativity (LN, 600–750 ms) ERPs in a cross-modal oddball paradigm (Žarić et al., 2014). Specifically, both dyslexic groups exhibited reduced audiovisual integration of letters and speech sounds in the later time window (cross-modal LN), while severely dysfluent dyslexics additionally showed a reduction in the earlier perceptually driven audiovisual MMN response (Žarić et al., 2014). Here, we employ a visual word recognition paradigm (Fraga González et al., 2014, 2016b) to investigate whether directed connectivity during the processing of visual words and letter-like meaningless false font strings indicates a different functionality of the reading network in these groups. In particular, as the false fonts were designed to be letter-like, both word reading and false font 'reading' may be impaired in the severely dysfluent dyslexic group due to the weakest orthographic–phonological connectivity at word and/or subword level (Blomert, 2011; Wimmer and Schurz, 2010). Instead moderately dysfluent dyslexic children may more efficiently differentiate these stimulus types and exhibit impairments predominantly during the word reading condition. We quantify directed connectivity using the DTF which provides both the strength and direction of connectivity between selected electrodes (Kamiński and Blinowska, 1991). Focusing on the level of (dys)fluency in reading allowed us to examine whether children differing in fluency and letter-speech sound integration capability exhibit different patterns of directed connectivity that could potentially contribute to the mixed and inconclusive results obtained in previous functional connectivity studies.

2. Methods

2.1. Participants

Participants were 55 9-year-old children including 35 dyslexic and 20 typical readers, who also participated in a previous cross-modal oddball study (Žarić et al., 2014). Children were diagnosed as dyslexic at a specialized institute for dyslexia and reading problems using an extensive cognitive psycho-diagnostic test battery. Dyslexic children were included in our study based on their poor reading skills, i.e. below 10th percentile of the age appropriate group on 3DM (Dyslexia Differential Diagnosis) word and pseudoword reading fluency subtests (Blomert and Vaessen, 2009) and were divided into groups of severely dysfluent (SDD) and moderately dysfluent (MDD) dyslexics based on a composite score of reading fluency (including the 3DM word and pseudoword reading subtests (Blomert and Vaessen, 2009), the one-minute word reading test – EMT (Brus and Voeten, 1973), and the short story 'De kat' ('The cat') reading test (de Vos, 2007); for details see: Žarić et al., 2014). Children also completed other subtests of the 3DM battery, i.e. spelling, letter-speech sound identification, letter-speech sound discrimination, phoneme deletion, rapid automatized naming (RAN) and basic reaction time subtests (Blomert and Vaessen, 2009). Individual behavioral testing was performed on average (SD) 1.4 (1.2) months prior to the EEG experiment. In comparison to Žarić et al. (2014), data of two children in the severely dysfluent group could not be included, one due to an incomplete dataset, and the other because of the absence of correct responses in both experimental conditions. The present data thus includes 20 typical readers (TR), 18 moderately dysfluent dyslexics (MDD) and 16 severely dysfluent dyslexics (SDD). All children performed a battery of reading-related and cognitive behavioral tests (Table 1). As the exclusion of the 2 participants did not change the group differences on any of the behavioral tests, we refer to Žarić et al. (2014) for a more detailed description of these tests and behavioral scores. Note that the typical readers and a subset of the dyslexic children were also part of a previous investigation of early visual ERP responses using the same paradigm (Fraga González et al., 2014). In the present study, we included a larger number of dyslexic children which allowed for the division into moderately dysfluent and severely dysfluent groups (see also Žarić et al.,