# The contribution of auditory attention to reading processes of school-age children with and without dyslexia

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# The contribution of auditory attention to reading processes of school-age children with and without dyslexia

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A thesis submitted for the degree of Doctor of Philosophy

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# Originality Statement

I, Giada Guerra, hereby declare that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

This thesis includes work that appears in the following article:

**Guerra**, G., Tijms, J., Vaessen, A., Tierney, A., Dick, F., & Bonte, M. (2020). Loudness and intelligibility of irrelevant background speech differentially hinder children's short story reading. *Mind, Brain, and Education*, *15*(1), 77-87.

During my PhD, I have contributed to the following paper:

Holt, L., Tierney, A. T., **Guerra**, G., Laffere, A., & Dick, F. (2018). Dimension-selective attention as a possible driver of dynamic, context-dependent re-weighting in speech processing. *Hearing research*, *366*, 50-64.

# Abstract

Mastering proficient reading skills is essential for an individual's personal and professional development. However, there are considerable individual differences in reading skills among children, and several potential environmental and cognitive factors underlying this variability. The overarching aim of this thesis was is to establish whether auditory attention is among these factors.

The first study explored the effects of background speech on children reading performance and found that speech loudness and intelligibility differentially disrupted reading speed and comprehension. Moreover, weaker inhibitory control was associated with greater interference on reading comprehension.

In the following two studies, I examined inhibitory control and behavioural and neural (EEG) measures of non-verbal sustained selective attention in a relatively large sample of children with and without dyslexia. As a model mimicking one of the first steps of reading acquisition, I also asked participants to learn to associated novel symbols with speech sounds. At the group level, auditory attentional measures did not differ between children with and without dyslexia. However, auditory attentional skills were related to reading fluency, and to the ability to learn novel audio-visual associations. Both of these skills were compromised in dyslexic readers.

A final objective was to identify cognitive abilities predicting individual benefits of intensive intervention for dyslexia. I found that an interplay between auditory attentional and reading-specific (e.g. phonological awareness) abilities predicted individual reading and spelling intervention outcomes.

Taken together, these studies indicated that auditory attention plays a role in children's reading, for example, by supporting fundamental processes underlying reading acquisition, such as letter-speech sound learning, as well as by facilitating learning processes during interventions. They also showed that auditory attention could modulate the harmful effects of background speech. The novel findings presented in this thesis represent a starting point for future investigations into the relationship between auditory attention and reading abilities during development.

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I dedicate this work to Maria Crespan, 91, lifelong learner, and my beautiful grand mum.

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# *Chapter 1*

# General Introduction

## 1.1. Prologue

Reading is an integral part of most human lives. People read to gain new knowledge (from scientific articles or newspapers) and also for pleasure (enjoying the newest thriller on a beach in August). Reading is also indispensable for carrying out the most mundane tasks, like checking a new painkiller package insert for drug interactions, following a lasagne recipe, or skimming the latest COVID safety briefing. Mastering reading is perhaps the most significant accomplishment of primary education. During these few years, reading shifts from being a learning goal in itself to being the essential tool for learning about the world.

Reading, together with writing, composes literacy (UNESCO, 2006). Several declarations and initiatives have recognised literacy as a fundamental human right (ELINET, 2016) and the foundation for lifelong learning (UNESCO, 2015). Literacy is considered an instrument to access health, educational, economic, political and cultural opportunities for individuals, families and societies (UNESCO, 2006). In the last decade, changes in the job landscape made literacy assume an even more central role in the workplace. Job positions traditionally considered 'low-skilled' now require a higher level of knowledge and innovation (ELINET, 2015). In this regard, increasing levels of digitalisation also require the constant acquisition of new skills, whereby literacy is the crucial tool (ELINET, 2016). In turn, digitalisation changes the complexity of the required literacy skills. Regardless of the medium, reading is a complex function that involves the execution and coordination of multiple cognitive processes. However, reading in the digital world may place higher demands, for example due to the need to inhibit distractors, integrate different sources of information and critically evaluate that information (Salmerón, Strømsø, Kammerer, Stadtler, & van den Broek, 2018; Wylie et al., 2018).

According to recent figures (PISA, 2018), in Europe, around one in five students under 15 years of age has literacy difficulties, with literacy defined as "understanding, using, evaluating, reflecting on and engaging with texts in order to achieve one's goals, to develop one's knowledge and potential, and to participate in society" (OECD, 2019, p. 4). Europe missed the benchmark of reducing underachieving pupils in literacy below 15% by 2020 (as well as in mathematics and science), with a slight increase of pupils underachieving in literacy (from 20.1% to 21.7%) in the last few years. In other words, the trend is going in the opposite way from the stated policy.

Psychological sciences divide reading difficulties into two main categories, one encompassing processes in decoding print (the degree of accuracy and fluency when reading aloud) and the other including processes of reading comprehension (the adequacy of text understanding) (Hulme & Snowling, 2016). Developmental dyslexia is the most widely used term for diagnosing children who experience severe impairments in decoding text, with a global prevalence varying between 3 % and 7 % (Landerl et al., 2013; Peterson & Pennington, 2012). Reading fluency, in particular, has been indicated as the most impaired domain in dyslexic readers (Shaywitz, Morris, & Shaywitz, 2008) and the least susceptible to intervention (Fraga González et al., 2015; Thaler, Ebner, Wimmer, & Landerl, 2004; Tijms & Hoeks, 2005). Some authors suggested that, next to deficits in reading-specific skills such as phonological and letter-speech sound processing, attentional mechanisms contribute to this 'fluency barrier' (Shaywitz & Shaywitz, 2008, p. 1329). However, it remains unclear whether and how attention contributes to the emergence of reading impairments.

The main focus of this thesis is to examine the relationship between auditory attention and reading in school-age children with and without dyslexia. It aims to identify factors involved in the success or failure to develop fluent reading and to predict the individual response to dyslexia treatment. With the further aim of delineating the link between attention and reading, I also explore auditory distraction as one of the elements in the learning environment that can affect children's reading performance. In this introductory chapter, I present an overview of the pathway to the acquisition of fluent reading, along with current evidence showing the contribution of attention to this process. I will also examine the role of attention in performing reading and listening tasks in challenging acoustic environments. Furthermore, theoretical accounts and current interventions of dyslexia are reviewed.

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## 1.2. The route to fluent reading

### 1.2.1. The reading network

Reading, decoding print and extracting meaning from it, is a relatively recent skill, and unique to humans. Written language was developed only about 5000 years ago, and it is unlikely that the human brain has evolved an intrinsic capacity to learn to read subserved by specialised brain structures. Instead, as we develop into skilled readers, existing neural systems are likely to re-organise to meet new cognitive demands to process written characters, turn the visual representations into speech sounds, and extract lexical meanings (Dehaene & Cohen, 2007). In the adult brain, neuroimaging studies have identified a left-hemispheric network of temporoparietal, frontal and occipito-temporal cortical regions involved in reading (Pugh et al., 2001; Sandak, Mencl, Frost, & Pugh, 2004; Schlaggar & McCandliss, 2007).

The temporoparietal cortical regions include the inferior parietal lobule (comprising the angular and supramarginal gyri), the posterior aspect of the superior temporal gyrus (STG) and the superior temporal sulcus (STS). These regions are involved in phonological processing (Sandak et al., 2004) and are also considered essential for linking orthography to phonology (Pugh et al., 2001). Areas in the STS/STG, in particular, have been linked to audio-visual integration due to its multi-modal sensitivity to letter-speech sound pairs (Raij, Uutela, & Hari, 2000; van Atteveldt, Formisano, Goebel, & Blomert, 2004).

The frontal cortical regions involved in reading include sites in and around the inferior frontal gyrus (IFG) and extend to the dorsal premotor cortex. These regions have been associated with speech production (Fiez, Petersen, & Street, 1998), high-level analysis of phonological elements (Peschke, Ziegler, Eisenberger, & Baumgaertner, 2012; Pugh et al., 2013; Zatorre, Meyer, Gjedde, & Evans, 1996), overt segmentation of speech (Burton, Small, & Blumstein, 2000) and active discrimination of incongruent letter-speech sound pairs (van Atteveldt, Formisano, Goebel, & Blomert, 2007). Due to its involvement in more active and metalinguistic tasks, the IFG has been related to top-down cognitive control of language and reading processes (Bitan, Cheon, Lu, Burman, & Booth, 2009; Pollack, Luk, & Christodoulou, 2015).

The ventral occipito-temporal cortex (vOT) is situated on the occipito-temporal sulcus adjacent to the fusiform gyrus and extends laterally onto the medial crest of the inferior temporal gyrus. A specific area in the left vOT cortex has been often referred to as the visual word form area (VWFA), given that word stimuli preferentially modulate its activation compared with other types of visual stimuli (Cohen et al., 2002). However, the specificity of this region's processing is debated (e.g., Price & Devlin, 2011; Price, Winterburn, Giraud, Moore, & Noppeney, 2003; Vogel, Petersen, & Schlaggar, 2014). While in adults, the frontal and the temporoparietal areas have been associated with more slow sublexical reading because of their greater activity in response to pseudowords as compared to words (Pugh et al., 2001; Sandak et al., 2004), neural activation of the ventral area is suggested to be related to fast and automatic word recognition and in general, to greater expertise in fluent reading (Benjamin & Gaab, 2012; Brem et al., 2006).

In electrophysiological studies, the activation of the ventral occipito-temporal cortex (vOT) in response to orthographic stimuli has been indexed by the N1/N170 component, a left-occipito-temporal negativity with peak latencies between 150 and 250 ms after the stimulus onset. Visual sensitivity for print, reflected by the N1, has been described at varying levels: from a coarse sensitivity, indicative, for example, of differential processing of words and symbol strings (e.g., Brem et al., 2006), to a finer one, necessary for discriminating between words and consonant strings (e.g., Zhao et al., 2014). The emergence of visual sensitivity for discriminating between familiar letter strings and symbol strings occurs rapidly in children after 1-2 years of formal reading instruction at school (Brem et al., 2013; Maurer et al., 2006), and then reduces in adolescence and adulthood (Brem et al., 2006), in line with the hypothesised inverted "U" shaped developmental trajectory of print sensitivity (Price et al., 2011). N1 responses are modulated by reading skills in both adults (Pegado et al., 2014) and children (Fraga González et al., 2014). Although the sensitivity necessary to discriminate between words and consonant strings was thought not to emerge before 10 years of age (as indexed by the N1, Posner & McCandiss, 1999), a more recent study with 7-years-old children found that children with high reading proficiency displayed sensitivity to orthographic regularities (Zhao et al., 2014). However, less skilled children did not (Zhao et al., 2014).

### 1.2.2. Critical processes underlying reading acquisition

To develop fast word recognition in alphabetic writing systems, children are initially required to learn the alphabetic principle, the arbitrary associations between graphemes (orthographic symbols) and phonemes (speech sounds; Byrne & Fielding-Barnsiey, 1989; Castles, Rastle, & Nation, 2018). In this process, termed phonological recoding, children also refine their ability to consciously segment speech at the phonemic level (e.g., Ziegler & Goswami, 2005). In fact, prior to reading acquisition, children already have sophisticated spoken language skills, including linguistic awareness at the level of words, followed by syllables and onset-rime (Anthony, Lonigan, Driscoll, Philips, & Burgess, 2003). Whilst children acquire reading skills, they also refine their phonemic awareness (Castles & Coltheart, 2004; Mann & Wimmer, 2002; Perfetti, Beck, Bell, & Hughes, 1987; Wimmer, Landerl, Linortner, & Hummer, 1991; but see: (Hulme, Snowling, Caravolas, & Carroll, 2005 for a causal account of phonological awareness on reading). Phonemic awareness is defined as the metacognitive skill of segmenting spoken sequences and manipulating the extracted individual phonemes (Melby-Lervåg, Lyster, & Hulme, 2012)

Learning letter-speech sound correspondences has thus been defined as the *sine qua non* of reading acquisition (Blomert, 2011; Share, 1995). Crucially, learning letter-speech sound correspondences also provides novice readers with a self-teaching strategy. This strategy allows them to phonologically decode new words and generate a word's orthographic representation, and subsequently enables fast word recognition (Share, 1995). A recent study with pre-reading kindergarten children using combined EEG and fMRI showed that learning artificial symbol-speech sound associations elicits a preferential N1 response along with functional activation in the ventral occipito-temporal (vOT) cortex for trained compared to passively-viewed symbols (Pleisch et al., 2019). These neural responses were modulated by learning performance, with faster learners showing greater neural responses. Such effects suggest that efficient learning of letter-speech sound correspondences is critical for the emergence of preferential activation to print in the vOT cortex (Pleisch et al., 2019). These results are consistent with the hypothesis of phonologically-guided tuning of vOT regions to print (Pugh et al., 2001; Sandak et al., 2004), and with the left vOT cortex conceived as an interface area providing access from visual-orthographic information to phonological information (Price et al., 2011).

Evidence showing that the ability to learn artificial symbol-speech sound correspondences in pre-schoolers predicts reading skills in first grade (Horbach, Scharke, Cröll, Heim, & Günther, 2015; Karipidis et al., 2018) and three years later (Horbach et al., 2018) also underlines the overall relevance of cross-modal integration (the integration of information from different sensory modalities in one percept) for skilled reading. Additionally, functional co-activation for print and speech in left perisylvian regions was shown to predict concurrent reading abilities (Chyl et al., 2018) as well as reading performance two years later (Preston et al., 2016). In individuals with dyslexia, a deficit in the automatic integration of letter-speech sounds (Aravena, Snellings, Tijms, & van der Molen, 2013; Blomert, 2011; Froyen, Willems, & Blomert, 2011; Žarić et al., 2014) is thought to affect the emergence of the left ventral sensitivity to print, and thus, reading fluency development (Brem et al., 2010; Fraga González et al., 2016; Pleisch et al., 2019; Richlan, 2019).

In relatively transparent orthographies (e.g. Dutch, the native language of participants in studies in the following chapters), typical readers acquire knowledge of letter–speech sound associations approximately within the first year of formal reading education (Blomert & Vaessen, 2009). However, evidence from neuroimaging studies shows a dissociation between knowing the letter-speech sound correspondences, and the automatic neural integration of these correspondences. After one year of reading instruction, in an oddball paradigm, beginning readers showed no influence of the letter on mismatch negativity (MMN) response – thought to index automatic change detection (c.f. Sussman, 2007) - to the speech sound. This result indicates a lack of automatic neural letter–speech sound integration. After four years, a more developed, but still not adult-like, audio-visual MMN response appeared in 11-year-old typically developing children (Froyen, Bonte, van Atteveldt, & Blomert, 2009). This protracted developmental time course towards automatic integration of letter-speech sound correspondences in typical readers appears to mirror the pathway towards the accomplishment of fluent reading. While reading accuracy approaches ceiling levels after just one year of school, fluency continues to develop over the years

(Cossu, Gugliotta, & Marshall, 1995; Landerl & Wimmer, 2008; Wimmer & Hummer, 1990).

To summarise, the route towards fluent reading takes place through sequential processes and begins with learning the alphabetic code while jointly developing phonemic awareness. The novice reader will progressively be more able to link larger orthographic chunks to the corresponding speech sounds until entire words can be decoded. With repeated practice and exposure, it will become possible to read fluently, e.g., "quickly, accurately, and with proper expression" (National reading panel, 2000).

## 1.3. Developmental dyslexia: definition, symptomatology and theoretical accounts

In the Diagnostic and Statistical Manual (DSM) of the American Psychiatric Association (APA, 2013), developmental dyslexia (hereafter, dyslexia) is defined as a "specific learning disorder with impairment in reading" and is described as characterised by problems with accurate or fluent word reading, poor decoding and poor spelling "that must have persisted for at least six months, despite the provision of interventions that target those difficulties" (p. 66).

The prevalence rate of dyslexia varies across languages, possibly due to orthographic consistency (Landerl, Wimmer, & Frith, 1997; Paulesu et al., 2001), but it occurs globally with an estimate of 3–7 % (Landerl et al., 2013; Peterson et al., 2012). The prevalence rate also varies according to the diagnostic criteria defining the disorder. For example, a widely-used classification, the International Classification of Diseases (ICD-11), states that the reading level also has to be below what would be expected for the level of intellectual functioning (i.e., IQ), following the assumption that children with low IQ are likely poor readers because of general learning difficulties and not because of a specific decoding problem (Peterson & Pennington, 2015). By contrast, the last edition of the DSM (V) removed the IQ-achievement discrepancy criteria. The use of one or the other medical classification affects prevalence estimates (e.g., Folco, Guez, Peyre, & Ramus, 2020). Prevalence estimates also depend on whether definitions set the cut-off for reading achievement to 1.5 standard deviations (SD) below the mean for age or less stringent criteria (Peterson & Pennington, 2015).

One of the earliest definitions of dyslexia, "congenital word blindness", hinted already to a heritable component, although its complex phenotype challenges the isolation of genetic markers (Fisher & DeFries, 2002). Disfluency is one the most characteristic and developmentally persistent symptoms of dyslexia, universal across languages (Shaywitz et al., 2008) and less susceptible to improvements after interventions compared to reading accuracy (Shaywitz et al., 2008; Shaywitz & Shaywitz, 2008; Thaler et al., 2004; Tijms & Hoeks, 2005). Effortful and slow reading is also assumed to exhaust cognitive resources needed for reading comprehension (Laberge & Samuels, 1974). Because impaired word decoding skills may partially limit reading comprehension abilities, especially in beginner readers (García & Cain, 2014), some children with dyslexia may also experience some difficulties with reading comprehension (Hulme & Snowling, 2016). Impaired reading fluency and sometimes impaired reading accuracy persist into adulthood (Ferrer et al., 2015; Shaywitz et al., 1999), suggesting that a developmental delay in acquiring fluent reading skills is not a viable hypothesis.

As in any other complex cognitive skill, there is a continuum of reading abilities (Kuhn, Schwanenflugel, Meisinger, Levy, & Rasinski, 2010; National reading panel, 2000), and dyslexia represents the low end of this continuum (Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). An arbitrary cut-off for establishing the deficit has been argued not to reflect the continuous nature of reading abilities (Lopes, 2012) and that neural differences between dyslexic and typical readers reflect documented behavioural differences rather than indicate atypical neural development (Protopapas & Parrila, 2018), bringing into question the definition of dyslexia as a categorical neurodevelopmental disorder. However, clinical practice requires cut-offs to provide early diagnoses and interventions, and to ultimately lower the risk of socio-psychological consequences and reduced quality of life associated with dyslexia (Fraga González, Karipidis, & Tijms, 2018; Hakkaart-Van Roijen, Goettsch, Ekkebus, Gerretsen, & Stolk, 2011; Undheim, 2003). In research practice, combining a categorical with a dimensional perspective may be informative in identifying the variety of cognitive and environmental factors contributing to a child's individual reading ability (Astle & Fletcher-Watson, 2020; Ring & Black, 2018; van Bergen, van der Leij, & de Jong, 2014).

For the last decades, the prevalent view of dyslexia is of a language-based developmental disorder whose core deficit is impaired phonological processing (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Despite evidence that a deficit in various facets of phonological processing (access, encoding and retrieval) is typical of dyslexia, the mechanistic link between the phonological deficit and reading impairments has been questioned (e.g., Castles & Coltheart, 2004). Evidence has shown that phonological awareness and reading influence each other (Mann & Wimmer, 2002; Morais, Cary, Alegria, & Paul, 1979). Moreover, not all individuals with dyslexia show a phonological deficit (e.g., Ring et al., 2018; Valdois, Bosse, & Tainturier, 2004), and not all individuals with a phonological deficit have dyslexia (e.g., Snowling, 2008).

These observations have prompted alternative proposals of mechanisms that contribute to reading impairments. For instance, a basic auditory processing deficit has been proposed as the underlying cause of phonological difficulties, stemming from the observation that some individuals with dyslexia show difficulties on a broad range of auditory tasks, encompassing processing of both temporal and spectral cues (Hämäläinen, Salminen, & Leppänen, 2013). A considerable amount of research initially focused on the temporal aspects of auditory processing (Amitay, Ahissar, & Nelken, 2002; Christmann, Lachmann, & Steinbrink, 2015; Ortiz, Estévez, Muñetón, & Domínguez, 2014), suggesting that a deficit in processing fast acoustic cues in (speech) streams would lead to degraded and noisy representations of speech sounds (Boets et al., 2011; Tallal, 1980, 2004; Vandermosten et al., 2010, 2011). Difficulties in processing spectral acoustic properties would have similar consequences on the establishment of phonological representations (Ahissar, Protopapas, Reid, & Merzenich, 2000; Christmann et al., 2015; Steinbrink, Klatte, & Lachmann, 2014; Walker, Givens, Cranford, Holbert, & Walker, 2006). However, the evidence of an auditory processing deficit is not unequivocal. It probably characterises only a small subgroup of dyslexic readers, and there is no clear relationship between auditory processing deficits and reading impairment (Rosen, 2003; Hämäläinen et al., 2013).

Recently, a deficit in the automatic integration of letters and speech sounds has been proposed as a proximal cause of reading difficulties in dyslexia (Blau et al., 2010; Blomert, 2011; Froyen et al., 2011; Kronschnabel et al., 2014; Richlan, 2019; Žarić et al., 2014; Yang, Yang, Li, Xu, & Bi, 2020). Reduced automatization of letter-speech sound integration (Blau et al., 2010; Žarić et al., 2014; Froyen et al., 2011) would result in slow and effortful reading and in inadequate refinement of phonemic abilities during reading acquisition. Evidence of the letter-speech sound integration hypothesis received support from functional magnetic resonance imaging (fMRI) studies showing reduced differential activation for congruent versus incongruent letter-speech sound pairs ("congruency effect") in pre-readers at risk for dyslexia (Plewko et al., 2018), and in children (Blau et al., 2010) and adolescents (Kronschnabel et al., 2014) with dyslexia compared to control groups.

However, the directionality of the congruency effect was not consistent across studies, possibly due to differences in task demands and orthographic depth (Holloway, van Atteveldt, Blomert, & Ansari, 2015; van Atteveldt & Ansari, 2014), with higher activation for congruent compared with incongruent letter-speech sound pairs (e.g., van Atteveldt et al., 2004), or lower activation for congruent compared with incongruent letter-speech sound pairs (e.g., Kronschnabel et al., 2014).

Converging evidence for this hypothesis is found in electroencephalography (EEG) studies (e.g., Froyen et al., 2011; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012; Žarić et al., 2014). For example, Froyen and colleagues showed that readers with four years of reading instruction (10-12-year-old) exhibited an enhanced MMN response when spoken vowels were presented together with letters, indicating fast and automatic letter-speech sound integration (Froyen et al., 2009). However, this pattern of neural response was absent in 11-year-old children with dyslexia (Froyen et al., 2011). Using the same paradigm, Žarić and colleagues showed that reduced audio-visual integration in 8-10-year-old dyslexic readers was correlated with individual differences in reading disfluency (Žarić et al., 2014).

Behavioural evidence for a letter-speech sound integration deficit is less consistent. Clayton and Hulme (2017), and Nash et al. (2016) used a priming task with children with and without dyslexia, showing that both groups responded faster in a congruent condition (when the speech sound was primed with the congruent English letter) compared to a baseline condition (when the speech sound was primed with a letter unknown to participants). Romanovska, Janssen, and Bonte (2019, 2021) used a text recalibration paradigm with 8-10-year-old children with and without dyslexia, showing comparable behavioural text-induced shifts in the perception of ambiguous speech sounds in the two groups. By contrast, behavioural training studies that focused on the learning of letter-speech sound found that children with dyslexia were less able to learn symbol-speech sound associations and manipulate newly learned associations (Aravena et al., 2013; Aravena, Tijms, Snellings, & van der Molen, 2017; Law et al., 2018). Some of these studies found a significant contribution of artificial letter-speech sound learning to reading skills (e.g., Aravena et al., 2017), but other studies did not (Law et al., 2018).

In recent years, the validity of a single cognitive deficit model of dyslexia (as for other developmental disorders, see, e.g. Happé, Ronald, & Plomin, 2006) has come into question (e.g., Pennington, 2006; Van Bergen et al., 2014; Astle et al., 2020). A single deficit model does not account for the heterogeneity of symptoms reported in dyslexic readers, often beyond the language domain (e.g., Heim et al., 2008; Menghini et al., 2010; Willems, Jansma, Blomert, & Vaessen, 2016), including, for example, attentional deficits (Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; Facoetti et al., 2010; Gabay, Gabay, Schiff, & Henik, 2020; Lallier et al., 2010; Lallier & Valdois, 2012; Menghini et al., 2010). Moreover, a single deficit explanation does not account for comorbidity or symptoms overlap arising among disorders. For example, poor inhibitory control (the ability to control one's attention, behaviour, thoughts; Diamond, 2013) and phonological impairments, considered the core deficits of ADHD and dyslexia respectively, should not occur in the other disorder, generating a "double dissociation". However, reading difficulties are often described in individuals with ADHD, and attentional and inhibitory control impairments have also been reported in individuals with dyslexia (Pennington, 2006). According to the multiple cognitive deficits model, the phenotypic manifestations of dyslexia can result from a combination of risk factors (Pennington, 2006; Peterson & Pennington, 2012). Thus, several distinct causal pathways could explain individual differences in reading abilities.

## 1.4. The multiple pathways linking attention and reading in children

### 1.4.1. Introduction

The ability to direct and regulate attention is a fundamental cognitive process, one that from the early stages of development influences many forms of learning (Karmiloff-Smith, 1992; Posner & Rothbart, 2005). From this perspective, it is critical to study how attention is deployed and develops, the neural mechanisms associated with attention, along with the effects that it exerts on children's learning processes (Posner et al., 2005; Steele, Karmiloff-Smith, Scerif, & Cornish, 2012; Welsh, Nix, Blair, Bierman, & Nelson, 2010). In the specific case of reading, studies reported how early reading difficulties are associated with teachers' ratings of inattentive behaviour in pre-schoolers (Dally, 2006; Sims & Lonigan, 2013) and in 6-7-year-old children in the first grade (Martinussen, Grimbos, & Ferrari, 2014; Plourde et al., 2018). Ratings of inattentive behaviour are often found to be weakly correlated with cognitive assessments of (visual) attention (e.g., Rezazadeh, Wilding, & Cornish, 2011; Sims & Lonigan, 2013; Steele et al., 2012); thus, they may capture different facets of attention (Sims & Lonigan, 2013). In turn, cognitive assessments of attentional abilities help pinpoint which and how attentional mechanisms influence reading development.

In clinical samples, the link between attention and reading is underscored by the high comorbidity between dyslexia and attention deficit hyperactivity disorder (ADHD), predominantly of the inattentive subtype (Greven, Harlaar, Dale, & Plomin, 2011; Hendren, Haft, Black, White, & Hoeft, 2018; Plourde et al., 2015), with approximately 15–45% of children with ADHD also receiving a diagnosis of dyslexia and vice-versa (Gayán et al., 2005; Germanò, Gagliano, & Curatolo, 2010; Langberg, Vaughn, Brinkman, Froehlich, & Epstein, 2010). Even when clinical cut-offs for comorbidity are not met, inattention symptoms in individuals with ADHD are often associated with reading fluency difficulties (Kibby, Lee, & Dyer, 2014; Plourde et al., 2015), especially in those with poor sustained attention (Stern & Shalev, 2013) and attentional lapses (Jacobson, Ryan, Denckla, Mostofsky, & Mahone, 2013). Moreover, studies reported impairments in reading-related abilities in individuals with ADHD, such as rapid naming (e.g, Tannock, Martinussen, & Frijters, 2000). One explanatory framework for the high comorbidity between the two disorders is the multiple cognitive deficits model (e.g., Pennington, 2006). The model postulates that comorbidity across symptoms or disorders arises because of common etiological factors interacting at different levels (genetic, environmental, neurological and cognitive).

At the cognitive level, impaired attentional control may interfere with the acquisition of critical abilities underlying reading development, such as phonological awareness and grapheme to phoneme conversion (van de Sande, Segers, Verhoeven, 2013; Sims & Lonigan, 2013; ten Braak, Kleemans, Størksena, Verhoeven & Segers, 2018). Impaired attentional control could also affect how much children might benefit from reading instructions and literacy-related activities at school (Dally, 2006; Lonigan et al., 1999). As a case in point, teaching in schools is based to a large extent on oral communication. Perhaps for this reason, auditory attention skills seem to play a more significant role in classroom behaviour than visual attention skills (Lehman, Olson, Aquilino, & Hall, 2006). Therefore, in real classroom conditions, children with poor auditory attentional control may not be able to attend to teacher instructions and may struggle in establishing stable phoneme categories and in learning letter-speech sound correspondences, ultimately affecting the acquisition of proficient reading abilities (Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Certain environmental conditions, such as ambient noise and distracting speech in the background, can exacerbate the difficulty in perceiving and following verbal instructions at school, and may constitute a source of distraction or interference while children are reading (Klatte, Bergström, & Lachmann, 2013).

In these challenging environments, auditory attention may act as a moderator of background noise or speech effects on speech perception (e.g., Oberfeld & Klöckner-Nowotny, 2016; Strait & Kraus, 2011; Thompson, Woodruff Carr, White-Schwoch, Otto-Meyer, & Kraus, 2017) and hypothetically, on concurrent reading processes. In the following sections, I examine potential underlying mechanisms of the association between attention and reading acquisition and the evidence of attentional deficits in individuals with dyslexia. Finally, I explore the link between acoustic distraction (background noise/speech), auditory attention and speech perception and reading.

### 1.4.2. Influence of attention on processes underlying reading acquisition of typical and dyslexic readers and non-verbal attention deficits in dyslexic readers

A general account of learning (Chein & Schneider, 2012) postulates that in early learning stages, the cognitive control network (including dorsolateral prefrontal, anterior cingulate, posterior parietal and inferior frontal cortices) is engaged in directing novice's attention toward task- and goal-relevant information. By doing this, cognitive control enhances and speeds up skill acquisition, until the task can be automatically executed and the involvement of cognitive control gradually reduces (Chein & Schneider, 2012). Specific to reading, in an early paper, Laberge and Samuels (1974) considered the sequence of subskills required to learn to read (e.g. letter knowledge, grapheme-to-phoneme recoding), emphasising, in particular, the pivotal role of attention in developing automaticity in each subskill, which, in turn, allows to attain fluent (automatic, effortless) reading.

For beginner readers, reading depends on metalinguistic skills including the ability to direct and focus attention on the structural features of language (Castles, Rastle, & Nation, 2018). Selective attention mechanisms may be required to abstract salient speech characteristics, and effectively associate and integrate orthographic and phonological information in an audio-visual object (McCandliss & Yoncheva, 2011; Yoncheva, Wise, & McCandliss, 2015).

Phonological skills relevant for reading rely upon phonemic categorisation mechanisms (e.g., Vandermosten et al., 2010), which allow for discrimination, integration and organisation of speech's acoustic dimensions into appropriate phonemic categories. This ability continues developing beyond early childhood until the cognitive system is able to categorise speech units consistently and flexibly using cue-weighting strategies, especially when limited cues are available (Hazan & Barrett, 2000). In this process, directing attention to the most informative acoustic dimensions for speech categorisation allows learners to enhance dissimilarities between categories, and enhance similarities within categories (Francis & Nusbaum, 2002), both crucial to phonemic learning (Heald & Nusbaum, 2014). In addition, directing attention to the most informative acoustic dimensions provides even the most experienced listener with a strategy to cope with context- and talker-dependent variability (Heald & Nusbaum, 2014).

Selective attention may also play a role in learning letter-speech sound associations, a critical process underlying reading fluency development (e.g., Horbach et al., 2015; 2018; see section **1.2.2.**). According to an account of general audio-visual integration, when multiple stimuli within each unisensory modality compete for further processing, top-down selective attention mechanisms are likely to be needed for multisensory integration to take place (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Thus, it is plausible that beginner readers may be required to selectively direct attention to relevant graphemes and phonemes to facilitate the formation of integrated neural representations of letter-speech sound correspondences. Specific to linguistic audio-visual integration, a recent study with adult participants showed the involvement of selective attention processes in linguistic audio-visual integration (Hämäläinen, Parviainen, Hsu, & Salmelin, 2019). While participants were learning symbol-syllable associations there was an enhanced bilateral neural activity at 350 ms in the caudal middle frontal cortex, which was interpreted as indicative of selective attention to relevant features of the audio-visual pairs (Hämäläinen et al., 2019). In line with previous studies investigating long-term learning effects (Karipidis et al., 2018, 2017), after 5-10 minutes of training, they found changes in neural activation at 350 ms after stimulus presentation in the posterior superior temporal sulcus and at 500 ms in temporal-occipital areas (Hämäläinen et al., 2019).

Other work showed how selective attention might influence letter-speech sound integration and phonological processing, both essential for fluent reading acquisition. For instance, in a series of studies with adult participants, Yoncheva and colleagues (2010) showed that in a rhyming task, directing attention to phonological information within spoken words led to increased functional activity in the left mid-fusiform gyrus, associated with sensitivity to orthographic stimulus properties, but directing attention to tone-triplets embedded in spoken words did not (Yoncheva, Zevin, Maurer, & McCandliss, 2010). Furthermore, selective attention to artificial symbol-phoneme mappings during training resulted in a left-lateralized modulation of the N1 amplitude in a subsequent reading task (Yoncheva, Blau, Maurer, & McCandliss, 2010), associated with reading abilities (e.g., Maurer, Zevin, & Mccandliss, 2008), while holistic focus at the word level did not (Yoncheva, Blau, et al., 2010).

Electrophysiological studies investigating phonological and audio-visual integration processes reported diminished attentional-mediated responses in individuals with dyslexia (Savill & Thierry, 2011b, 2011a, 2012; Žarić et al., 2014). For instance, in an audio-visual oddball paradigm used with typical, disfluent and severely disfluent children, Žarić and colleagues (2014) compared two event-related potential components: the MMN - thought to index automatic change detection - and the late negativity (LN) - thought to index more attentionally-mediated change detection. In contrast to typical readers, dyslexic readers had reduced LN responses. Severely disfluent readers also displayed differences in the MMN window, possibly signalling a more basic (perceptual) failure in forming letter-speech sound representations (Žarić et al., 2014). Savill and Thierry (2011a) used a sentence reading task during EEG recording with adults with dyslexia, showing comparable amplitudes of early components (N1, P2, N2) in typical and dyslexic readers. However, dyslexic readers showed a smaller amplitude of the P3a component, thought to index automatic engagement of focal attention, indicating that adult dyslexic readers may have intact phonological perceptual processing but impaired automatic attentional capture by phonological information.

In a follow-up study, the authors replicated these results, employing an adapted visual word oddball paradigm where participants were asked to detect semantically related targets (Savill & Thierry, 2012). Typical readers showed the anticipated pattern of increased P3a amplitudes to pseudo-homophone targets of similar magnitude as those elicited by targets, and larger than those elicited by control pseudo-homophones. Dyslexic readers showed similar amplitudes across conditions. In a non-linguistic control task, dyslexic readers did show expected differences among conditions as the typical readers. Moreover, P3a responses in dyslexic readers were in general attenuated in both linguistic and non-linguistic tasks (Savill & Thierry, 2012). Dyslexic readers have also shown reduced P3 responses to non-verbal visual and auditory stimuli, with differences in the context of rapid stimuli presentation (Lallier et al., 2009, 2010). By employing various attentional paradigms, behavioural studies have also demonstrated that groups of individuals with dyslexia show attentional deficits beyond the language domain (**Table 1.1.**).

Studies investigating visual attentional skills often found attentional deficits in individuals with impaired pseudoword reading skills (Facoetti et al., 2010, 2006; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014), and significant associations between these skills and attentional abilities across dyslexic reader participants (Facoetti et al., 2010, 2006; Jones, Branigan, & Kelly, 2008; Ruffino et al., 2014). Thus, the authors of these papers hypothesised that visuo-attentional skills play a role in graphemic parsing (the visual segmentation of grapheme strings into their constituent graphemes) (Facoetti et al., 2008, 2006; Ruffino et al., 2014).

Fewer studies have investigated auditory attention in individuals with dyslexia. While limited, this literature has shown an association between adults' auditory interference control and pseudoword reading fluency (Gabay et al., 2020), slower auditory spatial attention in children with impaired pseudoword reading accuracy (Facoetti et al., 2010) and impaired automatic attentional shifting to non-verbal auditory stimuli in dyslexic readers with phonological deficits (Lallier, Thierry, & Tainturier, 2013). The studies showing auditory attention difficulties in dyslexic readers indicated that impaired auditory attention mechanisms might play a role in phonological deficits. For example, auditory attention may be needed for accurate speech segmentation mechanisms and speech units encoding, which are critical for developing adequate phonological representations (e.g., Goswami, 2011; Lallier & Valdois, 2012).

Complementary evidence of the potential involvement of auditory attention - particularly selective auditory attention - in dyslexic readers stems from studies showing that individuals with dyslexia present with difficulties in perceiving speech in complex acoustic environments, for example with concurrent distracting speech (e.g., Dole, Hoen, & Meunier, 2012; Nittrouer, Krieg, & Lowenstein, 2018; see Calcus et al., 2018 for a review). In other populations of adults and children, the ability to perceive speech with distracting speech in the background was shown to draw upon attentional skills (Oberfeld & Klöckner-Nowotny 2016; Strait & Kraus 2011; Laffere, Dick, Holt, & Tierney, 2020; Tierney, Rosen, & Dick, 2020) and to share underlying neural mechanisms with attentional selection (e.g., Obleser & Kayser, 2019; Zion Golumbic, Poeppel, & Schroeder, 2012; see section **1.4.2.1.**). Some authors hypothesised that auditory attention might be one of the factors underlying speech-in-noise perception and reading difficulties in dyslexia (Calcus et al., 2018; Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009; Ziegler et al., 2009). To date, there is no empirical evidence showing that auditory attentional abilities predict speech-in-noise perception in children with dyslexia.

To summarise, there is some empirical evidence that attentional mechanisms influence processes underlying reading acquisition such as phonological awareness and letter-speech sound learning. It is still unclear whether attentional skills influence children's ability to learn letter-speech sound correspondences during reading acquisition and contribute to dyslexic readers' difficulties in learning these correspondences.

Behavioural studies have also shown attentional impairments in dyslexic readers beyond the language domain, both in the auditory and visual modalities, although studies examined more extensively the visual modality. Evidence reporting difficulties in perceiving speech in challenging acoustic environments in dyslexia suggests that selective auditory attention may be one of the factors underlying these difficulties (e.g., Ziegler et al., 2009; Calcus et al., 2018). To date, it is not clear whether non-verbal selective attention and its underlying neural mechanisms are impaired in children with dyslexia and to which extent these deficits relate to individual reading skills and speech perception abilities in suboptimal listening conditions.

### 1.4.3. The problem of noise: speech perception and reading in challenging acoustic settings and the potential moderating role of auditory attention

In everyday life, children often perform various tasks in noisy surroundings. For example, in the classroom, children's activities may involve listening to the teacher and performing tasks alone, such as reading silently a paragraph from a textbook. Various sounds inside the classroom can make it difficult for pupils to focus on teaching instructions and distract them from their tasks. For example, outdoor noise such as road traffic and aircraft noise, and indoor noise such as ventilation, reverberation, chatting of pupils in the classroom and from adjacent rooms, can make the listening reality in schools seldom pristine (Bradley & Sato, 2008; Jamieson, Kranjc, Yu, & Hodgetts, 2004; Woolner & Hall, 2010; Shield & Dockell, 2003).

In the sections below, I will further discuss the effects of background noise/speech on children's speech perception and reading and the putative role of auditory attention in modulating these effects.

#### 1.4.3.1. Speech perception in noise

Poor auditory attention can affect reading acquisition indirectly, by preventing children from benefiting from reading-related activities at school. For example, they may not fully follow teacher instructions related to phonological and grapheme-phoneme decoding (Dally, 2006; Lonigan et al., 1999; Martinussen et al., 2014;

Plourde et al., 2015). Another potential factor affecting the perception of verbal inputs from the teacher is the level of noise inside the classroom. Noise significantly reduces speech intelligibility (Bradley & Sato, 2008; Jamieson et al., 2004), particularly in younger children who seem to be more vulnerable than older children and adults (Klatte et al., 2013). In schools or other educational settings, this effect may translate into a loss of information, for example, when distracting sounds or other voices partially cover the teacher's voice. Correlational studies have shown that pupils constantly exposed to loud environmental noise are more at risk of reading acquisition delays (Evans & Lepore, 1993; Evans & Maxwell, 1997). One of these studies also demonstrated that speech perception ability, measured with a masked word recognition task, partially mediated the association between noise exposure and reading deficit in elementary school children (Evans & Maxwell, 1997).

Further studies are needed to ascertain the mechanisms underlying the relationship between long-term exposure to noise and reading acquisition difficulties, but it is indeed plausible that noise affects the learning of relevant skills for reading that are mainly acquired through verbal instructions (Ziegler et al., 2009). On this view, both cognitive abilities (i.e. attention) and environmental characteristics (i.e. noise) may have an impact on reading acquisition via speech perception abilities. The levels of a child's attentional resources and auditory distraction in the environment may interactively contribute to speech perception challenges. In fact, individual differences in attention predict speech perception in the context of a noisy and multi-speaker acoustic environment (Oberfeld & Klöckner-Nowotny, 2016; Thompson, Woodruff Carr, White-Schwoch, Otto-Meyer, & Kraus, 2017; Tierney, Rosen, & Dick, 2020). As will be further illustrated below, speech perception and attentional selection possibly share underlying neural mechanisms (Ding & Simon, 2014; Haegens & Zion Golumbic, 2018; Obleser & Kayser, 2019; Zion Golumbic et al., 2013, 2012).

#### 1.4.3.1.1. Underlying neural mechanisms of speech in noise perception and auditory attentional selection

In order to follow the teacher's voice despite the scraping of chairs, the chattering of classmates or the road noise coming from outside, pupils must identify and separate the different sound sources, and orient attention to the target signal at the expense of competing inputs (Sussman, 2017; Zion Golumbic et al., 2012).

In the presence of noise, speech recognition requires additional cognitive control, potentially mediated by frontal brain regions. For example, Wild and colleagues showed that left inferior frontal gyrus activation was increased by attention when participants were listening to noise-vocoded speech (where temporal information in the speech envelope is preserved but spectral clarity is reduced compared to clear speech (Wild et al., 2012)). Similarly, Erb, Henry, Eisner and Obleser (2013) observed enhanced activity in regions comprising the insula and the supplementary motor area/anterior cingulate cortex when the participants listened to similar noise-vocoded speech. The authors interpreted this finding in light of the contribution of executive and attentional processes in complex listening situations (Erb, et al., 2013).

In the context of multiple speakers, attention can influence responses directly in the auditory cortex by enhancing the cortical representation of features of the attended speaker, while the representation of features of other competing acoustic inputs is attenuated. For example, utilising the tonotopic organisation of the auditory system, frequency-selective attention can act as a filtering mechanism that enhances responses to an attended frequency (da Costa, van der Zwaag, Miller, Clarke, & Saenz, 2013; Dick et al., 2017; Fritz, Elhilali, & Shamma, 2005; Mesgarani & Chang, 2012; Riecke et al., 2017). Similarly, selective attention boosts auditory cortical representations of behaviourally relevant speech features (e.g. speaker or speech sound identity; Bonte, Valente, & Formisano, 2009; Bonte, Hausfeld, Scharke, Valente, & Formisano, 2014; Mesgarani & Chang, 2012). In the spatial domain, orienting auditory attention to a particular spatial location enhances responses contralaterally to the attended location (Wu, Weissman, Roberts, & Woldorff, 2007). Orienting auditory attention to a spatial location can also activate a supramodal functional frontal-parietal network (Wu et al., 2007), which may interact with sensory-specific control systems during deployment of spatial attention (Banerjee, Snyder, Molholm, & Foxe, 2011).

Another viable strategy for perceiving speech in complex listening environments is to deploy temporally-selective attention, thereby capitalising on the quasi-rhythmic temporal structure of speech (Giraud & Poeppel, 2012; Schroeder, Lakatos, Kajikawa, Partan, & Puce, 2008) at both syllabic and prosodic level (Rosen, 1992). This strategy is especially advantageous when certain conditions like reverberation affect the reliability of spatial and frequency cues. In other words, the listener can find and selectively process time points where the target speech stream is more likely to occur than the distractor ones (Cooke, 2006; Nobre & van Ede, 2018; Zion Golumbic et al., 2012). By doing so, processing of other features of the attended acoustic object are also likely to be boosted, since they all share the same temporal pattern (Ding & Simon, 2012; Zion Golumbic et al., 2012).

Oscillatory mechanisms have been considered a suitable neural candidate to subserve these selective gains in specific moments, given their putative role in controlling the timing of neuronal excitability (Fröhlich & McCormick, 2010; Lakatos et al., 2005; Schroeder & Lakatos, 2009). According to this hypothesis, when directing attention to the temporal regularities of the relevant sound source, moments of heightened neural excitability corresponding to particular oscillatory phases become aligned to the temporal regularities of the exogenously occurring stimulus (Obleser & Kayser, 2019; Schroeder & Lakatos, 2009). This mechanism, named neural entrainment, has been observed particularly in low-frequency oscillations, in the delta (1-4 Hz) and theta (4-8 Hz) frequency range. In a first study, Lakatos and colleagues introduced the idea of entrainment as a putative mechanism for selective temporal attention by presenting non-human primates with quasi-rhythmic streams of visual and auditory stimuli in antiphase in respect to each other (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008). When attending to one of the two streams, delta oscillations in primary visual and auditory areas became entrained to the relevant modality, such that maximal excitability corresponded with expected events in the attended stimulus stream, and oscillations were in opposite phase in the two attention conditions.

Subsequently, similar findings have been replicated in humans (Besle et al., 2011; Laffere, Dick, & Tierney, 2020; Stefanics et al., 2010), demonstrating that directing attention to temporal structure of stimuli can modulate the timing of measures of neural activity (i.e. the phase of the oscillation) (Obleser & Kayser, 2019; Schroeder & Lakatos, 2009). Notably, the phase of entrained activity was predictive of listeners' performance in sound-feature detection paradigms (Henry & Obleser, 2012; Laffere et al., 2020). However, it is still debated whether neural activity alignment to the temporal structure of an exogenous signal reflects modulation of endogenous oscillatory processes, or whether it arises from a sequence of evoked neural responses, which can be modulated by attention (Hillyard, Hink, Schwent, & Picton, 1973; see e.g., Haegens & Zion Golumbic, 2018; Zoefel, ten Oever, & Sack, 2018).

In naturalistic acoustic environments, cortical entrainment to speech shares characteristics with cortical entrainment to non-linguistic sounds (Ding & Simon, 2014). Neural entrainment to continuous speech has been shown in both single-talker speech perception and multi-talker speech selection tasks (Luo & Poeppel, 2007; Zion Golumbic et al., 2013). For instance, in a dual-talker task, Zion Golumbic and co-workers showed that the phase of low-frequency neural activity (1–7 Hz) correlated with the attended speech temporal envelope (Zion Golumbic et al., 2013).

In children, there is some evidence showing neural entrainment to speech (Power et al., 2012; Ríos-López et al., 2020). However, with a few exceptions (Vander Ghinst et al., 2019), few data are available on children's neural *selective* continuous tracking of speech or non-speech auditory stimuli. In order to investigate the neurophysiological mechanisms accounting for children's typical larger difficulties in speech in noise perception compared to adults (Klatte et al., 2013; Leibold & Neff, 2007; Wightman & Kistler, 2005), vander Ghinst and colleagues (2019) presented a group of young adults (21-40 years old) and a group of children (6-9 years old) with the voice of a talker reading a story in four listening conditions: a noiseless condition, and three conditions with multi-talker background with different signal-to-noise (-5, 0, and 5 dB). Compared with adults, children displayed reduced cortical tracking of speech at 1-4 Hz, and particularly at 4-8 Hz, even in the noiseless condition, suggesting that neural mechanisms supporting speech in noise abilities develop later on in adolescence.

#### 1.4.3.2. "Reading in noise": future research avenues for identifying individual susceptibility to auditory distraction in children

Background noise can also interfere with non-listening tasks, such as reading (Klatte et al., 2013). While reading, children, as well as adults, may be distracted by different noise sources, with immediate consequences for reading speed and comprehension (Vasilev, Kirkby, & Angele, 2018). Several studies have investigated the effect of background noise or speech on adults' reading, with particular evidence for the interfering effect of speech on reading comprehension processes (see for a recent meta- analysis: Vasilev et al., 2018). Only a few studies have examined the short-term effects of noise on children's concurrent reading performance. Dockrell and Shield (2006) investigated the effect of classroom noise on reading comprehension in 8-year-old children, finding more accurate reading comprehension in a quiet condition than with babble in the background. Reading performance was best when babble was combined with intermittent environmental noise, which was interpreted as a consequence of an active re-focusing of attention. Ljung, Sörqvist, & Hygge (2009) found that road traffic noise slowed down reading in 12-to-13-year-old children, but did not affect their comprehension. A mix of background babble and conversational speech did not affect either measure.

Interestingly, it has been suggested that children's higher distractibility to noise or speech during cognitive tasks may be due to their poorer attentional control than adults' (Klatte et al., 2013; Meinhardt-Injac et al., 2015) and that increased ability to cope with noise occurs in parallel and is related to the refinement of attentional processes (Leech, Aydelott, Symons, Carnevale, & Dick, 2007). To date, no studies have directly measured children's attentional skills to investigate whether individual differences in attention explain the amount of disruption on reading performance. In adults, Sörqvist and colleagues showed that participants who were more susceptible to intrusions during a number-updating memory task also had greater disruptions in their reading comprehension performance when speech was in the background (Sörqvist, Halin, & Hygge, 2010). These findings suggested that the ability to suppress immediately irrelevant speech may determine individual susceptibility to distraction (Sörqvist et al., 2010).

Although Sörqvist and colleagues employed a working memory task, in developmental studies, the ability to select an object of attention and suppress interference from irrelevant distractors, is referred to as inhibitory control (Diamond, 2013). Therefore, measuring inhibitory control abilities (rather than working memory) may be a valid initial approach for identifying candidate moderators of the effect of noise on children's reading. Ultimately, gaining more insight into these moderators would provide better understanding of the mechanisms of auditory distraction effects on reading. It will also help to identify children likely to be more at risk in noisy environments.

## 1.5. Interventions for children with dyslexia

Reading disorders affect negatively individuals' quality of life (Hakkaart-Van Roijen et al., 2011). In childhood, reading disabilities have been associated with both externalizing disorders (e.g., conduct problems) and internalizing disorders (e.g., anxiety, depressive symptoms) (Carroll, Maughan, Goodman, & Meltzer, 2005; Livingston, Siegel, & Ribary, 2018; Willcutt & Pennington, 2000). In adulthood, individuals with dyslexia are more likely to experience socio-emotional problems (Ghisi, Bottesi, Re, Cerea, & Mammarella, 2016; Moojen et al., 2020), challenges in the workplace (de Beer, Engels, Heerkens, & van der Klink, 2014) and are less likely to attain a higher level of education and thus of income (McLaughlin, Speirs, & Shenassa, 2014). Given its potentially severe academic, economic and psychosocial consequences, dyslexia requires clinical intervention.

Evidence has shown that systematic cognitive reading interventions can improve reading skills. Meta-analyses identified phonics instruction treatments as the most effective programs (Ehri, Nunes, Stahl, & Willows, 2001; Galuschka, Ise, Krick, &

Schulte-Körne, 2014; McArthur et al., 2012). Phonics instruction includes interventions that systematically teach letter-sound correspondences and decoding strategies. These might involve blending or segmenting letters or phonemes, or segmenting spoken or written words into syllables or onset and rimes. This type of intervention combines some elements of phonological awareness treatments (which focus exclusively on promoting the ability to recognize and manipulate phonemes), with elements of reading fluency treatments (which focus on repeated oral word reading practice) (Galuschka et al., 2014).

Even if a child with dyslexia achieves considerable improvements in reading accuracy, his or her reading fluency - the ability to read words correctly, but also fast and effortlessly (National reading panel, 2000) - is likely to be less susceptible to intervention, even after long, systematic and intensive treatments (Shaywitz & Shaywitz, 2008; Singleton, 2009; Snowling & Hulme, 2011; Torgesen et al., 2001). The Regional Institute for Dyslexia (RID), the industrial partner in this PhD project, has developed a phonics-based intervention that aims at establishing strong, explicit knowledge of phonemic and orthographic regularities with intensive and repetitive practice of letter-speech sound correspondences. This is designed to ensure their automatic integration (Fraga González et al., 2015; Tijms, 2007, 2011; Tijms & Hoeks, 2005). Results of a randomized controlled trial have shown that this treatment approach can lead to significant improvements in reading fluency (Fraga González et al., 2015).

Most intervention studies observed substantial inter-individual variability in reading fluency gains (Galuschka et al., 2014; Singleton, 2009; Snowling & Hulme, 2011; Tijms, 2011). Children identified as 'non-responders' typically show improvements in phonological and letter-speech sound knowledge, but reading scores do not show functional improvements. In other words, reading abilities remain below what would be expected for the child's age or reading development stage (Snowling & Hulme, 2011). A child's response to evidence-based interventions is thought to be indicative of the severity of the disorder (Fuchs & Fuchs, 2006; Snowling & Hulme, 2011).

Currently, there is little knowledge about factors moderating response to intervention for children with dyslexia. According to review studies, reading-specific abilities (e.g. phonological and rapid naming skills, knowledge of grapheme-phoneme associations) along with behavioural and attentional problems affect responses to early intervention in pupils at risk for reading disabilities (al Otaiba &

Fuchs, 2002; Nelson, Benner, & Gonzalez, 2003). It is unclear whether these factors also moderate the outcome of intensive interventions for children already diagnosed with dyslexia. Some studies have found that reading-specific abilities predict reading fluency gains (e.g., Tijms, 2011; Tilanus, Segers, & Verhoeven, 2019) but other have not (e.g., Scheltinga, van der Leij, & Struiksma, 2010).

To date, evidence on the role of attentional abilities during intervention is limited. Torgesen et al. (2001) showed that teachers' inattention ratings were associated with degree of response to intensive intervention for reading disabilities. In contrast, Ring & Black (2018) did not find that a diagnosis of attention deficit (hyperactivity) disorder (ADHD/ADD) affected treatment response. Both studies included a high percentage of children diagnosed with ADHD/ADD, limiting our understanding of whether attention affects intervention processes in children with dyslexia without co-occurrence of ADHD/ADD. If empirical evidence indicates that attention abilities influence the extent to which a child can benefit from intervention, inclusion of attentional measures in diagnostic assessments should be informative for customising interventions based on a child's needs. For example, for some children, attentional training before interventions targeting domain-specific deficits (e.g. (Chenault, Thomson, Abbott, & Berninger, 2006) may maximise the benefits of current interventions that are focused on aspects of grapheme-phoneme relations and decoding.

It is still unclear whether attention training alone improves reading abilities. A small number of studies employed action videogames to train visual attention, but results are inconsistent concerning whether improvements in visual attention transfer to reading fluency gains (Antzaka et al., 2017; Franceschini et al., 2017; cf. Łuniewska et al., 2018)

## 1.6. Summary, aims and outline of the dissertation

The overarching goal of this thesis is to investigate the relationship between auditory attention and reading processes in school-age children. The reviewed literature suggests that multiple potential pathways may link attention to individual differences in children's reading abilities. However, there are some limitations in the existing literature which are addressed in the present work.

First, during reading acquisition, attention may facilitate the development of crucial abilities such as the learning of letter-speech sound correspondences. This hypothesis is also supported by evidence showing both attentional and letter-speech sound learning deficits in children with dyslexia. To date, behavioural evidence of letter-speech sound deficits in children with dyslexia is limited and shows contrasting findings. No previous research has investigated whether individual differences in children's attention are predictive of their ability to learn letter-speech sound correspondences.

Second, selective attention is likely engaged when children perceive speech with distracting sounds and voices in the background, a common everyday environment. This is ultimately relevant for reading as i) speech-in-noise perception difficulties may hamper the acquisition of precise phoneme representations prior to and during reading acquisition; ii) selective attention abilities may determine the extent to which a child benefits from reading-related activities in noisy classrooms. The link between speech-in-noise and reading is also supported by observations that speech-in-noise perception is impaired in individuals with dyslexia. To date, no studies have investigated whether auditory attention is predictive of both reading and speech-in-speech perception abilities in children with dyslexia.

Third, background noise or speech can be a source of distraction while children are reading. Attention, more specifically inhibitory control, might be a candidate moderator of children's susceptibility to background speech. To date, only a few studies have examined the short-term effects of noise on children's reading performance and no studies have directly assessed children's attentional abilities in order to examine whether they are predictive of individual susceptibility to background speech or noise while reading.

Fourth, attention is likely to be engaged in the context of reading interventions. In such interventions, an individual is required to direct and sustain attention to acoustic and visual speech inputs for long periods. Therefore, we can hypothesise that poor attentional skills may constrain intervention benefits. To date, empirical evidence is limited, and studies have mainly employed teachers' or parents' ratings of children's inattentiveness, which limits our understanding of the attentional mechanisms moderating response to intervention.

In the present work, I investigated the auditory modality of attention based on the evidence that: i) auditory attention has primarily been linked to language development (e.g., de Diego-Balaguer, Martinez-Alvarez, & Pons, 2016; Gomes, Wolfson, & Halperin, 2007); ii) putative speech-in-noise/speech-in-speech perception impairments in dyslexic readers suggest a link between reading and auditory attention (e.g. Calcus et al., 2018); iii) in developmental studies, the auditory modality has received less attention, and thus less is known about its underlying mechanisms in children. Given the multi-sensory characteristic of reading, we do not exclude the possibility that visual attentional mechanisms are predictive of individual differences in children's reading abilities and may contribute to reading difficulties in dyslexia.

In the present work, I will address the aforementioned open questions for improving our understanding of the contribution of auditory attention to individual differences in children's reading as follows.

**Chapter 2** explores the effects of background speech on reading speed and comprehension of school-age children. In this study, I experimentally manipulated two characteristics of speech - intensity and intelligibility - and examined whether children's inhibitory control modulates the effects of these characteristics on reading performance.

**Chapter 3** examines the neural (EEG) correlates of auditory non-verbal sustained selective attention in a large sample of children with and without dyslexia. Here, I also investigate whether speech-in-speech perception abilities are impaired in children with dyslexia and are predicted by non-verbal auditory attention.

**Chapter 4** investigates putative letter-speech sound association deficits in children with dyslexia by asking children to learn novel audio-visual pairs. It also examines whether greater learning abilities scale with two auditory attentional components: non-verbal sustained selective attention and inhibitory control.

**Chapter 5** explores the predictiveness of reading-specific and domain-general (i.e., attentional) abilities for reading fluency and spelling gains during intensive phonics-based intervention for children with dyslexia.

**Chapter 6** discusses how the work of this thesis provides insight into the relationship between auditory attention and reading processes. This chapter highlights how the experimental findings of the chapters are related to each other and previous work in the field, discusses the theoretical and practical implications and limitations of the studies and gives potential directions for future research.

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# *Chapter 2*

# Loudness and intelligibility of background speech differentially hinder children’s short story reading

## 2.1. Abstract

Reading skills are usually assessed in silent conditions, but children often experience noisy educational settings. Effects of auditory distraction on children’s reading skills remain relatively unexplored. The present study investigates the influence of two features of background speech - intelligibility and loudness - on children’s reading speed and comprehension. Sixty-three 8-to-10-year-old elementary school children performed a reading task in the context of single-talker background speech. Background speech was either intelligible or unintelligible and presented at low (45-50 dB SPL) or moderate (65-72 dB SPL) sound intensity (here termed ‘loudness’). Results showed a differential effect of intelligibility and loudness, respectively affecting children’s comprehension and reading speed. In addition, the intelligibility effect was larger in children with lower interference control, as assessed with an auditory Stroop task. Our findings provide evidence for the influence of different properties of background speech on children’s text reading with implications for reading in everyday classroom environments.

## 2.2. Introduction

Whereas reading skills are typically investigated in silent conditions, children often experience noisy learning environments, for example in crowded classroom settings at school or at home. Reading in such environments requires ignoring potentially distracting background sounds while mapping visual onto spoken language representations and integrating semantic information into a narrative or argument. There is some evidence that background noise has detrimental effects on reading, but the evidence and underlying mechanisms are still under debate (Vasilev, Kirkby, & Angele, 2018; Klatte, Bergström, & Lachmann, 2013). Rather surprisingly, it is still unclear whether and how different acoustic- and content-related characteristics of background noise might influence children's concurrent reading comprehension and speed.

The effect of noise on children's reading performance has typically been investigated in terms of its long-term consequences, with results showing (for example) that protracted exposure to traffic or aircraft noise at school is related to poorer reading comprehension (e.g., Clark, et al., 2005; Papanikolaou, Skenteris, & Piperakis, 2015; Haines, Stansfeld, Job, Berglund, & Head, 2001). Only a handful of studies - with somewhat conflicting results - have experimentally tested how background speech and other noise types might have an impact on children's reading skills. For instance, Shield and Dockrell (2006) investigated the effect of classroom noise on reading comprehension in 8-year-old children, finding more accurate reading comprehension in a quiet condition than with recorded children's babble in the background. Unexpectedly, reading performance was best when babble was combined with intermittent environmental noise, which the authors interpreted as an active re-focusing of attention in the context of their relatively short and time-unlimited reading task. Ljung, Sorqvist, and Hygge (2009) found that previously-recorded road traffic noise slowed down reading in 12-to-13-year-old children, but did not affect their comprehension. A mix of background babble and conversational speech featuring one talker at a time did not affect either measure.

Single-talker background speech is also a common source of auditory distraction in daily life situations and may be particularly difficult to ignore given its salience for human listeners. In fact, for adults, speech is typically observed to have a more deleterious effect on reading comprehension than non-verbal acoustic noise (Vasilev, et al., 2018; Landström, Söderberg, Kjellberg & Nordström, 2002) with comparable but less well-studied effects on reading speed (Cauchard, Cane, & Weger, 2012;

Hyönä & Ekholm, 2016, Vasilev et al., 2018; Vasilev, Parmentier, Angele, & Kirkby, 2019). Typically, our understanding of the potential causal mechanisms underlying auditory distraction has relied on measuring its effect on serial recall or other working memory tasks - but these factors may also affect complex tasks such as reading (Jones, 1995). An early account suggested that any type of irrelevant background speech, whether intelligible or not, automatically engages verbal working memory capacity, thus interfering with ongoing task performance (phonological-interference hypothesis; Salamé & Baddeley, 1982, 1987). However, accumulating evidence suggests that the disruptive effect of unattended speech is mostly due to its conveyed meaning rather than to its acoustic or phonological features, and therefore has a semantic origin. For instance, Martin, Wogalter, & Forlano (1988) found that English-speaking participants' reading comprehension was more affected by English than by Russian speech. To test whether phonological or semantic information was driving this effect, Martin et al. (1988) performed a subsequent experiment comparing the effect of random sequences of auditorily presented English words, non-words, white noise or silence on reading performance. Hearing random English words impaired reading comprehension significantly more than non-word speech, which had an effect comparable to that of white noise (Martin et al., 1988). These findings suggest that the semantic content of background speech plays a stronger role than familiar phonological characteristics, in line with a second theoretical account, the interference-by-process account (Marsh, Hughes & Jones, 2008; Hughes, 2014). This account suggests that intelligible background speech elicits automatic semantic processes that interfere with the extraction of meaning from the text.

Further evidence for the interference-by-process account comes from recent eye-tracking studies showing how online reading processes are affected by different types of background speech. These studies (Hyönä & Ekholm, 2016, Yan, Meng, Liu, He & Paterson, 2018; Vasilev et al., 2019) showed that overall reading time slows down in the presence of intelligible background speech. In addition, background speech was found to affect the latency of word frequency effects (Yan et al., 2018). Specifically, when reading in quiet conditions, word frequency influenced first fixation duration, with longer fixation times for low- compared to high-frequency words. By contrast, when reading in the presence of background speech, this effect was seen for later fixations (Yan et al., 2018). Vasilev et al. (2019) found similar word frequency effects in the context of intelligible and unintelligible background speech, suggesting a similar effect on lexical access. But intelligible background speech was found to increase re-reading fixations in close proximity to the initial, first-pass fixations on words, suggesting an increased difficulty in integrating recently-read words into the sentence context due to the intelligibility of the speech. Finally, offline reading comprehension scores were reduced only when participants were prevented from re-reading the text (Vasilev et al., 2019), suggesting that re-reading may be an effective adaptive strategy to cope with noise. Overall, these results suggest that intelligibility of distracting speech can affect both reading speed and comprehension.

To date, the immediate effects of the loudness of background speech on reading remain unexplored. Effects of loudness have only been experimentally investigated using other types of cognitive tasks such as verbal memory and reasoning (Ellermeier, & Hellbrück, 1998; Schlittmeier, Hellbrück, Thaden, & Vorländer, 2008; LaPointe, Heald, Stierwalt, Kemker, & Maurice, 2007) and math (Schlittmeier et al., 2008). Among them, only the study of LaPointe and colleagues (2007) found that louder speech adversely affected adults' working memory performance. On the other hand, correlational studies investigating the relationship between long-term exposure to low versus high levels of road traffic or aircraft noise in school environments and scholastic performance have suggested that high noise levels may have a considerable effect on children's reading comprehension (Papanikolaou, et al., 2015; Haines, et al., 2001). However, to our knowledge, there are no published studies that have investigated whether differences in the intensity or perceived loudness of background speech differentially affect reading performance. It also remains unknown whether the effects of intelligibility and loudness interact; for example, high-intensity intelligible background speech might be particularly decremental for reading performance.

Children's task performance may be more susceptible to distracting sounds due to both their immature cognitive and attentional skills, and their less automatized reading skills. Greater distractibility by noise in children has indeed been shown for a broad range of tasks, including speech perception and working memory (Hughes, 2014; Joseph, Hughes, Sorqvist, & Marsh, 2018, Klatte, Lachmann, Schlittmeier, & Hellbrück, 2010, Klatte et al., 2013). These previous studies did not directly assess children's attention skills. Accounting for individual differences in attentional control may allow us to hone in the processes by which background speech affects children's reading performance. Thus, the aim of the current study is to investigate how varying both the intelligibility and intensity of background speech affects children's reading speed and comprehension. Further, we asked whether individual differences in attentional skills - specifically in interference control - might modulate these effects. Finally, we also investigated whether children's vocabulary and reading proficiency modulate their susceptibility to the effects of background noise on reading.

## 2.3. Materials and Methods

### 2.3.1. Participants

Participants were 63 third- and fourth-grade children (33 boys, 31 in 3rd grade, age: 9.32± 0.65 years, range: 8.01-10.74), recruited from an elementary school in Amsterdam, the Netherlands. All were native Dutch speakers, with 11 also speaking a second language. None spoke Hungarian, the 'unintelligible' language used in the reading-in-distracting-speech task. The experiment was approved by the ethics committee of the Department of Psychology, University of Amsterdam, with informed consent obtained from the children's parents. Books were given to the school as a gift for participation. Children's cognitive and reading skills were assessed with standardized tests in Dutch (**Table 2.1**). Visuo-spatial skills and vocabulary skills were estimated using the Block Design subtest of the WISC-III and the vocabulary subtest of the Revisie Amsterdamse Kinder Intelligentie Test (RAKIT; Bleichrodt, Drenth, Zaal, & Resing, 1984). The RAKIT vocabulary test was administered at group level. Single word reading fluency was tested with the 'Een-Minuut-Test' (EMT, Brus and Voeten, 1997). 8 children were previously diagnosed with dyslexia (n= 5), ADHD (n= 2) or co-occurrence of dyslexia and ADD (n= 1). These children were not excluded from the analyses, as the study explicitly aimed to test a representative sample of school-aged children. Importantly, reanalyses showed that the statistical significance (at $p < .05$ thresholds) of our results did not change after excluding the 8 children with dyslexia and/or ADHD.

### 2.3.2. Procedure and measures

All children were tested individually in a quiet room at school. Testing sessions lasted 1.5 hours and included a range of behavioural measures. Here we present the results from two experimental tasks: a reading in distracting speech task and an auditory Stroop task. In addition, we analysed these experimental measures in relation to participants' word reading fluency and vocabulary and visuo-spatial skills as assessed with the standardised tests mentioned above. Task order was counterbalanced across participants. The computerised tasks were programmed and presented with Psychtoolbox-3 in MATLAB 9.1.0 (Mathworks). Two Dell Latitude

E5570 laptops, with a 1920 x 1080 screen, Core i5-6200 microprocessor, Intel HD Graphics 520 were used.

#### 2.3.2.1. Reading in distracting speech

Here, children silently read four short narrative texts consisting of two paragraphs, each followed by a brief reading comprehension test. Texts and questions were adapted from a reading comprehension workbook for 3rd- and 4th-grade children (Ajodakt Lezen - Goed begrepen 5, Van Mersbergen, 2005). The number of words was kept comparable across texts (AVI E5 level length indicator, M = 84.5; SD = 4.9; range: 79-95 words per text) and provided a similar structure and plot. To reduce the time between reading and testing phases, paragraphs were presented one at a time on the laptop screen, each followed by two multiple-choice questions. Children advanced to the reading comprehension questions by pressing the space bar; the measure of reading speed was the time between paragraph appearance on the screen and spacebar press to advance, averaged across all paragraphs in a condition.

During paragraph presentation, children heard either a native Dutch female talker (intelligible speech) or a native Hungarian female talker (unintelligible speech) reading a newspaper article in their native language. Background speech was presented over headphones (IMG Stage Line MD-5000DR) at two different intensity levels, 45-50 dB and 65-72 dB SPL (measured using a RION NA-27 Sound Level Meter with a NH-20 microphone). The sound intensity levels were chosen so that the moderate intensity was close to the maximum sound intensity considered safe for young children, 75 dB (WHO, 2018). The low intensity level was chosen so that the speech was still understandable but clearly different from the moderate level. Thus, the four experimental conditions were the following: (1) intelligible speech at low intensity level, (2) intelligible speech at moderate intensity level, (3) unintelligible speech at low intensity level, and (4) unintelligible speech at moderate intensity level. Texts were presented in the same order to each participant, but condition order was randomized. Children were asked to silently read through the texts as accurately and quickly as possible without going back to previously read sentences, and then to answer the comprehension questions. They were also told they would hear speech in the background they could ignore.

#### 2.3.2.2. Interference control

Interference control was tested with an auditory version (Green & Barber, 1981) of the Stroop task (Stroop, 1935). Similar to the original Stroop test, it requires the listener to ignore lexical information and to respond on the basis of a perceptual feature. The stimuli consisted of four words: 'boy', 'girl', 'house' and 'game' ('jongen', 'meisje', 'huis' and 'spel' in Dutch) spoken by two female and two male Dutch native talkers. There were congruent, incongruent and neutral trials. On congruent trials, the word 'boy' and the word 'girl' were spoken by a male and female talker, respectively. On incongruent trials, the word 'boy' was spoken by a female talker, and the word 'girl' was spoken by a male talker. Neutral trials used the words 'game' and 'house', both spoken by a female and a male talker. The participants were asked to ignore the meaning of the words and to respond to the gender of the talker by pressing one of two keys (one on the left, one on the right side of the keyboard, each marked by an orange sticker to guide the children to the correct key). Trials timed out after 1500 milliseconds (ms). There were 32 trials per condition, with presentation order randomized. Before beginning the experimental task, children practiced 10 or 20 trials (with more trials indicated if the child performed poorly) which included all conditions. During practice trials only, response feedback (happy/sad cartoon face) was displayed. Both accuracy and reaction time (RT) of correct trials were used for analysis.

### 2.3.3. Statistical analyses

For the 'reading in distracting speech task', data from two children were excluded because the task was not administered due to time constraints, with data from an additional five children excluded due to a procedural error that occurred in one of the four conditions when children inadvertently pressed the button to advance to the next paragraph too early.

All remaining data were inspected for outliers that were identified based on standardized residuals, and data points with values below −3 and above 3 were excluded from the analyses (Osborne & Overbay, 2004). Based on this criterion, one datapoint was excluded from the reading speed data (standardized residuals > 3 in two of the four conditions, intelligible moderate and unintelligible moderate), and one datapoint was excluded from the reading comprehension data (standardized residuals < 3 in the intelligible moderate condition, and in the average reading comprehension scores). In summary, we excluded 12.6% (8 out 63) of the 'reading-in-distracting-speech' participants. A repeated-measures ANOVA (SPSS version 26.0, IBM Corp., Armonk, NY, United States) was conducted to test for main and interaction effects of speech intensity (low, moderate) and intelligibility (intelligible, unintelligible) on reading speed; reading speed was log-transformed to normalize the underlying reading time distribution. Log-transformed reading speed data met ANOVA assumptions, with analyses showing homoscedasticity and normality of the residuals. Effect sizes reported are partial eta-squared ($\eta p^2$). Reading comprehension scores showed limited variance and were negatively skewed so a Generalized Estimating Equation (GEE; SPSS version 26.0, IBM Corp., Armonk, NY, United States) for repeated categorical data was constructed, again with speech intensity and intelligibility as within-subjects factors.

We also ran Spearman's rank correlation analyses between children’s overall text reading comprehension and speed and word reading fluency (EMT test), vocabulary (RAKIT test) and visuo-spatial skills (WISC block design) scores. All results were Bonferroni-corrected for multiple comparisons.

For Auditory Stroop data, one participant (1.6% of total N) was excluded because s/he omitted 45% of responses. For the remaining 62 participants, we used non-parametric Friedman tests with post-hoc Wilcoxon pairwise analyses corrected for multiple comparison (Bonferroni) to analyze the median RTs and mean accuracy because the data did not meet the assumption of normality.

Finally, we used two linear regression models to ask whether individual differences in interference control (children’s accuracy on incongruent – congruent Stroop task trials, see Results) were associated with effects of background speech on text reading. In a first model, we included only Stroop-based interference control and age in months as regressors. In a second model, we added reading fluency (measured by the Een-Minuut-Test) and vocabulary size (the vocabulary subscore of the Revisie Amsterdamse Kinder Intelligentie Test) as regressors in order to clarify the extent to which background speech interference on reading might be modulated by individual differences in these skills, above and beyond that contributed by interference control and age. The assumptions of linearity, independence of errors, homoscedasticity and normality of residuals were met for each of the regression models.

## 2.3. Results

Descriptive statistics of reading fluency (EMT) and estimates of vocabulary (RAKIT) and visuo-spatial (WISC block design) skills are presented in **Table 2.1**.

**Table 2.1. Descriptive statistics showing verbal and non-verbal scores, and word reading fluency.**

| N = 56 | Mean | SD | Min. | Max. |
|---|---|---|---|---|
| EMT [a] – Word Reading fluency | 9.84 | 3.25 | 1 | 17 |
| WISC [a] - Block Design | 11.45 | 3.12 | 4 | 18 |
| RAKIT [b] - Vocabulary | 50.34 | 3.64 | 42 | 60 |

[a] *Standard scores (range 1-19, mean 10)*
[b] *Raw scores (range 1-65).*

### 2.3.1. Text reading speed and comprehension accuracy

The children who completed all the four conditions took on average 39.42 seconds (SD = 13.1) to read a paragraph (**Table 2.2**) with considerable variability between children. Most of them correctly understood the texts (mean reading comprehension 81.7 % (SD = 11.8)).

On average, faster readers were also more able to accurately respond to the comprehension questions (rho = - 0.359, p = 0.032). More fluent readers, indicated by the number of correctly-read words within one minute on a standardised reading fluency test (EMT), were faster in reading the texts (rho = -0.766 , p < 0.001), but were not significantly more accurate in responding to comprehension questions (rho = 0.212 , p = 0.480). Children with richer vocabulary required less time to read (rho = -0.445, p = 0.004), and had higher reading comprehension scores (rho = 0.444, p = 0.004). Visuo-spatial skills were not correlated with average reading comprehension (rho = 0.245, p = 0.284) nor with reading speed (rho = -0.084, p ≅ 1).

**Table 2.2. Children's text reading speed and comprehension results.**

| | N | Mean | SE | Min | Max |
|---|---|---|---|---|---|
| **Reading Speed[a] (Intelligible, Low intensity)** | 55 | 38.38 | 1.90 | 16.02 | 73.83 |
| **Reading Speed[a] (Intelligible Moderate intensity)** | 55 | 41.17 | 1.82 | 21.44 | 86.72 |
| **Reading Speed[a] (Unintelligible Low intensity)** | 55 | 38.59 | 2.02 | 16.98 | 82.23 |
| **Reading Speed[a] (Unintelligible Moderate intensity)** | 55 | 39.58 | 1.80 | 19.25 | 69.99 |
| **Reading Speed [a] (Average)** | 55 | 39.42 | 1.76 | 21.40 | 70.27 |
| **Reading Comprehension [b] (Intelligible Low intensity)** | 55 | 80.45 | 2.5 | 25 | 100 |
| **Reading Comprehension [b] (Intelligible Moderate intensity)** | 55 | 78.18 | 3.0 | 25 | 100 |
| **Reading Comprehension [b] (Unintelligible Low intensity)** | 55 | 82.27 | 2.7 | 25 | 100 |
| **Reading Comprehension [b] (Unintelligible Moderate intensity)** | 55 | 85.91 | 2.5 | 25 | 100 |
| **Reading Comprehension [b] (Average)** | 55 | 81.7 | 1.6 | 50 | 100 |

[a] *Reading speed: average reading time (in seconds) for both paragraphs per text*
[b] *Reading comprehension: percentage of correctly responded comprehension questions.*

### 2.3.2. Effects of background speech: intensity versus intelligibility

Reading comprehension and speed were differentially influenced by acoustic (speech intensity) versus semantic (speech intelligibility) characteristics of distracting speech. Reading speed was significantly slowed when the distracting speech was more intense (F(1,54) = 12.389, p = 0.001, $\eta p^2$ = .187; **Figure 2.1A**). However, distractor speech intelligibility did not significantly influence reading speed (F(1,54) = 1.123, p = 0.294, $\eta p^2$ = 0.020) and did not significantly interact with intensity (F(1,54) = 1.505, p = 0.225, $\eta p^2$ = .027).

By contrast, intelligible distracting speech did significantly affect reading comprehension more than unintelligible speech (GEE model; Exp(B) = 0.484; CI = 0.253 to 0.925, p = 0.028; **Figure 2.1B**). Reading comprehension was not significantly influenced by distracting speech intensity (Exp(B) = 0.700, p = 0.283, CI = 0.365 to 1.342), and there was no significant interaction (Exp(B) = 1.621, p = 0.290, CI = 0.662 to 3.969).

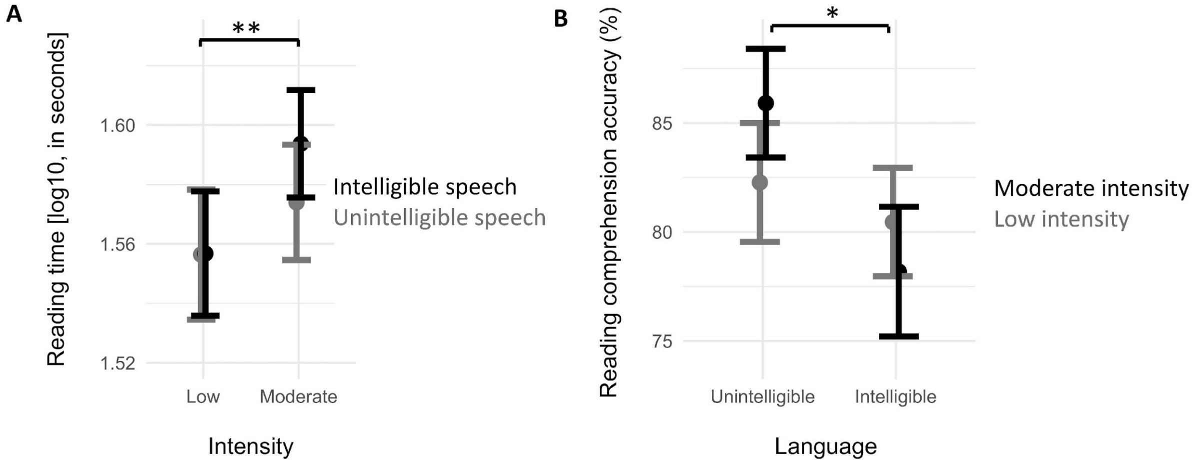

**Figure 2.1. A) The intensity of the background speech (low versus moderate) significantly affected children's text reading speed. Reading speed is expressed in seconds on a logarithmic scale. B) The intelligibility of the background speech significantly affected children's reading comprehension. Reading comprehension is expressed as the percentage of correctly responded questions.** ***Error bars*** **= ±** ***1 standard error. **p < .01, *p < .05.***

### 2.3.3. Interference control – Auditory Stroop task

Children showed accurate task performance with an average accuracy of 87.03% (SD = 9.04%). In the congruent condition, children's average accuracy was 90.67% (SD = 9.93%), 81.12% (SD = 12.4%) in the incongruent condition and 89.32% (SD = 9.19%) on the neutral trials (**Table 2.3**).

A Friedman test with Condition as a within-subjects factor (Congruent, Incongruent, Neutral) revealed a significant Stroop effect on accuracy ($\chi^2(2) = 44.451$, $p = < 0.001$; **Figure 2.2A**), with accuracy in the incongruent condition lower than in the congruent ($Z = -5.823$, $p < 0.001$) and neutral conditions ($Z = -5.741$, $p < 0.001$), neutral and congruent condition did not differ from each other ($Z =-1.391$, $p = 0.492$), Bonferroni-corrected.

There was also a main effect of Condition on reaction times ($\chi^2(2) = 21.77$, $p < 0.001$), with slower RTs in the neutral as compared to the congruent condition ($Z = -3.600$, $p = 0.001$) and to the incongruent condition ($Z = 3.923$, $p < 0.001$), which did not differ from each other ($Z = -0.011$, $p = 0.992$, Bonferroni-corrected; **Figure 2.2B**).

This unexpected result may be due to the fact that the words used for the neutral condition (game, house) appeared only in 33.3% of trials whereas words used in both congruent and incongruent conditions (boy, girl) appeared in 66.7 % of the trials. This difference in relative frequency of occurrence may have resulted in an 'oddball' effect and thus in longer RTs (Miller, 1998). Accuracy scores were not affected and were similar to those of the congruent condition (compatible with the fact that the neutral condition was not semantically incongruent).

Because the classic Stroop effect was reflected in accuracy scores, we quantified children’s interference control skills as the accuracy difference between incongruent and congruent trials **(Table 2.3;** note that higher values indicate better interference control).

**Table 2.3. Auditory Stroop task. Accuracy (percentage correct) and RT on correctly responded trials (in milliseconds) for the congruent, incongruent and neutral conditions.**

| | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Accuracy Congruent | 62 | 90.7 | 9.9 | 48.1 | 100 |
| Accuracy Incongruent | 62 | 81.1 | 12.4 | 50 | 100 |
| Accuracy Neutral | 62 | 89.3 | 9.2 | 60 | 100 |
| Accuracy Total | 62 | 87.0 | 9.0 | 54.6 | 100 |
| **Stroop interference effect (Accuracy Inc. – Cong.)** | **62** | **-8.54** | **10.56** | **-50** | **7.4** |
| RTs Congruent | 62 | 746 | 113 | 407 | 1035 |
| RTs Incongruent | 62 | 742 | 123 | 274 | 1106 |
| RTs Neutral | 62 | 776 | 107 | 340 | 1028 |
| RTs Total | 62 | 755 | 105 | 340 | 1004 |

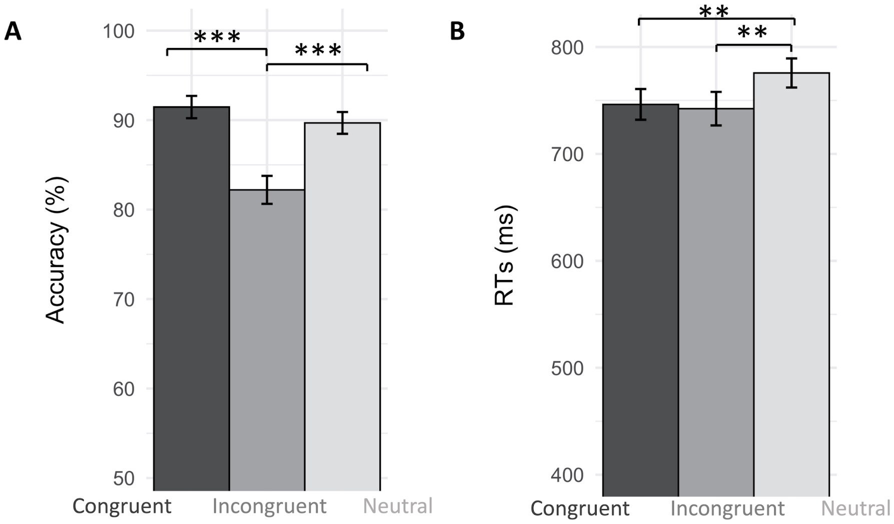

**Figure 2.2. A) Children's accuracy in the Auditory Stroop task per condition. B) Children's reaction times (RTs) on correctly responded trials of the Auditory Stroop task per condition.** *Error bars = ± 1 standard error.***p < 0.001, **p < 0.01.*

### 2.3.4. Potential modulatory effects of interference control, vocabulary, and reading fluency on children's susceptibility to background speech during reading

In a final analysis we investigated whether variability in interference control explained individual differences in susceptibility to auditory distraction during reading. Specifically, we wanted to understand whether interference control predicted change in reading speed and comprehension, due to the intensity and the intelligibility of the distraction, respectively. As described above, interference control was quantified as the accuracy difference on incongruent versus congruent Auditory Stroop trials, where positive scores indicate greater interference control. We used difference scores to create a measure that quantifies the effect of each experimental manipulation. The loudness effect on speed was quantified as the reading speed difference between moderate- versus low-intensity speech distractor conditions, and the intelligibility effect on comprehension as the reading comprehension difference between unintelligible versus intelligible conditions. The loudness effect on speed and the intelligibility effect on comprehension measures were first analysed in two separate linear regression models, with interference control (Stroop effect interference) and age in months as predictors.

Here, the degree to which intelligibility affected a child's reading comprehension was associated with their interference control (β = -.374, p = 0.007; CI = -1.145 to -

0.192; **Figure 2.3**), but not with children's age (β = .014, p = 0.916; CI = -0.589 to 0.654; overall regression model: $R^2$ = 0.142, F(2,51) = 4.244, p = 0.020**)**. Thus, the less interference control a child had, the more strongly influenced s/he was by the intelligibility of background speech. By contrast, the difference in reading speed due to the intensity of the background speech was neither predicted by the amount of interference experienced during the interference control task (β = 0.096, p = 0.494; CI = -0.082 to 0.168), nor by age (β = .240, p = 0.091; CI = -0.023 to 0.307; overall regression model: $R^2$ = 0.057, F(2,51) = 1.539, p = 0.224).

In a second step, we additionally entered both EMT (reading fluency) and RAKIT (vocabulary) scores in our linear regression models. Similar to above, results showed that the intelligibility effect on comprehension was associated with children's interference control (β = -0.418, p = 0.005; CI = -1.251 to 0.241), but not with their age (β = -0.028, p = 0.851; CI = -0.751 to 0.622). Vocabulary skills (β = .208, p = .133; CI = -0.333 to 2.441) and reading fluency skills (β = -0.022, p = 0.879; CI = -0.372 to 0.319) did not explain additional variance ($R^2$ change = .039, F(2,49) change = 1.166; p = 0.320; overall regression model: $R^2$ = 0.182, F(4,49) = 2.719 , p = 0.040). These results suggest that the reading comprehension of children with richer vocabulary and more fluent reading skills was not less susceptible to the effect of intelligibility of background speech.

The extended regression model further showed that the loudness effect on reading speed was not predicted by vocabulary skills (β = .165, p = 0.234 ; CI = - 0.140 to 0.559). However, we did find a significant effect of reading fluency on the loudness effect on reading speed (β = .318, p = 0.033; CI = 0.008 to 0.182; **Figure 2.4**). Unexpectedly, for children with better word reading fluency, background speech loudness had a greater effect on reading speed compared to children with poorer reading fluency. Interference control (β = -.033, p = 0.813; CI = -0.142 to 0.112) and age (β = .079, p = 0.592; CI = -0.127 to 0.220) remained non-significant ($R^2$ change = .119, F(2,49) change = 3.543; p = 0.037; overall regression model: $R^2$ = .176, F(4,49) = 2.618, p = 0.046).

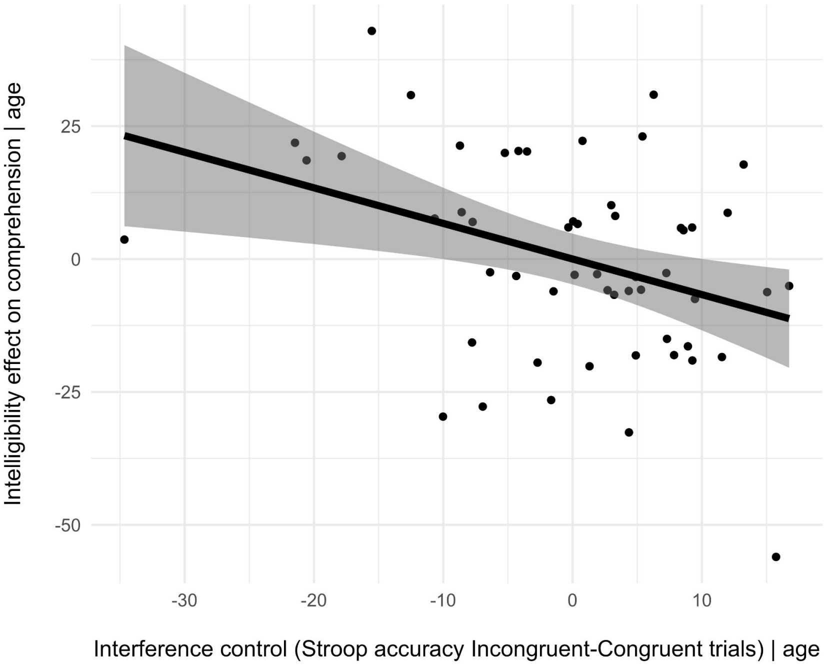

**Figure 2.3. Added variable (partial regression) plot displaying the modulatory effect of interference control on the effect of intelligibility of background speech on children's reading comprehension, once the effect of age was removed. Interference control was measured as the Stroop interference effect (accuracy for incongruent versus congruent trials). The effect of intelligibility on comprehension was quantified by children's comprehension during the unintelligible versus intelligible speech conditions.**

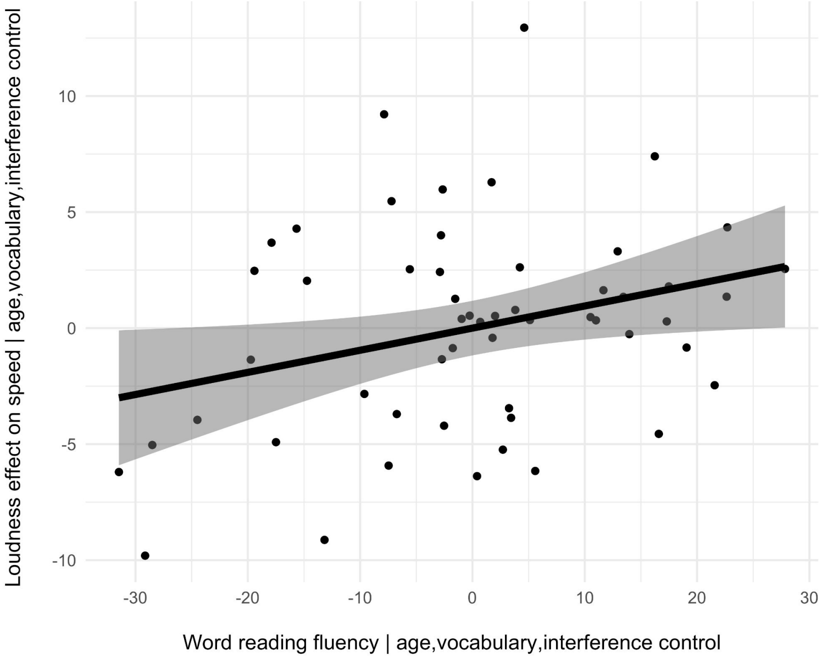

**Figure 2.4. Added variable (partial regression) plot displaying the modulatory effect of reading fluency skills on the effect of the loudness of background speech on children's reading speed, after removal of age, vocabulary and interference control effects. The effect of background speech loudness on reading speed was quantified by taking the difference between reading speed in moderate versus low background speech loudness conditions.**

## 2.4. Discussion

Here we asked how intensity and intelligibility of an irrelevant background talker affected school-age children's text reading speed and comprehension. We also asked whether children's ability to successfully ignore the irrelevant talker and focus on reading was related to interference control. On average, children's reading speed was more adversely affected by 'louder' irrelevant speech, whereas their comprehension was more adversely affected by intelligible speech, with the latter result modulated by children's interference control. Finally, as compared to children with lower reading proficiency, those with higher proficiency were faster in reading the texts in distracting speech, but their speed was more strongly affected by speech loudness.

Our newly-developed reading-in-noise task featured an appropriate level of difficulty, as children performed well and were able to correctly answer most, but not all, of the comprehension questions. Furthermore children who were faster in reading the texts also scored higher on a separately administered standardised reading fluency test, indicating that our text reading task reflects relevant individual variability in reading ability. The observation that simultaneously presented intelligible speech drives poorer reading comprehension is in line with previous findings in adults (Martin, et al., 1988; Vasilev et al., 2019) and is predicted by the interference-by-process-account according to which intelligible speech evokes automatic semantic processes which interfere with the ongoing processes relevant for text comprehension (Marsh et al., 2008; Hughes, 2014; Hughes, & Jones, 2009).

In support of this interpretation, the intelligibility effect was stronger in children with less efficient interference control. Specifically, in our Stroop task, children were asked to ignore auditory semantic information. Therefore, greater interference due to meaningful background speech may occur in children who are less capable of inhibiting or suppressing automatic activation of this information. This finding is in keeping with previous evidence showing that auditory disruption is greater for adults and children who are more susceptible to intrusions, during number-updating memory tasks (Sörqvist, Halin, & Hygge, 2010) and creativity tasks (Massonniée et al., 2019). Contra our expectations, the effects of intelligible background speech on reading comprehension were not modulated by its relative intensity. Given that we only tested a narrow age range, it is possible that such effects might occur at different points of development, and might also depend on the familiarity of the distracting sounds (Matusz et al., 2019) or on the strategies used to cope with auditory distraction (Massonniée et al., 2019). Useful follow-up experiments might more parametrically vary the perceptual and semantic features of distracting speech and test these across children in different age groups.

While previous studies have shown detrimental effects of long-term exposure to loud noise on children's reading ability (e.g.: Papanikolaou et al., 2015; Haines et al., 2001), to our knowledge, this is the first study testing the immediate effect of background speech loudness on children's online text reading performance. Children's reading speed was significantly slower in the presence of higher compared to lower intensity speech, although the degree of slowing was mild. The small magnitude of this effect may relate to the fact that the background speech used here was homogeneous and continuous, i.e. without dynamic changes in loudness, long silent pauses or other interruptions that may have been more distracting and may have yielded larger time effects due to the re-direction of attention (Escera, Alho, Winkler & Näätänen, 1998). Nonetheless, this finding and the fact that the difference in reading speed was not predicted by children's performance on the interference control task, suggests that louder sounds may hinder reading on a more general perceptual level, possibly including early stage processes, such as the recoding of letters into their corresponding speech sounds or lexical access based on visual word forms (Schlaggar & McCandliss, 2007). As this hindrance may not only result in slower reading but also in re-reading previously read words or sentences, it would be very interesting to further clarify the online mechanisms underlying this effect in future studies using eye-tracking methodology (Hyönä et al., 2016; Yan et al., 2018; Vasilev et al., 2019). Of note, the effects of the loudness of the background speech on reading speed were not modulated by its intelligibility. It is possible that an interaction between background speech loudness and intelligibility might be observed if one were to use a more engaging (semantic) auditory distraction (like entertaining children's stories), or a more complex and informative text.

Longer reading times as a consequence of re-reading behaviours could be a functional coping mechanism in the context of auditory distraction, particularly in order to facilitate better text comprehension (Vasilev et al., 2019). Thus, the fact that more skilled readers actually take longer to read when background speech levels increase could indicate greater flexibility in adapting their reading strategies in order to preserve reading's ultimate goal, which is understanding what is written. Another possible explanation could be that louder background sounds affect the automaticity of the reading decoding processes, possibly due to the attentional burden imposed by suppressing the distracting speech (Elliot, 2002). In poorer readers, especially younger ones, decoding processes are not fully automatized (Froyen, Bonte, van Atteveldt & Blomert, 2009; Chein & Schneider, 2012), and their reading speed thus might be less affected by loud background noise relative to more fluent readers. Future studies are needed to shed light on the mechanisms underlying this effect.

## 2.5. Conclusions

To our knowledge, this is the first study investigating the effect of different types of background speech on online text reading performance of children. Our results indicate that reading speed decreased with louder background speech while reading comprehension was disrupted by the intelligibility of the distraction. The larger intelligibility effect in children with poorer interference control suggests that these children may be more vulnerable in environments where background speech is present. The present study provides insight in the influence of different properties of background speech on children's text reading performance with relevant implications for reading in everyday classroom environments. In future studies it would be interesting to further investigate the observed effects as well as their underlying mechanisms by (for example) adding different types of speech conditions, including children's voices, testing in a virtual reality set-up simulating classroom environments, and using eye-tracking methodology and/or measurements of children's brain activity with electro-encephalography (EEG). Furthermore, our reading-in-noise paradigm may provide a valuable tool for studying the effect of different types of auditory distraction on reading skills in more vulnerable groups, such as children with developmental disorders and/or learning difficulties. In the current PhD project, it was not possible to address this question, for example, by including the reading under distracting speech paradigm among the measures of the study presented in **Chapters 3 and 4** with dyslexic and typical readers due to the already long testing sessions.

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# *Chapter 3*

# Attention modulation of neural entrainment to sound in children with and without dyslexia

## 3.1. Abstract

Critical to everyday life, selective auditory attention enables the prioritisation of relevant stimuli over distractors, facilitating the encoding of relevant information. For this reason, it forms an important foundation of children's learning. The auditory modality of attention, in particular, may affect critical skills underlying children's reading acquisition, which relies on awareness of the sound structure and discrete units of the continuous speech signal. Following this reasoning, poorer selective auditory attentional skills might contribute to problems in learning to read. In the current EEG study, we tested this hypothesis by assessing non-verbal auditory sustained selective attention in 106 7-to-12 years old children with and without developmental dyslexia. Children attended to one of two sound streams, and detected occasional tone sequence repeats in the attended stream, while ignoring repeats in the other stream. We also assessed their speech-in-speech perception and reading fluency abilities. When children directed their attention to one of two the tone-streams, inter-trial-phase-coherence (ITPC) at the attended tone stream rate increased in fronto-central sites; this, in turn, was associated with better target detection. Although behavioural and neural correlates of selective attention did not differ as a function of dyslexia diagnosis, behavioural selective attention did explain individual differences in reading fluency and speech-in-speech perception abilities, both of which were impaired in children with dyslexia. Taken together, our results show that at the group level, children with dyslexia do not show sustained auditory selective attention deficits. They also suggest that in children with dyslexia auditory attention may represent a risk for severe reading fluency and for problems with speech perception in complex acoustic environments.

## 3.2. Introduction

Much of our daily life relies on successful auditory attention, whether we are trying to listen to our boss in a meeting while children enjoy the nearby playground, or indeed when one of those children is listening to her online school teacher while her younger brother is watching a cartoon on TV next door. Such situations often force us to single out a sound stream from a complex mixture of sounds and maintain focus on the target over time to extract and make use of relevant information. Selective attention allows us to filter out unimportant sounds while facilitating the encoding of task-relevant information; thus, it is vital for learning (Posner & Rothbart, 2005; Stevens & Bavelier, 2012). In the auditory modality, the development of the attention system is thought to shape the way language is processed and acquired starting very early in development (de Diego-Balaguer, Martinez-Alvarez, & Pons, 2016; Gomes, Wolfson, & Halperin, 2007; Myachykov & Posner, 2005).

Auditory attention may be particularly relevant for reading acquisition, which requires awareness of the sound structure and discrete units of the continuous speech signal (e.g, Goswami, 2011) and relies on explicit verbal instruction. On a global level, inattention may prevent children from benefiting from reading-related activities in the classroom and may predispose them to early reading acquisition difficulties (Dally, 2006; Dittman, 2013; Sims & Lonigan, 2013). Less effective attentional mechanisms may hinder the development of crucial cognitive skills associated with reading acquisition, such as phonemic awareness (ten Braak, Kleemans, Størksen, Verhoeven, & Segers, 2018; van de Sande, Segers, & Verhoeven, 2013; Dally, 2006; Martinussen, Grimbos, & Ferrari, 2014; Plourde et al., 2018). Phonemic awareness development and the learning of sub-lexical spelling-sound mappings relies upon consistent categorization of the speech units (Boets, Wouters, van Wieringen, de Smedt, & Ghesquière, 2008; Vandermosten et al., 2010). Auditory selective attention may facilitate phonetic categorisation learning by biasing perception towards the most informative acoustic cues of each phonemic category, thus enhancing the perceived differences between categories (Francis, Kaganovich, & Driscoll-Huber, 2008; Francis & Nusbaum, 2002; Gordon, Eberhardt, & Rueckl, 1993). Finally, attentional mechanisms may play a role in developing automaticity in reading (Laberge & Samuels, 1974), for example, by facilitating access to phonological information from print (Reynolds & Besner, 2006). Conversely, less effective attention mechanisms or skills may make it difficult for children to become fluent readers (Shaywitz & Shaywitz, 2008).

Links between auditory attention, language, and reading processes may have particular implications for developmental dyslexia (hereafter, dyslexia). As defined by the American Psychological Association (2013), dyslexia is a specific learning disorder characterised by persistent problems with accurate and fluent word reading and poor spelling. Deficits in various aspects of phonological processing are often observed in children and adults with dyslexia (Goswami, 2000; Ramus & Szenkovits, 2008). Traditionally, weak phonological representations have been seen as the core causal factor underlying the disorder (e.g., Vellutino et al., 2004). However, the heterogeneity of symptoms found in dyslexic readers (e.g., Heim et al., 2008; Menghini et al., 2010; Willems, Jansma, Blomert, & Vaessen, 2016) has prompted a search for additional causal factors, including a letter-speech sound integration deficit (Blomert, 2011), an auditory temporal processing deficit (Tallal, 1980, 2004; Vandermosten et al., 2010, 2011), an attentional deficit (Bosse, Tainturier, & Valdois, 2007; Hari & Renvall, 2001) and individually variable combinations of multiple domain-general and language-specific deficits (Pennington, 2006; Peterson & Pennington, 2015). A theoretical framework moving beyond the identification of a single core deficit would also account for the high comorbidity among developmental disorders (Pennington, 2006). Indeed, up to 40% of individuals with dyslexia also receive a diagnosis of attention deficit and hyperactivity disorder (ADHD) and vice-versa (Germanò, Gagliano, & Curatolo, 2010; Willcutt & Pennington, 2000), with a stronger association of reading disorders with inattention than hyperactivity-impulsivity symptoms of ADHD (Greven, Harlaar, Dale, & Plomin, 2011; Hendren, Haft, Black, White, & Hoeft, 2018; Plourde et al., 2015).

Studies with dyslexic readers without a co-occurrent formal diagnosis of ADHD have often reported attentional problems beyond the language domain. For instance, groups of participants with dyslexia have shown poorer stimulus-driven engagement of attention in both auditory (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Facoetti et al., 2003, 2010) and visual modalities (Facoetti et al., 2005, 2003, 2010; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014; Ruffino et al., 2010). Similar trends have been seen in amodal attentional shifting (Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; Lallier et al., 2010; Lallier, Thierry, & Tainturier, 2013; Lallier et al., 2009). There have also been reports of poorer ability of suppressing irrelevant or distracting information in both visual (Roach & Hogben, 2007, 2008; Facoetti et al., 2006) and auditory domains (Gabay, Gabay, Schiff, & Henik, 2020).

Providing further indication of putative auditory attentional deficits in dyslexia, studies have frequently reported that speech perception in adverse listening conditions - an ability that draws upon attention skills (Oberfeld & Klöckner-Nowotny, 2016; Tierney, Rosen, & Dick, 2020) - is challenging for individuals with dyslexia. Children with dyslexia have shown difficulties under a wide range of distracting or masking conditions, including speech-shaped noise and babble noise (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009; Dole, Hoen, & Meunier, 2012; Nittrouer, Krieg, & Lowenstein, 2018; Ziegler, Pech-Georgel, George, & Lorenzi, 2009; see for a review: Calcus, Hoonhorst, Colin, Deltenre, & Kolinsky, 2018).

Because individuals with dyslexia do not usually show speech perception difficulties in quiet, some authors have hypothesized that the reduction in the availability of disambiguating acoustic cues makes it difficult for dyslexic listeners to compensate for their weak or unspecified speech sound representations (Ziegler et al., 2009). Given that everyday listening conditions are rarely pristine, such difficulties with speech-in-noise perception may hamper the acquisition of precise phoneme representations prior to reading acquisition, suggesting rather a bidirectional influence between difficulties in perceiving speech in noisy everyday environments, and phonological impairments (Boets et al., 2011; Ziegler et al., 2009).

Furthermore, there is considerable individual variability in speech-in-noise performance in dyslexic readers (Calcus et al., 2017; Messaoud-Galusi, Hazan, & Rosen, 2011), paralleling the heterogeneity of dyslexic readers' auditory processing profiles (Lallier et al., 2013). Most relevant to the present study, auditory attention has been proposed to be one of the factors underlying problems with both speech perception in challenging environments and reading in dyslexia (Calcus, Lorenzi, Collet, Colin, & Kolinsky, 2016; Calcus, Hoonhorst, Colin, Deltenre, & Kolinsky, 2018; Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009; Ziegler et al., 2009). To date, in individuals with dyslexia the link between auditory attention and difficulties with perceiving speech with distractors has not been examined yet, possibly due to the lack of methodological tools assessing auditory attention skills relevant to demands of complex acoustic environments (Calcus et al., 2018).

In the present EEG study, we assessed auditory sustained selective attention skills in children with and without dyslexia using a task requiring participants to direct attention to one of two rhythmic tone-streams and to detect occasional repeats within it while ignoring the competing tone-stream. We deliberately used a non-verbal auditory task to assess attentional skills while minimising potential confounding language difficulties. At the same time, the task assesses attentional demands characterising complex acoustic environments by requiring participants to direct and maintain attention to a target stream over time, integrate information within the attended stream while suppressing attention to a distractor stream.

Prior electrophysiological studies showed that directing attention to the temporal structure of stimuli modulates phase entrainment specifically at the frequency of the attended stimuli (Besle et al., 2011; Henry & Obleser, 2012; Laffere, Dick, Holt, & Tierney, 2020; Laffere, Dick, & Tierney, 2020). Moreover, selective phase entrainment was predictive of greater stimulus detection performance in sound-feature detection paradigms (Henry & Obleser, 2012; Laffere, Dick, Holt, et al., 2020; Laffere, Dick, & Tierney, 2020). These findings provided some evidence for the hypothesis that selective attention can modulate neural entrainment, i.e. the alignment of the timing of neural activity with the temporal regularities of an exogenous stimulus (Obleser & Kayser, 2019). In naturalistic environments, selective entrainment might serve as a mechanism to preferentially track relevant continuous speech at the expense of a concurrent distractor speech stream (Ding & Simon, 2012; Horton & Srinivasan, 2013; Kerlin, Shahin, & Miller, 2010; Zion Golumbic et al., 2013) by capitalising on the quasi-temporal structure of speech (Zion Golumbic, Poeppel, & Schroeder, 2012), with consequent benefits to speech intelligibility and recall (Hambrook & Tata, 2014).

In the current study, we examined the neural (EEG) correlates of non-verbal sustained auditory attention in 7-to-12-years-old children, hypothesising that sustained selective attention to one of two tone streams would be linked to increased phase entrainment at the attended frequency. Moreover, we compared behavioural and EEG correlates of sustained selective attention in children with and without dyslexia and examined whether they predict individual differences in speech-in-speech perception and reading fluency abilities.

## 3.3. Materials and method

### 3.3.1. Participants

106 7-to-12-year-old children (59 with dyslexia and 47 typically developing) were recruited for the study. All were native Dutch speakers. Children with dyslexia were recruited from the Regional Institute for Dyslexia (RID) and were on a waiting list for treatment. Dyslexia diagnosis was provided by the RID based on the results of cognitive psycho-diagnostic testing and standardized reading measures, including the Wechsler Intelligence Scale for Children (WISC) and the 3DM test battery (Differential Dyslexia Diagnosis; Blomert and Vaessen, 2009). Data from two

children were excluded due to hearing impairments; additional data from one participant was excluded due to having completed a treatment for dyslexia in another institution. None of the children with dyslexia were diagnosed with attention deficit and hyperactivity disorder (ADHD). Typically developing children were siblings or acquaintances of the participants with dyslexia, or were recruited via word of mouth; none of these children were diagnosed with dyslexia and/or ADHD. Parents gave written informed consent for participation, and children received a small gift and a certificate as a reward for participating. The study was approved by the ethics committee of the Faculty of Psychology and Neuroscience, Maastricht University.

Of the 103 participants, five did not complete all three conditions of the selective auditory attention task (see Electrophysiological Testing section) due to lack of compliance. Of the remaining 98 participants, six additional participants were excluded due to technical problems in saving the triggers; three more participants were excluded because of noise sourcing from adjacent electrodes which impeded signal replacement using the neighbouring electrodes' weighted average interpolation technique (ft_channelrepair.m from Fieldtrip; see EEG Recording and Data Processing).

After these exclusions, data from 89 participants remained. Participants' age, IQ, reading, and reading-related skills are reported in **Table 3.1.** Data from the 3DM battery test of four participants were not saved due to software issues and two participants were not administered the One-Minute-Test (EMT; Brus & Voeten, 1973) for reading fluency due to time constraints (see Reading and Reading-Related Skills section). Multiple imputation with SPSS (version 26.0, IBM Corp., Armonk, NY, United States) was then used to replace missing data of the reading fluency measure of the 3DM reading task. As none of these participants had missing values for both EMT and 3DM task, EMT score functioned as a predictor for the 3DM task measure which was used in the analyses as a measure of reading fluency.

**Table 3.1. Participants' characteristics, reading and reading-related skills of children with and without dyslexia.**

| | Dyslexic readers (N = 51) | | | Typical readers (N = 38) | | | Dyslexic vs typical readers | |
|---|---|---|---|---|---|---|---|---|
| | ratio | | | ratio | | | x(df)[a] | p |
| **Sex (m/f)** | 29/22 | | | 14/24 | | | .358(1) | .549 |
| | **Mean** | **SD** | **Range** | **Mean** | **SD** | **Range** | **t(df)[b]** | ***p*** |
| **Age (months)** | 114.88 | 13.932 | 92-149 | 115.47 | 15.02 | 88-148 | -.192(87) | .849 |
| **Verbal IQ (Vocabulary)** | 11.24 | 2.53 | 6-17 | 11.84 | 2.57 | 6-19 | -1.11(87) | .270 |
| **Non-verbal IQ (Block design)** | 9.80 | 2.95 | 3-19 | 10.50 | 3.13 | 5-17 | -1.073(87) | .286 |
| **EMT (Standardized)** | 2.96 | 2.41 | 1-10 | 9.05 | 3.31 | 2-19 | -10.052(87) | <0.0001 |
| **EMT (Raw)** | 30.92 | 13.25 | 5-65 | 56.84 | 16.92 | 20-102 | -8.108(87) | <0.0001 |
| **3DM Word Fluency (T)** | 29.25 | 6.13 | 20-41 | 49.97 | 10.24 | 34-75 | -11.079(56.38) | <0.0001 |
| **3DM Word Fluency (Raw)** | 61.57 | 26.79 | 2-112 | 113.16 | 29.56 | 23-166 | -8.597(87) | <0.0001 |
| **3DM Word accuracy (T)** | 32.86 | 11.50 | 20-55 | 51.25 | 9.47 | 23-61 | -8.031(87) | <0.0001 |
| | **N = 51** | | | **N = 34[c]** | | | | |
| **Phonological awareness (T)** | 37.76 | 8.14 | 21-54 | 48.06 | 10.29 | 27-67 | -5.134(84) | <0.0001 |
| **RAN – Letters (T)** | 34.37 | 7.79 | 20-51 | 45.44 | 10.92 | 24-71 | -5.106(55.016) | <0.0001 |
| **RAN – Digits (T)** | 36.69 | 7.88 | 20-52 | 45.59 | 10.09 | 28-68 | -4.556 (84) | <0.0005 |

[a] *Chi-squared test*

[b] *Independent sample t-test*

[c] *Data from four participants went lost due to software issues.*

## 3.3.2. Overview of the procedure

The children underwent electrophysiological and behavioural testing. The sessions lasted around 1 hour and 45 minutes each. The order of both sessions was randomised over participants, so that half of the participants of each group (dyslexic and typical readers) started with the behavioural testing, and the other half of each group started with the EEG testing. Children took short breaks between tasks and a longer break between sessions.

## 3.3.3. Electrophysiological testing

### 3.3.3.1. Selective auditory attention task

**Stimuli**

The basic stimulus unit was three cosine-ramped sine tone sequences followed by a silence. Tones were 166.67 ms long and were generated at a sampling rate of 44.1

kHz using MATLAB (Mathworks). Each tone in the sequence was followed by 166.67 ms silence, such that there was a tone onset every 333.33 ms.

The sequences were made up from two sets of three tone frequencies each; tones in each set were separated by two musical semitones, with the two sets separated by an octave. Low-frequency-band tones (with musical note name) were 370 Hz (F#4), 415.3 Hz (G#4) and 466.2 Hz (A#4) while high-frequency-band tones were 740 Hz (F#5), 830.7 Hz (G#5) and 932.5 Hz (A#5).

As shown in **Figure 3.1**, the high and low band sequences were temporally interleaved, such that the tone streams were separated in phase by 180 degrees. Thus, participants heard a sequence of six successive tones in each trial, each 166.67 ms in duration, with the first, third, and fifth tone taken from the low-frequency band, and the second, fourth, and sixth tone taken from the high-frequency band. The six tones were followed by a 333.33 ms silence; this unit was considered one trial. As a result, the within-band presentation rate was 3 Hz (one tone every 333 ms), with the dual-band presentation rate was 6 Hz (one tone every 166.67 ms).

Based on in-lab piloting, tones in the high-frequency band were presented at 40% of the amplitude of lower-frequency tones to ensure that the perceived loudness of the two bands was approximately balanced.

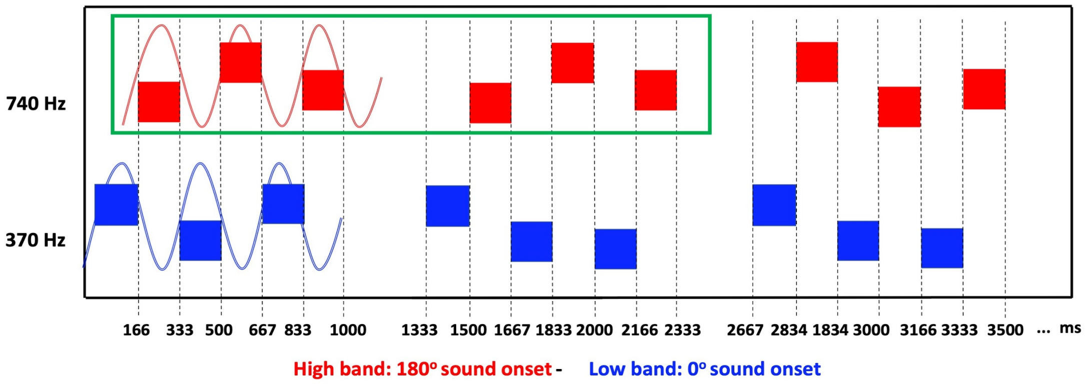

**Figure 3.1. Schematic of the selective attention task. The target and distractor tones streams were presented simultaneously in antiphase. Participants were asked to detect repetitions of sequences of three tones, such as the one in the green square, occurring five times within one block of 30 three-tones sequences.**

### Task

During the task, children were sitting in front of an Ilyama 21.5′ computer monitor. ER-3C insert earphones (Etymotic Research, Elk Grove Village, IL) were used for sound presentation at 72-73 dB SPL, as measured using a RION NA-27 Sound Level

Meter with an NH-20 microphone. The experiment consisted of three conditions of ten blocks each. In the first condition, participants were asked to attend to the high band, in the second condition, to attend to the low band, and in the third and final condition, to passively listen to the stimuli. This order was fixed across all subjects to minimise cross-subject variability.

Each block contained 30 trials, and was 41s long; there were 300 trials per condition. During the active conditions, participants were asked to detect and report within-attended-band sequence repeats via a Cedrus RB-844 response box. In each block there were five repeated sequences in each band; the timing of repeats was semi-random (repeated sequences were always separated by at least one non-repeated sequence). Participants were asked to ignore the distracting band and the sequence repeats within it; across blocks, there were equivalent numbers of repeats in both bands. A repeat was recorded as being correctly detected if the participant provided a response between 333 ms before and 1670 ms after the end of the last tone in a repeated sequence.

To ensure children's engagement, the EEG task and instructions were gamified. A spaceship at the centre of the screen and moving dots in the background mimicking a space environment were displayed. The participants were told that the stimuli were produced by the ship's radar and that they would need to listen to them to detect asteroids which were approaching from above (attend high band) or from below the spaceship (attend low band). An approaching asteroid was signalled by the repeated sequences; to avoid it, they had to press the button. Feedback for correct and incorrect responses was given at the centre of the screen (Dutch: "Raak/Faut"; English: "Hit/Wrong") and a score on the top right corner of the screen. Players received an increase of 20 points for each identified target, a decrease of 2 points for each missed target and a decrease of 5 points for each false alarm.

Before the task, children underwent a short practice with the experimenter to familiarise themselves with the stimuli. This session included an initial short practice in attending to single-stream stimuli and identifying related targets and practice blocks with dual-streams stimuli per condition (attend-high and attend-low).

#### 3.3.3.2. EEG recording and data processing

Electrophysiological data were recorded from a 64-channel ActiChamp system (Brain Products). EEG data were recorded with a sampling rate of 25000 Hz and referenced online to FCz. Impedance was kept below 20 kΩ. To achieve precise temporal synchronisation between stimulus presentation and triggering signal, an RTBox was used for detecting stimulus onsets and sending trigger pulses to the EEG data acquisition laptop. Stimulus onsets and trigger pulse events were then referenced to the same system clock.

Pre-processing was carried out with customised scripts including Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) and EEGLAB (Delorme & Makeig, 2004) for MATLAB (Mathworks) functions. Independent Component Analysis (ICA) was performed to remove ocular artefacts, identified by visual inspection of the topography and the time course of the components. EEG data were then downsampled to 500 Hz and segmented into 1.333 second epochs, time-locked to the stimulus onset. A high-pass Butterworth filter at 1 Hz and a low-pass filter of 30 Hz were applied.

Electrodes showing noise across the experiment were interpolated using the neighbours weighted average technique (ft_channelrepair.m from Fieldtrip; applied to three participants). Epochs with voltage exceeding ±125 $\mu$V were automatically marked for rejection. On average, 94.4% of trials were kept for analysis, with no significant difference between conditions for participants with dyslexia (attend-high: mean 285.37 trials (SD = 14.78, range = 232-299); attend-low: 284.66 trials (SD = 13.97, range: 247-299); passive: 277.21 trials (SD = 22.11, range = 200-299)) and without dyslexia (attend-high: mean 286.34 trials (SD = 14.77, range: 238-299); attend-low: 284.74 trials (SD = 22.29, range = 209-299); passive: 281.46 trials (SD = 18.17, range = 231-299)).

Following previous in-lab studies that characterised attention-driven neural entrainment (Laffere, Dick, and Tierney 2020; Laffere, Dick, Holt, et al. 2020), we extracted inter-trial phase coherence (ITPC) at the attended-band presentation rate (3 Hz) and at the overall stimuli presentation rate (6 Hz). A Hann-windowed Fast Fourier Transform (FFT) was first applied to each epoch. Then, at each frequency, the complex vector was converted to unit length to retain the phase component while discarding amplitude. Unit vectors were then averaged, with ITPC defined as the length of the resulting averaged vector. ITPC ranges from 0 to 1, with 0 for non-phase locked activity and 1 for strictly phase-locked activity.

### 3.3.4. Behavioural testing

#### 3.3.4.1. Speech-in-speech perception

Speech-in-speech-perception was assessed using an adapted version of the Coordinate Response Measure task (Bolia, Nelson, Ericson, & Simpson, 2000) for Dutch children. The task was programmed and presented with Psychtoolbox-3 in MATLAB 9.1.0 (Mathworks). An HP ProBook 640 G2 laptop, with a 1920 x 1080 screen and Core i5-6200 microprocessor was used to present the task. The auditory stimuli were presented over headphones (Sony Professional MDR-7510) at 70-72 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone.

**Stimuli**

Auditory stimuli were of a male and a female voice simultaneously uttering variants of similar sentence frame, where the variable elements were colour and number words: “Show the dog where the [colour] [number] is” (Dutch: “Wijs de hond aan waar de [kleur] [nummer] is”). The two sentences always contained different monosyllabic colours (black, blue, green, red, white, or yellow; Dutch: zwart, blauw, groen, rood, wit, geel) and numbers (1, 2, 3, 4, 5, 6, or 8; Dutch: één, twee, drie, vier, vijf, zes, acht). The sentences were spoken by two native Dutch talkers. The stimuli were recorded at a sampling rate of 44.1 Hz separately for each talker in a soundbooth. A customised MATLAB script (MathWorks) was used to align and overlap the female and the male spoken sentences to ensure simultaneous sentence onset time.

**Task**

Two conditions of 25 trials each were included. In one condition, the participants had to selectively attend to the male voice and in the other condition to the female voice. After the sentences were presented, children saw a grid of coloured numbers that included every possible colour and number combination. They were asked to report by mouse-click the colour/number combination spoken by the attended talker. To facilitate children’s understanding of task instructions, they were told to help a dog to learn colours and numbers by pointing to the coloured numbers spoken by either a female or a male teacher. To remind the children of the voice they were meant to be attending to, the cartoon characters of a dog and of a male (in the attend-male condition) or of a female (in the attend-female condition) teacher were displayed on top of the response grid. The proportion of correct trials, averaged across both conditions, was used as the measure of performance accuracy. D-prime measure could not be computed for all participants, as 34% participants in the attend female speaker condition and 60% in the attend male had false alarm rate to 0.

### 3.3.4.2. Reading and reading-related skills

#### Reading tests

Participants were administered the One-Minute-Test (EMT; Brus & Voeten, 1973) and the reading task from the 3DM battery (Dyslexia Differential Diagnosis; Blomert & Vaessen, 2009). The One-Minute-Test includes 116 words (both low- and high-frequency words) that vary from one to four syllables presented in four columns of 29 words. The score was calculated as the number of words read correctly within one minute. The 3DM reading task includes three subtasks: one with high-frequency words, one with low-frequency words and one with pseudowords. The child was instructed to read correctly as many (pseudo)words as possible within the time limit (30 seconds per level). The words of each level increased in the number of syllables and syllabic complexity.

#### Rapid automatized naming (RAN; 3DM battery subtest; Blomert & Vaessen, 2009)

The rapid naming task of the 3DM battery consist of two subtasks: letters and digits naming (Blomert & Vaessen, 2009). In each subtask, 15 items (five letters or digits repeated three times) are presented on the screen. Each set of 15 items is presented two times on the screen, with the items presented in a different order. The participant was instructed to name the items as quickly and accurately as possible. Performance is measured as response time obtained by averaging the response time of the two screen presentations.

#### Phonological awareness (phoneme deletion; 3DM battery subtest; Blomert & Vaessen, 2009)

The phoneme deletion task contained 23 pseudowords (Consonant-Vowel-Consonant (CVC) or CCVCC structure) presented orally. Participants were asked to leave out the first consonant, the last consonant, or a consonant within a consonant cluster and to pronounce the remaining pseudoword (e.g., ''/dauk/ – /d/, what is left?''). Here, we reported only the accuracy scores, as RTs are not generated if the accuracy is below 21.8% (i.e. < 5 correct pseudowords), which happened for 17 out of 51 children with dyslexia.

### 3.3.5. Statistical analyses

Statistical analyses were performed using the Statistics and Machine Learning Toolbox in MATLAB (Mathworks) and SPSS (version 26.0, IBM Corp., Armonk, NY, United States). To investigate the effects of attentive listening on neural entrainment to rhythmic sound, we compared ITPC at 3 Hz (the within-band presentation rate) in active and passive conditions on a channel-by-channel basis. Here, we used a Repeated Measures ANOVA, with channel (n = 63), condition (active vs. passive) and channel-by-condition interaction as within-subjects factors. Greenhouse-Geisser correction was used as the assumption of sphericity was violated (indicated by the Mauchly's sphericity test). Prior to analysis, ITPC values were log-transformed to normalize the underlying distribution. We also investigated whether the differences in ITPC between conditions (active-passive) at 3 Hz and 6 Hz was related to behaviourally measured selective attention abilities. To accomplish this, we carried out Spearman correlations to relate selective attention task performance (d-prime) to ITPC differences (active-passive) at 3 and 6 Hz at each channel. Similarly, we used Spearman correlations to explore the relationship between selective attention performance and neural metrics (ITPC difference at 3 and 6 Hz) with age (in months) and with reading fluency scores (3DM reading task).

To test whether children with dyslexia differed from typical readers in selective attention ability, we compared task performance and ITPC differences (active-passive) at 3 Hz or 6 Hz between the two groups with Wilcoxon rank-sum tests, as ITPC differences were not normally distributed.

Finally, we used linear regression models to ask whether children with dyslexia had difficulties in speech-in-speech perception and whether these difficulties were modulated by selective attention performance and ITPC difference at 3 Hz or 6 Hz. In a first step, age and diagnosis were entered in the model. In a second step, selective attention performance or ITPC difference at 3 Hz or 6 Hz per channel were also entered as regressors. The assumptions of linearity, independence of errors, homoscedasticity and normality of residuals were met for each of the regression models. Data were inspected for outliers that were identified based on standardized residuals, and data points with residual values below −3 and above 3 were excluded from the analyses (Osborne & Overbay, 2004). All channel-based analyses were corrected for multiple comparisons with False Discovery Rate (FDR; Benjamini & Hochberg, 1995).

## 3.4. Results

### 3.4.1. Selective attention behavioural performance

On average, children were able to perform the task, but we observed considerable variability in children's performance ((hit rate: M = 0.358, SD = 0.159; false-alarm rate: M = 0.116, SD = 0.077; d-prime = 0.916, SD = 0.725). In the following analyses, d-prime (Stanislaw & Todorv, 1999) was taken as a comprehensive measure of behavioural performance.

### 3.4.2. Neural effects of auditory selective attention in children

**ITPC at 3 Hz:** ITPC differed significantly across channels (F(11.46, 1008.51) = 21.437; $< 0.001$, $\eta p^2 = 0.196$), but with no significant difference between active and passive conditions across all electrodes (F(1,88) = 1.470; $p = 0.229$, $\eta p^2 = .016$). However, there was a significant condition by channel interaction (F(13.751, 1210.12) = 3.259; $p < 0.001$, $\eta p^2 = .036$). Subsequent pairwise comparisons showed that in fronto-central areas (Fz, AF4, F5, FC3), ITPC at 3 Hz was greater in active conditions than during passive listening. By contrast, in temporo-parietal sites (TP8, TP10), ITPC at 3 Hz was higher in the passive condition. The t-statistics of the pairwise comparisons are displayed in the topographic plots in **Figure 3.2.**

**ITPC at 6 Hz:** Similarly to 3 Hz, ITPC at 6 Hz differed significantly across channels (F(6.383, 561.71) = 62.545; $p < 0.001$, $\eta p^2 = .415$), but with no overall significant difference between active and passive conditions (F(1,88) = .007; $p = 0.934$, $\eta p^2 = 0.000$). As with 3 Hz ITPC, a significant condition by channel interaction was found (F(15.187, 1336.425) = 3.672; $p < 0.001$, $\eta p^2 = .040$,). Pairwise t-tests revealed that ITPC at 6 Hz was greater in two fronto-temporal channels (AFz, AF4) but was lower on temporo-parieto-occipital areas (TP9, TP7, P7, PO7, O1, O2, Oz, PO8, P8) in active conditions as compared to the passive condition (**Figure 3.2**; statistics are reported in **Appendix of Chapter 3).**

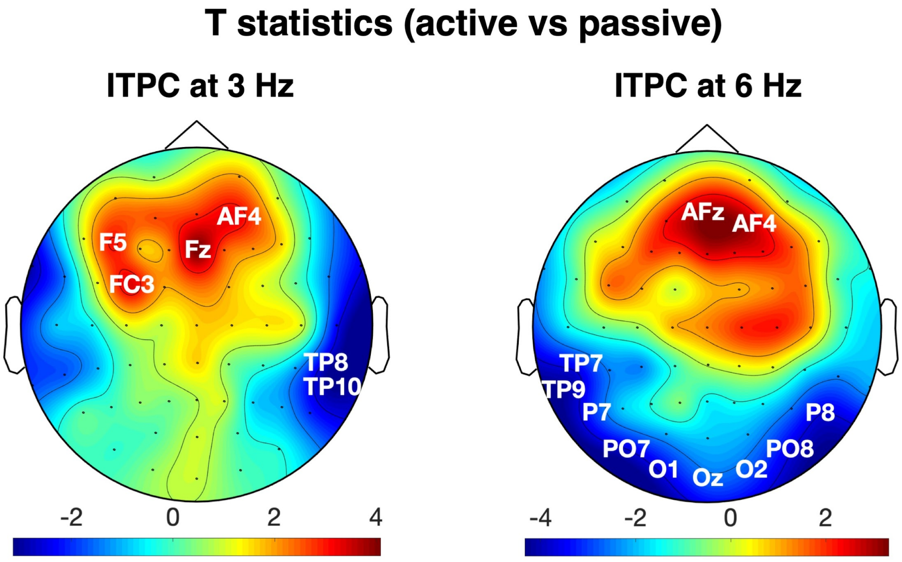

**Figure 3.2. T-statistics of the channel-wise pairwise comparisons between ITPC in the active and in the passive conditions at 3 Hz and 6 Hz. The labelled channels are the ones found significant after FDR-correction was applied.**

### 3.4.3. Relationship between neural metrics and selective attention performance

The difference in ITPC at 3 Hz between the active and passive conditions was significantly correlated with selective attention task performance in fronto-central sites ($p < 0.05$; **Figure 3.3**). Task performance was not correlated with ITPC difference (active-passive) at 6 Hz at any electrode (see **Appendix of Chapter 3** for channel-wise statistics**)**.

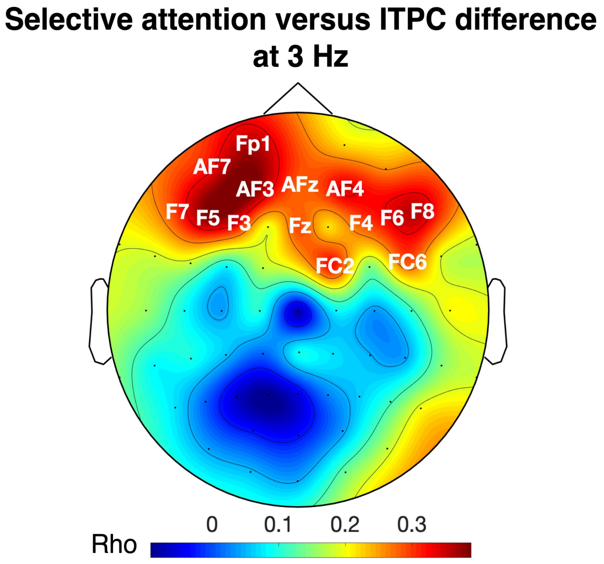

**Figure 3.3.Topographic plot displaying the rho values of the Spearman correlations between selective attention performance (d-prime) and ITPC difference between active and passive conditions at 3 Hz. The labelled channels are the ones remaining significant after FDR-correction was applied.**

### 3.4.4. Relationship between chronological age and auditory selective attention

We found a significant correlation between selective attention performance and age (in months), with performance improving between 7-12 years of age (rho = 0.235, p = 0.027). Results of channel-wise Spearman correlations revealed no significant relationship between age on the one hand, and ITPC difference (active-passive) at 3 Hz or 6 Hz (p > 0.05, FDR-corrected; statistics in **Appendix of Chapter 3**).

### 3.4.5. Comparison of children with and without dyslexia in non-verbal selective attention

Children with and without dyslexia did not perform significantly differently in the selective attention task (Z = -0.979, p = 0.328; **Figure 3.4**).

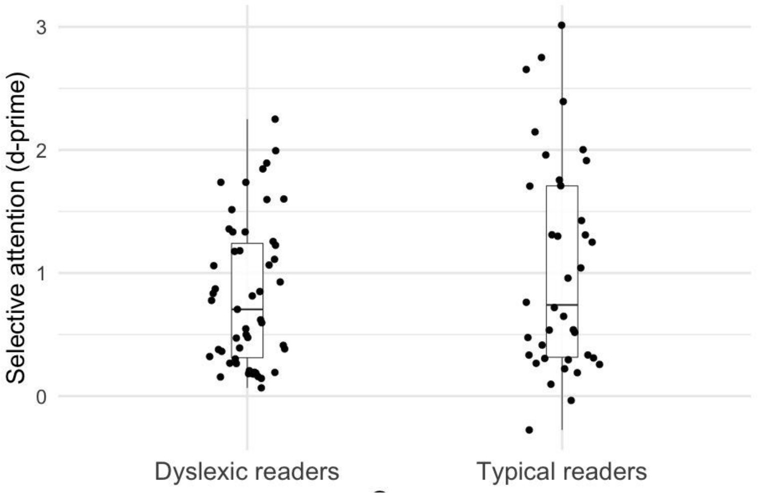

**Figure 3.4. Selective attention task performance of children with and without dyslexia did not differ significantly.**

Similarly, no significant differences were observed in ITPC differences (active-passive) at 3 and 6 Hz (p > 0.05, FDR-corrected; **Figure 3.5;** statistics in **Appendix of Chapter 3**). As the observation of the topographic plots (**Figure 3.5**) suggested some differences between the group in ITPC difference(active-passive), especially at 3 Hz, which however, did not reach significance, we further investigated by looking at the distribution of ITPC values (active-passive) at 3 Hz within the groups (**Figure 3.6**). As expected, we observed substantial variability within the groups.

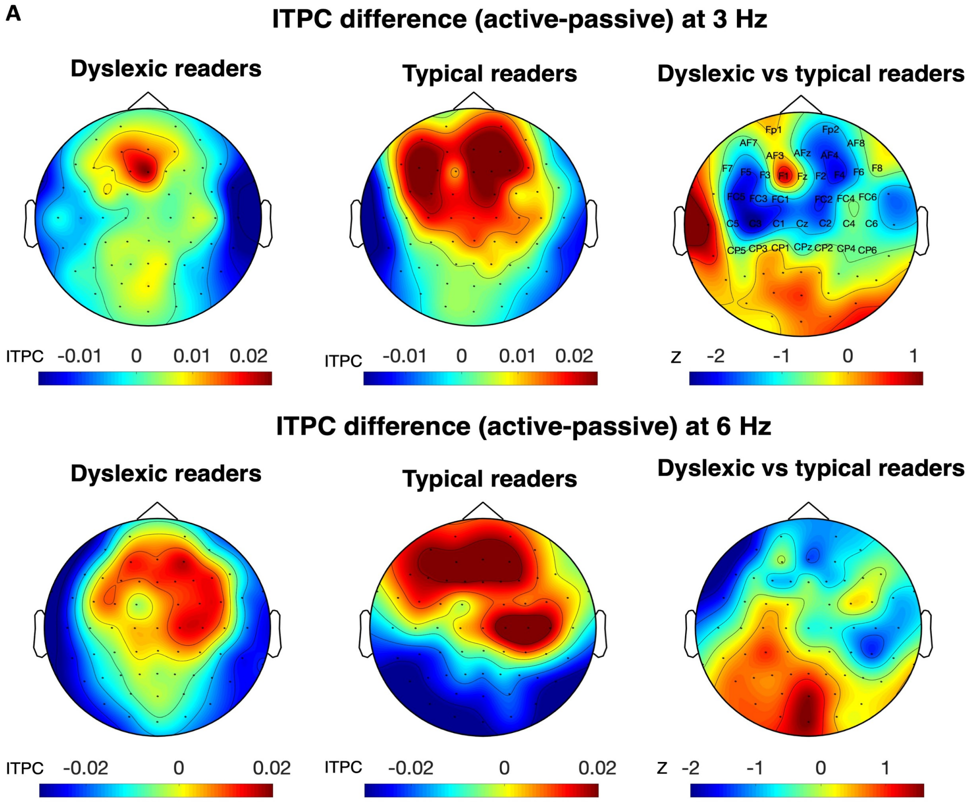

**Figure 3.5. ITPC differences (active-passive) at 3 Hz and at 6 Hz for the group of children with and without dyslexia and the z values of the pairwise comparisons. No significant group differences were found at any channels after FDR-correction was applied. The labelled channels in the topographic plot with z values are a selection of fronto-central channels displayed in the boxplots in Figure 3.6.**

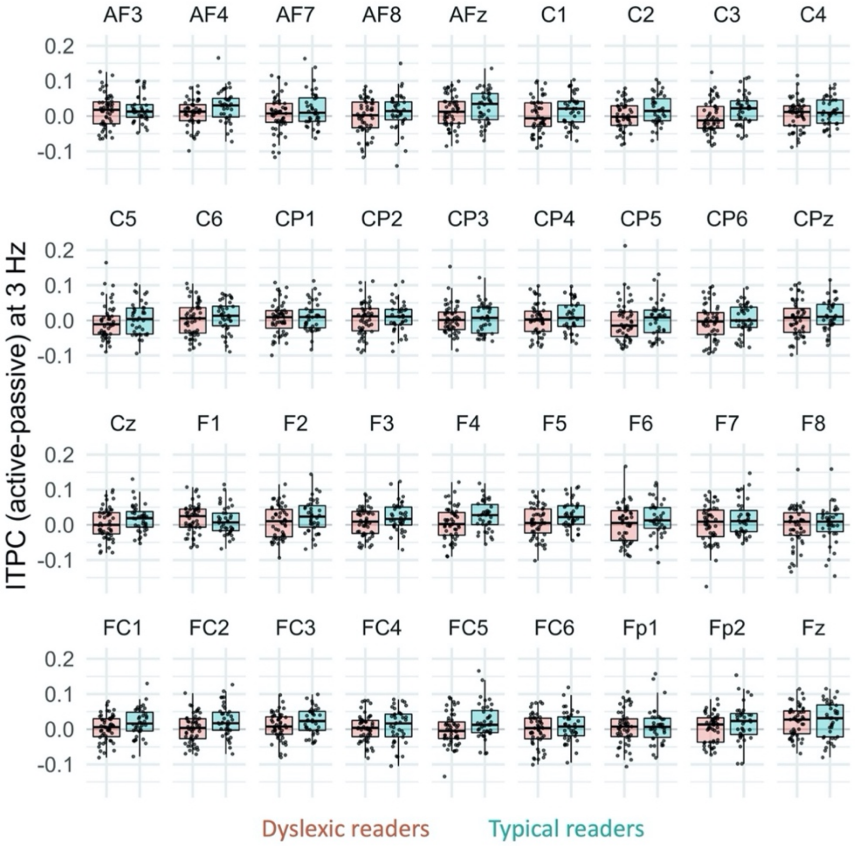

**Figure 3.6. The distribution of ITPC difference values (active-passive) at 3 Hz for the group of children with and without dyslexia in fronto-central channels.**

### 3.4.6. Contribution of auditory selective attention to children's reading fluency abilities

Selective attention performance and reading fluency (as assessed by the '3DM reading subtest') were positively correlated (rho = 0.288, p = 0.006), and remained correlated after both variables were age-detrended (rho = 0.236, p = 0.026). When the same correlational analyses were run separately for each group, we found that once the effect of age was removed, the reading fluency abilities were correlated with selective attention only in dyslexic readers (rho = 0.322, p = 0.022), but not in typical readers (rho = 0.089, p = 0.593; **Figure 3.6**). Channel-wise Spearman correlations revealed no significant relationship between reading fluency and ITPC difference (active-passive) at 3 Hz or 6 Hz (p > 0.05, FDR-corrected; statistics in **Appendix of Chapter 3**).

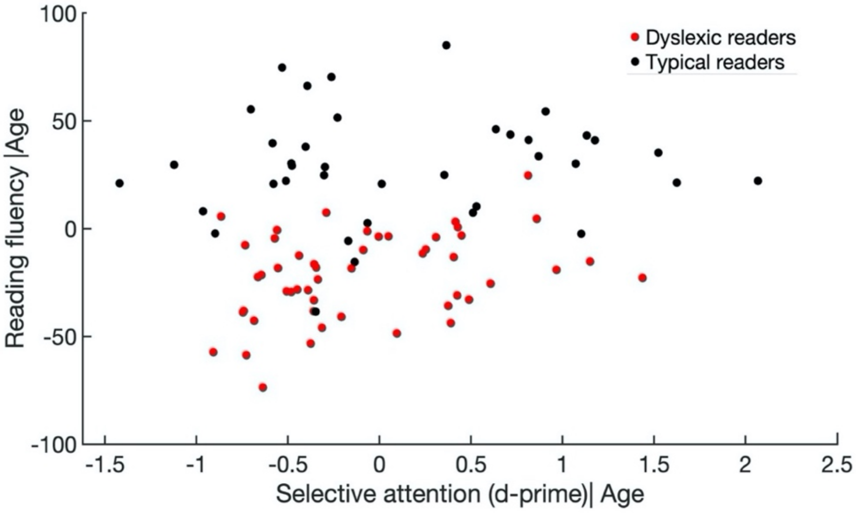

**Figure 3.7. Selective attention (d-prime) was significantly correlated with reading fluency abilities in dyslexic readers (in red) but not in typical readers (in black), once the effect of age was removed from both variables. Note that fit line is not included because Spearman's rank correlations are used.**

### 3.4.7. Speech-in-speech perception is impaired in children with dyslexia and modulated by non-verbal selective attention performance

Two participants were excluded from the analyses as they did not perform correctly in one of the two conditions (with accuracy ≤ 4%) of the speech-in-speech perception task. An additional subject with dyslexia was removed from the model for having standardised residuals below 3. Results showed that age ($\beta$ =.437, $p < 0.001$, 95% CI = .002 to .006) and diagnosis ($\beta$ = -.200, p = 0.041, 95% CI = -.100 to -.002) significantly predicted speech-in-speech perception abilities (overall regression model: $R^2 = .229$, $F(2,83) = 12.337$, $p < 0.001$), with older children and children without dyslexia (**Figure 3.7A**) showing greater speech-in-speech perception skills. Adding selective attention performance revealed that speech-in-speech perception abilities were associated with selective attention performance ($\beta = 0.248$, $p = 0.013$; CI = 0.009 to 0.77; **Figure 3.7B**). Age remained a significant predictor ($\beta = .371$, $p < 0.001$; CI = 0.002 to 0.005), but diagnosis did not ($\beta = -0.168$, $p = 0.079$; CI = -0.090 to 0.005; $R^2$ change = .056, $F(1,82)$ change = 6.469; $p = 0.013$; overall regression model: $R^2 = 0.286$, $F(3,82) = 10.923$ , $p < 0.001$)

In contrast, adding to the model ITPC difference at 3 Hz or at 6 Hz on a channel by channel basis did not explain additional significant variance ($p > 0.05$, FDR-corrected; statistics in **Appendix of Chapter 3**). In the models, the statistical significance and the predictive value of age and group remained unchanged.

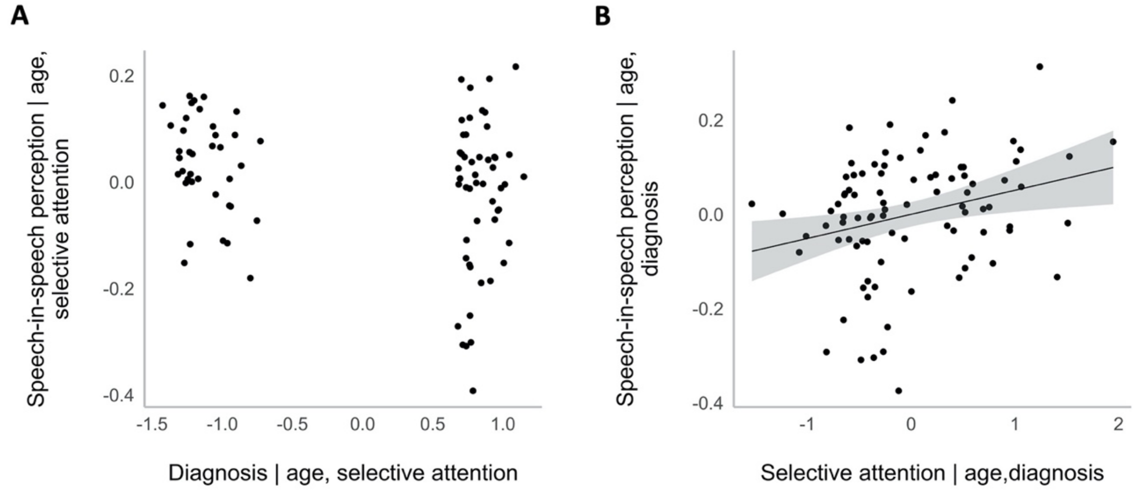

**Figure 3.8. A) Children with dyslexia performed worse in the speech-in-speech perception task. B) The behavioural measure of selective attention was related to speech-in-speech perception abilities.**

## 3.5. Discussion

In the present EEG study, we investigated the neural (EEG) correlates of non-verbal sustained auditory selective attention in 7-to-12-year-old children. We examined whether behavioural and neural correlates of sustained auditory selective attention differ between children with and without dyslexia and explained individual variability in children's reading fluency and speech-in-speech perception abilities.

### 3.5.1. Neural correlates of non-verbal auditory selective attention

We assessed non-verbal sustained auditory selective attention by presenting children with two three-tone isochronous streams in two frequency bands. We asked them to attend to one of the two streams and ignore the other one, and to detect occasional three-tones sequence repeats within the target stream. We compared the two conditions in which children selectively directed their attention to one of the two streams with a passive condition in which children passively listened to similar stimuli without performing any task. Both streams were presented at 3 Hz, and thus the overall sound presentation rate was 6 Hz. Based on previous findings from our lab with young adults (Laffere, Dick, & Tierney 2020) and older children (Laffere, Dick, Holt, & Tierney, 2020), we predicted that selective attention to either stream would be associated with an increase in inter-trial phase coherence at the attended frequency (3 Hz) but not at the cross-band frequency (6 Hz).

We found that inter-trial-phase-coherence at the attended band (3 Hz) increased in frontal areas and decreased in the temporal areas of the scalp when children were directing their attention to one of the two streams. This finding aligns with previous EEG and electrocorticography (ECoG) reports with human and non-human participants showing increased phase entrainment at the attended frequency (Besle et al. 2011; Laffere, Dick, Holt, et al. 2020; Laffere, Dick, & Tierney 2020; Lakatos et al. 2013). The observation that increased phase entrainment was found at other scalp locations than the ones where phase consistency was found to be greatest during passive listening may provide support for the notion that neural alignment with the temporal structure of external stimuli result from attention-driven modulation of endogenous oscillatory activity (Ding and Simon 2012; Zion Golumbic et al. 2013), in contrast to the interpretation of neural entrainment resulting from an attention-controlled gain of sensory responses (Choi et al. 2014; Dai, Best, and Shinn-Cunningham 2018; Hillyard et al. 1973).

Contrary to our expectations, we also found differences between active and passive conditions at the cross-band frequency rate (6 Hz), with the strongest effect being a decreased phase consistency in the active conditions in posterior regions of the scalp. Additionally, a minor effect was also found in two fronto-central channels, where phase consistency was higher when children were attending. On the one hand, the decreased phase consistency at the overall sound presentation rate could suggest a mechanism of suppression of representation of the cross-band stimuli favouring the selection and integration of the task-relevant sound stream. On the other hand, the fact that the relationship between task performance and phase consistency was only found at the attended frequency (3 Hz) does not further support this interpretation. In general, the specific neural metric-behaviour relationship indicates that increased phase entrainment at the attended band serves as a reliable index of children's ability to direct focus, sustain it over time, and integrate information within the attended stimuli.

### 3.5.2. Comparison of children with and without dyslexia: non-verbal sustained auditory selective attention and its relation to speech-in-speech perception and reading fluency

In recent years, researchers have emphasised the heterogeneity of domain-general and language-specific symptoms in developmental dyslexia, supporting a multiple deficits view of neurodevelopmental disorders (Astle & Fletcher-Watson, 2020; Pennington, 2006; Peterson & Pennington, 2015). Among these candidate deficits, there are difficulties with visual and auditory non-verbal attention (e.g., Gabay et al. 2020; Ruffino et al. 2014) and speech perception in complex acoustic settings (e.g., Calcus et al. 2018), which have been reported to be more common in children with dyslexia. Evidence regarding non-verbal auditory selective attention abilities and their neural mechanisms in children with dyslexia is limited. Here, we did not find that children with dyslexia performed significantly worse than typical readers on the sustained selective attention task. Similarly, no group differences were found in attentional modulation of neural entrainment, either at the frequency of the attended band (3 Hz) or at the overall sound presentation frequency (6 Hz). Although this suggests the absence of clear-cut deficits in non-verbal selective auditory attention, we cannot draw strong conclusions about this null effect, given that there was a trend at some fronto-central electrodes for dyslexic readers to show lower modulation of neural entrainment compared to typical readers. Future studies may clarify these findings, for example, by modulating the task difficulty, as the paradigm in the current study may have been challenging for young pupils. Possibly this may have obscured group differences that would have emerged by employing tasks with a lower level of difficulty.

The significant relationship between reading fluency and target detection performance in the sustained selective attention task indicates that auditory attention is one of the underlying factors explaining individual differences in children’s reading fluency. This observation corroborates and extends previous findings showing that visual attentional skills are associated with the development of reading abilities (e.g., ten Braak et al., 2018; van de Sande et al., 2013) and that visual and auditory attentional skills are linked to pseudoword reading abilities in dyslexia (Facoetti et al. 2006, 2010; Gabay et al. 2020). The fact that the association between reading fluency and behavioural selective attention held only in the group of dyslexic readers (but not in the typical readers' group) may indicate that in children with dyslexia, impaired auditory attention represents a risk for more severe problems with reading fluency, although sole auditory attentional deficits are not sufficient to develop reading deficits. These observations align with a multiple deficits account of dyslexia, proposing that no single deficit is either necessary or sufficient to lead to reading deficits but rather several interacting factors (e.g., Pennington, 2006). However, given the smaller sample size of the group of typical readers, these speculations warrant further investigations, as it is possible that the lack of significant correlation in this group resulted from a lack of statistical power.

In contrast, we did not find a significant relationship between our neural measure of selective attention and reading fluency. One possible interpretation is that the neural metric reflects purely sustained selective processes over a sound stream, while the behavioural measure of attention may also tap into other cognitive functions (e.g. other executive skills such as working memory or motivation), which, together with selective attention, facilitate the development of fluent reading. In particular, the repetition detection task required information maintenance, although an 1-back task minimises working memory load (compared to other n-back levels; e.g., Pelegrina et al., 2015).

In line with previous studies showing difficulties with speech perception in suboptimal listening conditions in dyslexia (e.g. Bradlow, Kraus, & Hayes, 2003; Calcus et al., 2015, 2017; Ziegler et al., 2009), we found that children with dyslexia performed worse in the speech-in-speech perception task. Given the importance of accurate perception of speech cues for phonological development (e.g. Goswami 2011), we speculate that these difficulties may hamper the establishment of stable phonological representations or access to phonological information, both mechanisms related to the proposed phonological impairment in dyslexia (Boets et al. 2013; Goswami 2000). Moreover, children's inter-individual variability in speech-in-speech perception was explained by selective attention task performance, but not by the neural metrics, consistently with a previous in-lab study with older children (Laffere, Dick, Holt, et al. 2020). This result provides empirical evidence for the hypothesis that auditory attention is related to speech-in-noise perception difficulties as well as reading impairments in dyslexia (Calcus et al., 2018; Ziegler et al., 2009). Future investigations employing multiple speech perception tasks with different maskers will potentially clarify whether the often reported intra-individual inconsistency across different noise conditions is also driven by differences in auditory attentional skills (Calcus et al., 2018; Hazan et al. 2009; Messaoud-Galusi, Hazan, & Rosen 2011). More generally, this finding supports and extends to young children with and without dyslexia the notion that domain-general skills facilitate speech perception under challenging acoustic environments (Oberfeld and Klöckner-Nowotny 2016; Strait and Kraus 2011; Tierney, Rosen, and Dick 2020).

To conclude, the present investigation highlights the importance of examining domain-general processes and their potential contribution to reading and reading-related skills. Further determining the nature, the magnitude and the extent to which selective attention is involved in reading acquisition impairments would potentially offer new perspectives for the individualisation of intervention programs. For example, it may provide valuable tools to assess attention skills during diagnostic assessments to identify children with specific attentional difficulties, which may not emerge with standard diagnostic assessment for ADHD. In turn, these assessments could indicate whether attention training may be beneficial for some children, in addition to standard remediation protocols targeting reading-specific processes, such as phonological and letter-speech sound learning processes. Finally, the observation of group-level speech-in-speech perception difficulties in children with dyslexia suggests that they may struggle to follow verbal instructions in complex listening environments. Strategies for noise reduction within classrooms or other educational settings may benefit children with dyslexia, especially those identified as more at risk for speech-in-noise perception difficulties.

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# *Chapter 4*

# Tracking artificial symbol-speech sound learning in children with and without dyslexia

## 4.1. Abstract

A deficit in developing automatised letter-speech sound associations has been proposed as a potential causal link to disfluent reading. Evidence for this link comes primarily from neuroimaging studies showing reduced audio-visual integration in dyslexic readers. However, the behavioural evidence is less consistent. Observed deficits in several attentional components in dyslexic readers suggest that attention may also be implicated in their difficulties in letter-speech sound learning. However, this link between attention and letter-speech sound learning has yet to be examined in children.

Here, we simulated the first steps of reading acquisition by asking children with and without dyslexia to learn associations between artificial symbols and speech sounds and to read aloud words and pseudowords in this artificial orthography. We also examined the relationship between children's learning abilities and their auditory attentional skills.

Children with dyslexia were less skilled in learning artificial symbol-speech sound associations but performed similarly to typical readers on reading tests within the artificial orthography. In addition, children's auditory attention skills predicted their ability to learn the novel correspondences and to read (pseudo)words written with the artificial symbols. Our findings indicate that a learning task may provide a valuable tool to identify difficulties in learning associations between graphemes and phonemes in children with dyslexia. They also show for the first time that children with weaker auditory attention skills may be more at risk for impairments in crucial abilities for reading acquisition.

## 4.2. Introduction

### 4.2.1. Letter-speech sound learning deficit in dyslexia

When children start learning to read, they must match distinctive visual symbols (graphemes) to sound units (phonemes), a fundamental skill that may predict later reading outcomes (Caravolas et al., 2012; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). While mastery of the associations between visual symbols and speech sounds forms a common basis for reading acquisition, spoken languages differ regarding the number of speech sounds associated with single characters, ranging from phonemes in alphabetic writing systems, to syllables and words in syllabic and logographic writing systems (Ziegler & Goswami, 2005). The characteristics of a particular orthography, and especially its transparency - i.e. the degree of regularity in letter-speech sound correspondences (Seymour, Aro, & Erskine, 2003) - influence the pace at which these correspondences are acquired. In transparent orthographies, most children master the knowledge of letter-speech sound pairs within one year of reading instruction (Blomert and Vaessen, 2009). However, significantly greater time and practice are needed to automatically process letter-speech sound correspondences as integrated audio-visual objects (Froyen, Bonte, van Atteveldt, & Blomert, 2009).

In light of the importance of letter-speech sound learning for successful reading acquisition, reduced automaticity in orthographic to phonological mapping has been suggested to constitute the most proximal cause of reading impairments in dyslexia (Blomert, 2011). Compared to typical readers, adults and children with dyslexia exhibit a smaller difference in activation between congruent and incongruent letter-speech sound pairs ("congruency effect") within superior temporal cortex (in particular the superior temporal gyrus and sulcus; Blau et al., 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009), a region consistently associated with audio-visual integration (e.g. van Atteveldt et al., 2004; for review see Richlan, 2019). This observation may indicate a lack of audio-visual integration in dyslexic readers, as differentiation between congruent and incongruent couplings can only emerge if the modalities are successfully integrated (Blomert, 2011). A reduced congruency effect was also found in German Swiss adolescents with dyslexia in superior temporal regions, the left inferior frontal gyrus, the angular gyrus, and the inferior temporal cortex, with more pronounced effects for CVC (consonant-vowel-consonant) sequences than for single letter-speech sound units (Kronschnabel, Brem, Maurer, & Brandeis, 2014), extending previous results with a comparison of audio-visual units of different grain sizes. Recently, audio-visual integration deficits were also found in Chinese children with dyslexia, indicating that these difficulties may apply also to logographic writing systems (Yang, Yang, Li, Xu, & Bi). In a recent functional MRI study with dyslexic readers using a text-based recalibration paradigm (which does not involve congruency manipulation), Romanovska and colleagues observed reduced audio-visual responses in the left fusiform gyrus in children with less automatised letter-speech sound associations fluency skills, as well as increased responses in those children in the superior temporal cortex (Romanovska, Janssen, & Bonte, 2021).

Converging evidence from electroencephalography (EEG) sheds light on the development of automaticity of letter-speech sound processing (e.g., Froyen et al., 2009; Froyen, Willems, & Blomert, 2011; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012; Žarić et al., 2014). For example, Froyen and colleagues showed that readers with four years of reading instruction (10-12-year-old) exhibited an enhanced audio-visual mismatch negativity (MMN) response to spoken/written vowels, indicating fast and automatic letter-speech sound integration (Froyen et al., 2009). Notably, this pattern was not seen in beginning readers with only one year of reading instruction (7-9-year-old) nor was it observed in 11-year-old children with dyslexia (Froyen et al., 2011). Furthermore, using the same paradigm, Žarić and colleagues showed that reduced audio-visual integration in 8-10-year-old dyslexic readers scaled with individual differences in reading (dis)fluency (Žarić et al., 2014). By employing a symbol-sound matching paradigm with non-verbal audio-visual stimuli (tones and patterns of rectangles), Widmann and colleagues showed that N2b and P3a event-related potential (ERP) responses to incongruent audio-visual pairs were reduced in 7-year-old children with dyslexia compared to control participants, suggesting that the audio-visual deficit may not be constrained to impairments in grapho-phonological integration (Widmann et al., 2012; but see e.g. Keetels, Bonte, & Vroomen, 2018, with young adults).

Behavioural evidence of a letter-speech sound integration deficit in children with dyslexia is scarcer, and findings are less consistent. For example, difficulties in associating letters and speech sounds were found in kindergarten children at familial risk of dyslexia (Blomert & Willems, 2010). In contrast, in a letter-speech sound priming task, 7–13 and 9-11-year-old children with dyslexia showed similar behavioural congruency effects as typical readers, indicated by faster reaction times in the congruent condition (when the speech sound was primed with the congruent English letter) compared to a baseline condition (when the speech sound was primed with a letter unknown to participants; Clayton & Hulme, 2017; Nash et al., 2016). Similarly, in a text-based recalibration paradigm, comparable behavioural text-induced shifts in perception of ambiguous speech sounds were found in 8-10-year-old typically reading children and children with dyslexia (Romanovska, Janssen, & Bonte, 2019; 2021).

Previous longitudinal studies have demonstrated that children's ability to *learn* letter-speech sound associations - rather than their current knowledge of these associations - is critical for predicting initial stages of reading development (Horbach et al., 2015, 2018; Gellert & Elbro, 2017). For this reason, some studies have taken a training approach, asking participants to learn novel audio-visual correspondences. For example, in a series of studies, Aravena and colleagues showed that after training with an artificial orthography, children with dyslexia performed more poorly than controls on a timed artificial character-speech sound association task and on a word reading task (Aravena, Snellings, Tijms, & van der Molen, 2013; Aravena, Tijms, Snellings, & van der Molen, 2017). Furthermore, children's learning ability was related to individual differences in reading and spelling (Aravena et al., 2017) and predicted responsiveness to a specialised reading intervention for dyslexia (Aravena, Tijms, Snellings, & van der Molen, 2016). Such training approaches directly measure children's learning ability (rather than prior knowledge), and thus permit the identification of factors that potentially facilitate - or interfere with - learning to associate letters and speech sounds, such as attentional control.

### 4.2.2. Interference control deficits in dyslexia

Among the candidate factors that could contribute to inefficient learning of novel letter-speech sound associations in readers with dyslexia, top-down processes such as attention may be particularly relevant (Fraga González, Žarić, Tijms, Bonte, & van der Molen, 2017). Studies of dyslexic readers have often reported deficits in non-verbal selective attention (e.g., Menghini et al., 2010) and inhibitory control (Lonergan et al., 2019). In this section, we summarise the current evidence on inhibitory control deficits in dyslexia; for a more extensive discussion of selective attention deficits in dyslexia, see **Chapter 3**.

Findings on inhibitory control deficits in dyslexia have been inconsistent, possibly due to experimental tasks having tapped into different inhibitory processes (Lonergan et al., 2019). Inhibitory control usually refers to two related yet distinct processes: the inhibition of a prepotent and automatic response (*response inhibition*, measured for example with the Stop signal task, Logan, 1994) and the suppression of irrelevant information while processing task-relevant information (*interference control*, measured for example with the Stroop and Simon tasks; Diamond, 2013). With respect to interference control deficits in dyslexia, most studies have employed the classical Stroop task (Stroop, 1935), and have reported greater interference in dyslexic readers (Faccioli, Peru, Rubini, & Tassinari, 2008; Protopapas, Archonti, & Skaloumbakas, 2007). However, the Stroop task taps into reading and rapid naming processes, and thus cannot control for the confounding influence of the deficits in dyslexia in these two domains.

To overcome this, Bexkens, van den Wildenberg, & Tijms, (2014) employed the Simon task (Craft & Simon, 1970), which does not require a verbal response. In this task, a coloured geometrical shape appears either on the left or right of the screen; the participant responds based on the colour of the stimuli (i.e. blue or green). Interference is generated by incongruence between the target position and that of the response button indicating the colour. Using this non-verbal task, Bexkens et al., (2014) did not find interference control differences between children with dyslexia and typically-reading children. By contrast, a recent study in young adults with and without dyslexia (Gabay, Gabay, Schiff, & Henik, 2020) reported dyslexia-related deficits in an *auditory* Simon task but not in the corresponding *visual* Simon task, suggesting that individuals with dyslexia may have particular difficulty inhibiting auditory distracting information.

### 4.2.3. The relationship between letter-speech sound learning and attentional processes

During explicit letter-speech sound learning, directing attention to the auditory and visual information may facilitate subsequent multi-sensory integration. For example, a recent MEG training study with typically reading adults found enhanced bilateral neural activity in the caudal middle frontal cortex, which was interpreted as indicative of selective attentional mechanisms to relevant features of the audio-visual pairs (Hämäläinen et al., 2019).

Because in real life situations the attended auditory and visual inputs very rarely correspond to one single small unit (e.g., multi-letter strings or multi-speaker environments; Lallier & Valdois, 2012), during reading acquisition, children may be required to suppression irrelevant representations in order to facilitate the integration of relevant ones in audio-visual units. Recent models of multisensory integration indeed emphasise the role of top-down attentional influences on multi-sensory processes, particularly when multiple stimuli within each unisensory modality are present and thus compete for further processing (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Demonstrating the importance of selective attention to grapheme-phoneme mapping for emerging decoding skills, Yoncheva, Wise, & McCandliss (2015) showed that directing attention to sublexical audio-visual mappings during learning may drive the neural lateralization that may support later word recognition. However, it remains unclear whether individual differences in different aspects of children's attentional skills are associated to the letter-speech sound learning abilities.

### 4.2.4. Summary and aims of the current study

Neuroimaging has shown reduced letter-speech sound integration in children and adults with dyslexia (e.g., Blau et al., 2009; Žarić et al., 2014). However, there is less evidence from behaviour, and results from these few studies are less consistent (Aravena et al., 2013, c.f. Nash et al, 2017). There are several factors that might contribute to children's ability to learn letter-speech sound associations, for example attentional control (Fraga González, Žarić, Tijms, Bonte, & van der Molen, 2017). Models of general (i.e. non-verbal) multi-sensory integration posited the role of attention for successful multi-sensory integration. Moreover, impaired attentional mechanisms are often reported in children with dyslexia (e.g., Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014; Gabay et al., 2020), suggesting that weak attention control may be implicated in the difficulty in dyslexia in associating letters and speech sounds. However, it is still unclear whether and how attentional skills are related to children's letter-speech sound learning abilities.

The first aim of the study is to investigate potential learning difficulties in associating letters and speech sounds in children with dyslexia. We employed a brief artificial orthography training paradigm asking children with and without dyslexia to learn eight novel artificial symbol-speech sound associations, and to read out loud words and pseudowords written with the artificial symbols. Second, we tested the hypothesis that auditory impaired attentional control affects the ability to learn novel audio-visual associations. Specifically, we evaluated the relationship between auditory sustained selective attention and auditory interference control, and the learning of artificial symbol-speech sound associations.

## 4.3. Materials and methods

### 4.3.1. Participants

113 7-12-year-old children participated in this study. 106 of these 113 children also participated in our EEG study (see **Chapter 3**).

All the participants were native Dutch speakers. 63 children had a diagnosis of dyslexia and 50 were typical readers. Children with dyslexia were recruited from the Regional Institute for Dyslexia (RID) and were on a waiting list for treatment. Dyslexia diagnosis was provided by RID, based on the results of psycho-diagnostic testing and of standardized reading measures including the Wechsler Intelligence Scale for Children (WISC) and 3DM test battery (Differential Dyslexia Diagnosis; Blomert and Vaessen, 2009). A complete description of the 3DM subtests used in the study is provided in **Chapter 3**. Parents gave written informed consent for participation in the study, and children received a small gift and a certificate as a reward for participating. The study was approved by the ethics committee of the Faculty of Psychology and Neuroscience, Maastricht University.

Data from two children with dyslexia were excluded due to hearing impairments, and additional data from one participant were excluded due to having completed treatment for dyslexia in another institution. None of the children with dyslexia was diagnosed with Attention Deficit and Hyperactivity Disorder (ADHD). The typically developing children were siblings or acquaintances of the participants with dyslexia or were recruited via word of mouth. None were diagnosed with dyslexia and/or ADHD.

Participants’ age, IQ, reading, and reading-related skills are reported in **Table 4.1.** Data from the 3DM battery test of four participants were not saved due to software issues, and two participants were not administered the One-Minute-Test (EMT) due to time constraints. Multiple imputation with SPSS (version 26.0, IBM Corp., Armonk, NY, United States) was then used to replace missing data of the reading fluency measures of the 3DM battery. As none of these participants had missing values for both tasks, EMT scores functioned as a predictor for the missing 3DM scores. 3DM reading task scores were used in the analyses as a measure of reading fluency (see Procedure and measures section for complete description).

**Table 4.1. Participants' characteristics, reading and reading-related skills of children with and without dyslexia.**

| | **Dyslexic readers (N =60)** | | | **Typical readers (N = 50)** | | | **Dyslexic vs typical readers** | |
|---|---|---|---|---|---|---|---|---|
| | **ratio** | | | **ratio** | | | **x(df)[a]** | **p** |
| **Sex (m/f)** | **32/28** | | | **31/19** | | | **.837(1)** | **.360** |
| | **Mean** | **SD** | **Range** | **Mean** | **SD** | **Range** | **t(df)[b]** | **p** |
| Age (months) | 114.58 | 13.19 | 92-149 | 114.62 | 15.72 | 88-148 | -.013(95.98) | .990 |
| Verbal IQ (Vocabulary) | 10.92 | 2.59 | 6-17 | 11.77 | 3.16 | 4-19 | -1.542(106) | .126 |
| Non-verbal IQ (Block design) | 9.78 | 2.93 | 3-19 | 10.27 | 3.25 | 4-17 | -.814(107) | .417 |
| EMT (Standardized) | 2.97 | 2.40 | 1-10 | 9.12 | 3.21 | 2-19 | -11.487(108) | <0.0001 |
| EMT (Raw) | 30.59 | 13.12 | 5-65 | 56.24 | 17.77 | 20-102 | -8.459(88.466) | <0.0001 |
| 3DM Word Fluency (T) | 29.45 | 6.15 | 20-41 | 49.84 | 10.14 | 34-75 | -12.439(77.580) | <0.0001 |
| 3DM Word Fluency (Raw) | 61.02 | 27.12 | 2-112 | 112.38 | 29.97 | 23-175 | -9.427(108) | <0.0001 |
| 3DM Word accuracy (T) | 31.63 | 11.35 | 20-55 | 50.75 | 9.35 | 23-61 | -9.518(108) | <0.0001 |
| 3DM Word accuracy (Raw) | 84.92 | 11.79 | 43-99 | 96.78 | 4.47 | 86-109 | -7.193(78.321) | <0.0001 |
| | **N = 60** | | | **N = 45*** | | | | |
| Phonological awareness (T) | 37.88 | 7.97 | 21-54 | 48.66 | 9.74 | 27-67 | -6.236(103) | <0.0001 |
| RAN – Letters (T) | 35.26 | 8.08 | 20-53 | 46.27 | 9.82 | 24-71 | -6.293(103) | <0.0001 |
| RAN – Digits (T) | 37.80 | 8.41 | 20-57 | 45.80 | 9.73 | 28-68 | -4.509 (103) | <0.0001 |

[a] *Chi-squared test*
[b] *Independent sample t-test*
**Data from four participants went lost due to software issues*

### 4.3.2. Procedure and measures

The children underwent electrophysiological and behavioural testing. Non-verbal sustained auditory selective attention was assessed during the electrophysiological session (see **Chapter 3** for a complete description of the paradigm, data processing, and analyses). During behavioural testing, children's artificial symbol-speech sound learning abilities, interference control, and reading/reading-related abilities were assessed. The computerised tasks (artificial symbol-speech sound learning and interference control tasks) were programmed and presented with Psychtoolbox-3 in MATLAB 9.1.0 (Mathworks). A HP ProBook 640 G2 laptop, with a 1920 x 1080 screen, Core i5-6200 microprocessor, and Intel HD Graphics was used. The auditory stimuli were presented over headphones (Sony Professional MDR-7510) at 70-72 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone.

#### 4.3.2.1. Artificial symbol-speech sound learning task

In this task, children were asked to learn eight novel symbol-speech sound pairs. The stimuli consisted of artificial characters taken from the BACS-1 Uppercase artificial alphabet (Vidal, Content, & Chetail, 2017) along with Dutch phonemes spoken by a native female speaker. The phonemes were matched to the corresponding artificial symbol as designed by Vidal and colleagues (2017) except for two cases (the Dutch phonemes/ʌu/ and /ɛɪ̯/ with no single correspondence with a single Latin phoneme), which were matched to different symbols. An overview of the symbol-phoneme pairs is displayed in **Table 4.2**.

The task consisted of two training blocks (48 trials each) and two testing blocks (56 trials each). In the training blocks, four out of the eight symbol-phoneme pairs were presented in one block and the remaining four pairs in the other block. The two testing blocks included all eight symbol-phoneme pairs.

As illustrated in **Figure 4.1**, the first three blocks (Training Blocks and Testing Block 1) required participants to perform a symbol identification task. On each trial, participants heard one of the phonemes, while two symbols were simultaneously presented for 1000 ms in black on a white background. The participant's task was to identify the symbol matching the presented phoneme by pressing the corresponding button on the left or right side of the keyboard. The button press was followed by a blank screen which remained on the screen for 1000 ms. This was followed by a feedback screen: for correct/incorrect responses, a happy/sad cartoon face appeared; when response time exceeded 4000 ms, a cartoon character appeared with the text "Faster!". After the feedback screen, a fixation cross was presented during the inter-trial intervals (ITI) with equiprobable durations of 500, 750 or 900 ms. Different ITIs were chosen to discourage anticipatory responses (see e.g., Verbruggen et al., 2019). In each block, symbol presentation was counterbalanced with respect to the possible combinations of symbols. In this way, each symbol was presented equally often within one block. The position on the screen of the correct symbol was randomised.

The last block (Testing Block 2) consisted of a match/mismatch task. Each trial included the presentation of one visual symbol followed by one of the phonemes; the participant's task was to decide whether the phoneme matched the symbol. The visual symbol was presented for 1000 ms at the centre of the screen; the phoneme was presented 500 ms after. After the button-press, the trial structure was the same as in the first three blocks.

Before the task, children were instructed to try to learn a secret code inferring the symbol-sound associations from the feedback received. A short explanation of the trial structure and feedback pictures was also provided. The task lasted approximately 14 minutes.

**Table 4.2. The symbols-speech sounds pairs presented in the task.**

| | **Training block 1** | | | |
|---|---|---|---|---|
| Grapheme |  | [b] |  |  |
| Phoneme[a] | [n] | [ʌu] | [ɛ] | [t] |
| Phoneme duration (ms) | 734 | 505 | 387 | 194 |
| | **Training block 2** | | | |
| Grapheme | [c] |  |  |  |
| Phoneme[a] | [ɛɪ̯] | [z] | [ɔ] | [f] |
| Phoneme duration (ms) | 527 | 516 | 383 | 303 |

*a International Phonetic Alphabet*
*b in the BACS-1 artificial alphabet (Vidal et al., 2017), this symbol corresponds to the Latin case 'A'*
*c in the BACS-1 artificial alphabet (Vidal et al., 2017), this symbol corresponds to the Latin case 'H'*

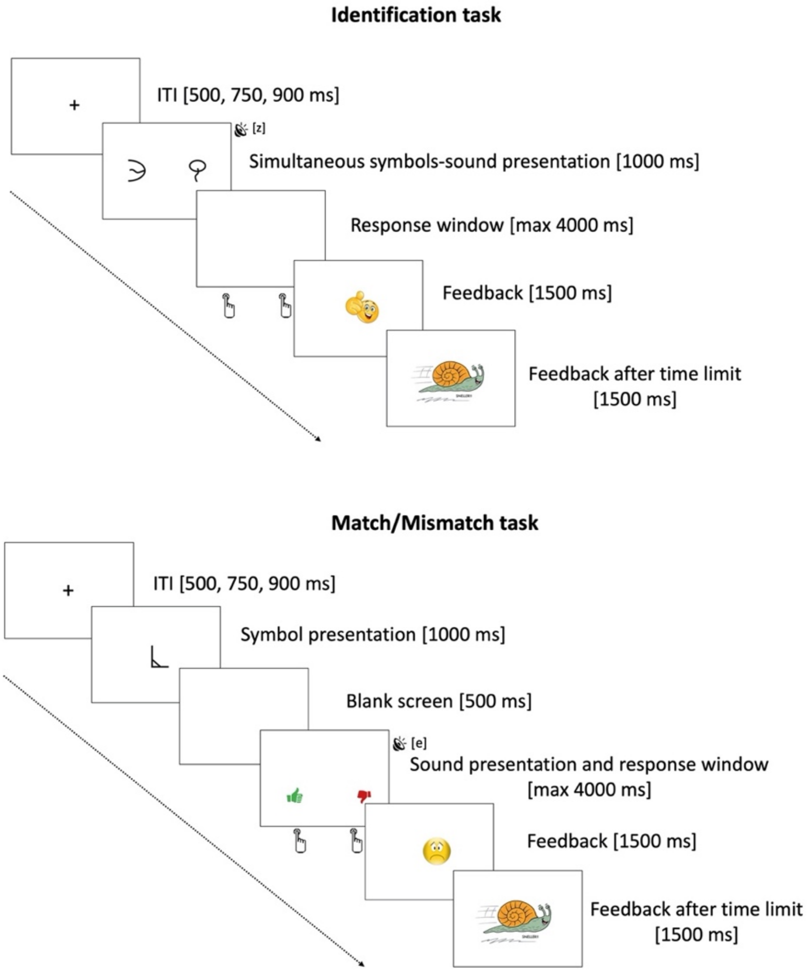

**Figure 4.1. Schematic of the trial design of the first three blocks (Identification task) and the fourth block (Match/Mismatch task) of the artificial symbol-speech sound learning paradigm. The trials were response-terminated but they timed out after 4000 milliseconds (ms).**

### 4.3.2.2. Word and pseudoword reading tests within the artificial orthography

After the computerised task, the children were presented with a list of fourteen high-frequency words, followed by a list of fourteen pseudowords, all written with the artificial symbols. The pseudowords were matched to the words for phonological complexity. The words of the two lists were arranged in a column, and presented to the children on a paper sheet (see Word and Pseudoword lists in the **Appendix of Chapter 4**). The children were instructed to read correctly as many words/pseudowords as possible. The children were encouraged to read quickly; however, the task had no time limit. Before being presented with the list of pseudowords, children were told that the words were not real words. The sum of the number of words and pseudowords correctly read in one minute served as measures of (pseudo)word reading ability within the artificial orthography. The participants were not aware of this part of the test before the start of the computerised task.

#### 4.3.2.3. Interference control

Interference control was tested with an auditory version (Green & Barber, 1981) of the Stroop task (Stroop, 1935). Similar to the original Stroop test, it requires the listener to ignore lexical information and to respond on the basis of a perceptual feature. The stimuli consisted of the words ‘boy’ and ‘girl’ (‘jongen’ and ‘meisje’ in Dutch) spoken by two female and two male Dutch native talkers. There were congruent and incongruent trials. On congruent trials, the word ‘boy’ and the word ‘girl’ were spoken by a male and female talker, respectively. On incongruent trials, the word ‘boy’ was spoken by a female talker, and the word ‘girl’ was spoken by a male talker. The participants were asked to ignore the meaning of the words, and to respond to the gender of the talker by pressing one of two keys (one on the left, one on the right side of the keyboard, each marked by a yellow sticker to guide the children to the correct key).

The button-press was indicated by a light blue circle at the centre of the screen. If the button-press occurred later than 4000 ms, a cartoon character with the text “Faster!” appeared on the screen. The inter-stimulus interval (ISI) was either 100, 250, 500, 750, or 900 ms with equal probability. Different ITIs were chosen to discourage anticipatory responses (see e.g., Verbruggen et al., 2019). There were 75 trials per condition, with presentation order randomized. Before the start, the children had a brief practice of 8 or 16 trials (16 if the child did not respond correctly to 6 of 8 trials in the first training set); the practice included both congruent and incongruent trials. During practice trials only, response feedback (happy/sad cartoon face) was displayed. Both accuracy and median reaction time (RT) to correct trials only were used for analysis.

#### 4.3.2.4. Reading fluency abilities

Children’s reading level was assessed with the standardized 3DM reading task which included three subtasks: one with high-frequency words, one with low-frequency words, and one with pseudowords (Blomert & Vaessen, 2009). The child is instructed to read correctly as many (pseudo)words as possible within the time limit (30 seconds per subtask). The words of each subtask increased in the number of syllables and syllabic complexity. Reading fluency is measured as the number of (pseudo)words read correctly within the time limit.

#### 4.3.2.5. Letter-speech sound identification and discrimination tasks (3DM battery)

Children's letter-sound association skills were assessed with the standardized 3DM letter-speech sound identification and discrimination tasks (Blomert & Vaessen, 2009). In the identification task a Dutch phoneme is presented via headphones simultaneously with four Roman letters or letter combinations appearing on the computer screen. The participant identifies the letter-speech sound pair by pressing the button corresponding to the correct letter on a response box. In the discrimination task, a speech sound is presented via headphones simultaneously with one letter or letter combination. The participant indicates whether the letter(s) and the sound match or mismatch. Accuracy (percentage of correct responses) and reaction times were measured for both tasks.

### 4.3.3. Statistical analyses

#### 4.3.3.1. Artificial symbol-speech sound learning

Statistical analysis of children's performance during our artificial symbol-speech sound learning paradigm first focused on the match/mismatch task (Testing Block 2). We explored whether the (in)congruence of the symbol-speech sound pairs affected children's performance, and whether the congruency effect differentially affected children with dyslexia. To do so, we separately computed accuracy and reaction times (RTs) for matching and non-matching trials of the artificial symbol-speech-sound match/mismatch task. Repeated measures ANOVAs were then carried out with congruence as a within-subjects factor, and diagnosis as a between-subject factor.

Second, to characterise children's learning trajectories, we first divided each block into three equal-size bins (16 trials per bin for training blocks, and 19, 19, and 18 trials for testing blocks). Then, for each participant, we calculated average accuracy, and RT for correct responses only. Prior to averaging RTs, outlier responses (±3 z-scores) in each bin were removed, and remaining RTs were log-transformed to normalise the underlying distribution. We then determined whether, and at which point, the learning trajectory of children with dyslexia significantly diverged from that of typical readers, using two Repeated Measures ANOVAs with 1) accuracy or 2) mean RTs at each bin as dependent variables. For both ANOVAs, block (1, 2, 3, 4) and timepoints within block (1, 2, 3) were the within-subjects factors, and diagnosis (typical reader/dyslexic reader) was the between-subjects factor. To understand whether learning trajectories differed between younger and older children, and whether age interacted with diagnosis - e.g., whether there were differences between older children with and without dyslexia, but not between younger children with and without dyslexia - we used a median split of age (in months) as a second categorical between-subjects factor along with diagnosis.

Third, in dyslexic readers only, we explored the relation between artificial symbol-speech sound learning measures and (alphabetic) letter-speech sound association skills (as assessed with the standardized 3DM letter-speech sound tasks). As 3DM scores were taken from the RID database, analyses were carried out only for the 55 of 60 children with dyslexia whose data were available. Using a one-sample t-test, we compared children's standardised scores (t-scores, i.e. M = 50, SD = 10) to the normative population mean (as typical readers were not administered these tasks). We then used partial Spearman correlations (controlling for age) to test the association between 3DM raw scores and the measures of the artificial symbol-speech sound learning paradigm.

To investigate whether the learning demonstrated during the task transferred to the ability to read stimuli created from the artificial orthography, and whether this artificial reading ability was affected by diagnosis, two regression analyses were carried out with word and pseudoword test performance as dependent variables. 106 children were included in the analyses (four children did not complete the reading tests with the artificial orthography). To reduce the number of predictor variables from the artificial symbol-speech sound learning paradigm, a principal component analysis (PCA) with oblique rotation (direct oblimin) was carried out on the artificial symbol-speech sound learning task measures of the testing blocks (accuracy and mean RTs). The extracted PCA scores were then entered in the regression models along with age (in months) and binary diagnosis. We only included the measures of the testing blocks (and not of the training blocks) in the PCA because 1) in the testing blocks, all eight symbol-speech sound correspondences were presented together; 2) the number of trials (56) was equivalent for both the identification and the match/mismatch tasks; and 3) RT values (computed on correct trials only) were more reliable due to greater accuracy in the testing blocks compared to the training blocks.

Multiple regression analyses were also used to test whether the measures of the artificial symbol-speech sound learning task (PCA scores) and performance in the reading tests within the artificial orthography predicted alphabetic reading fluency abilities (raw 3DM scores). Age in months was entered in the models.

For each statistical model, outliers were identified based on model standardized residuals, and data points with values above or below 3 were excluded from analyses (Osborne & Overbay, 2004). Following this method, the number of datapoints excluded is indicated in the Results section for each statistical analysis.

#### 4.3.3.2. Interference control

For Auditory Stroop data, as accuracy scores did not meet normality assumptions, a non-parametric Wilcoxon test was used to analyse mean accuracy, and a paired t-test was used to analyse median RTs. One participant from the typical reader group was excluded due to 9% accuracy in the incongruent condition. Across participants, omitted trials occurred only very rarely, with a maximum of 7 omitted trials, corresponding to less than 5% of total trials. We also used independent samples t-tests to ask whether children with dyslexia had weaker interference control. Interference control was measured by computing the difference between congruent and incongruent conditions in accuracy (incongruent-congruent) and RTs (congruent – incongruent; see Results section).

#### 4.3.3.3. The contribution of auditory attentional control to artificial symbol-speech sound learning

To investigate the contribution of attention control to artificial symbol-speech sound learning, we included the subset of participants (N = 89) who had completed all three conditions of the non-verbal selective attention task (attend to the high pitch stream, attend to the low pitch stream, and passively listen to the stimuli - see **Chapter 3**). First, preliminary Spearman's partial correlation analyses (controlling for age in months) were carried out between each artificial symbol-speech sound learning and auditory attention measure. Second, multiple regression analyses were carried out with the auditory selective attention measures and age (in months) as predictors of artificial symbol-speech sound learning performance (task and reading test performance).

## 4.4. Results

### 4.4.1. Artificial symbol-speech sound learning

**Table 4.3.** reports descriptive statistics of artificial symbol-speech sound learning paradigm measures per each block and the comparison between children with and without dyslexia on the testing blocks and reading tests performance. We observed that children with dyslexia responded significantly less accurately in the match/mismatch task (Testing block 2). No other significant group differences were observed.

**Table 4.3. Descriptive statistics and group comparisons of the artificial symbol-speech sound learning task and reading tests within the artificial orthography.**

| | **Dyslexic readers (N = 60)** | | | **Typical readers (N = 50)** | | | **Dyslexic vs typical readers** | |
|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Range** | **Mean** | **SD** | **Range** | **t(108)** | **p** |
| **Task accuracy (%)** | | | | | | | | |
| Total average | 70.4 | 13.0 | 46.6-92.6 | 74.8 | 12.6 | 44.6-93.6 | | |
| Training block 1[a] | 61.1 | 14.50 | 20.9-93.8 | 63.2 | 15.1 | 31.3-93.8 | | |
| Training block 2[a] | 67.7 | 15.16 | 37.5-100 | 72.3 | 14.5 | 38.6-95.8 | | |
| Testing block 1[a] | 76.6 | 15.42 | 39.3-98.2 | 80.6 | 14.3 | 41.1-100 | -1.408 | 0.162 |
| **Testing block 2[b] (overall)** | **76.3** | **14.28** | **44.6-98.2** | **83.0** | **13.2** | **48.2-96.4** | **-2.544** | **0.012** |
| Testing block 2[b] (matching) | 74.2 | 14.75 | 39.1-100 | 80.1 | 14.9 | 39.1-100 | | |
| Testing block 2[b] (non-matching) | 77.9 | 16.51 | 39.4-100 | 85.2 | 13.2 | 48.5-100 | | |
| **Task RTs (ms)** | | | | | | | | |
| Training block 1[a] | 1337.5 | 313.2 | 999.9-2238.9 | 1205.6 | 199.83 | 1016.5-1722.3 | | |
| Training block 2[a] | 1221.2 | 251.2 | 1003.6-2089.4 | 1117.5 | 109.5 | 999.8-1513.2 | | |
| Testing block 1[a] | 1192.8 | 176.9 | 998.7-1789.0 | 1139.1 | 152.5 | 1000.8-1634.9 | 1.778 | 0.078 |
| Testing block 2[b] (overall) | 1133.6 | 326.3 | 628.7-2072.0 | 1032.9 | 264.3 | 576.1-1726.1 | 1.714 | 0.089 |
| Testing block 2[b] (matching) | 1153.1 | 334.8 | 608.3-2199.7 | 1069.7 | 275.6 | 538.3-1729.6 | | |
| Testing block 2[b] (non-matching) | 1044.6 | 360.0 | 469.7-2158.1 | 932.3 | 255.6 | 507.3-1710.2 | | |
| **Reading tests within the artificial orthography** | | | | | | | | |
| | **Dyslexic readers (N = 58)** | | | **Typical readers (N = 48)** | | | **Dyslexic vs typical readers** | |
| | **Mean** | **SD** | **Range** | **Mean** | **SD** | **Range** | **t(104)** | **p** |
| Word reading[c] | 4.6 | 4.4 | 0-14 | 5.2 | 4.4 | 0-14 | -.714 | 0.477 |
| Pseudoword reading[c] | 4.2 | 4.3 | 0-14 | 4.9 | 4.7 | 0-14 | -.844 | 0.401 |

*a Discrimination task*
*b Match/mismatch task*
*c Number of correct (pseudo)words read in one minute*

#### 4.4.1.1. Sensitivity to artificial symbol-speech sound pair congruence in the match/mismatch task

We first focused on the match/mismatch task (Testing Block 2) to examine whether the (in)congruence of the symbol-speech sound pairs was discriminated similarly by children with and without dyslexia.

Both accuracy and RTs were significantly related to congruence (accuracy: $F(1, 108) = 13.923$, $p < 0.001$, $\eta p^2 = .114$; RTs: ($F(1, 108) = 57.888$, $p < 0.001$, $\eta p^2 = .349$). Here, children responded more accurately but more slowly when the presented speech sound and symbol did not match. Congruence effects on accuracy and RT were not significantly modulated by reading ability, as indicated by the non-significant congruence by diagnosis interaction (accuracy: $F(1, 108) = .304$, $p = 0.582$, $\eta p2 = .003$; RTs: $F(1, 108) = .615$, $p = 0.435$, $\eta p^2 = .006$; **Figure 4.2**).

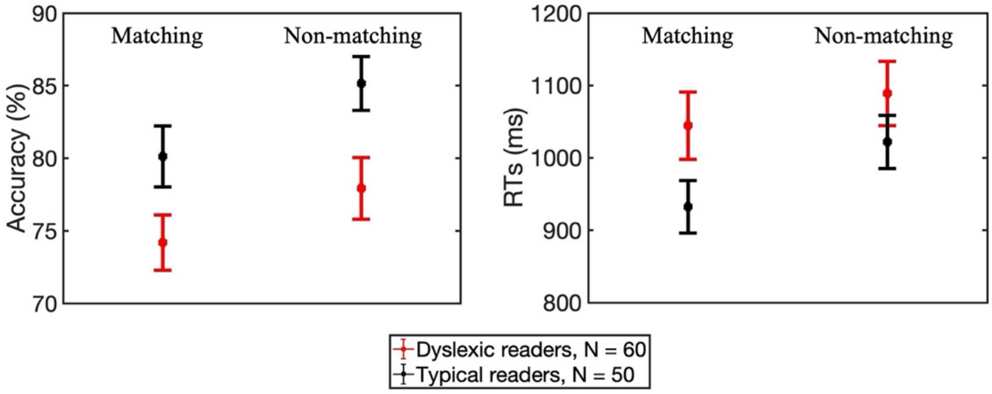

**Figure 4.2. Percentage of correct trials (accuracy) and mean RTs on the matching and non-matching trials of Testing Block 2 displayed for children with and without dyslexia.** *Error bars = ± 1 SE*

Given that we did not observe significant differences between children with and without dyslexia in discriminating matching and non-matching trials (Testing Block 2), these trials were collapsed in the following analyses.

#### 4.4.1.2. Artificial symbol-speech sound learning trajectories of children with and without dyslexia

As noted above, to examine learning trajectories we binned trials of each of the four artificial symbol-speech sound learning blocks into three timepoints. Binary age and diagnosis were entered as between-subjects factors. Binary age was computed by median split, with younger (age in months: M = 103.04, SD = 5.43) and older children (age in months: M = 126.59, SD = 10.18).

### Artificial symbol-speech sound learning accuracy

**Figure 4.3A** shows response accuracy for children with and without dyslexia. Two participants were excluded for having standardised residuals below -3. Results of the Repeated Measures ANOVA are reported in **Table 4.4**.

**Table 4.4. Results of the Repeated Measures ANOVA on the accuracy values of the artificial symbol-speech sound learning task.**

| Effects | F | df | p-value | ηp2 |
|---|---|---|---|---|
| **Block**[a] | **109.635** | **2.633, 273.809** | **<0.001** | **.513** |
| Block * diagnosis[a] | 1.223 | 2.633, 273.809 | 0.301 | .012 |
| Block * age[a] | .223 | 2.633, 273.809 | 0.856 | .002 |
| Block * diagnosis * age[a] | 1.579 | 2.633, 273.809 | 0.200 | .015 |
| **Timepoint** | **85.469** | **2, 208** | **<0.001** | **.451** |
| Timepoint * diagnosis | 6.061 | 2, 208 | 0.003 | .055 |
| Timepoint * age | 1.490 | 2, 208 | 0.228 | .014 |
| Timepoint * diagnosis * age | .353 | 2, 208 | 0.703 | .003 |
| **Block * Timepoint**[a] | **24.617** | **5.154, 535.996** | **<0.001** | **.191** |
| Block * Timepoint* | .607 | 5.154, 535.996 | 0.699 | .006 |
| Block * Timepoint* age[a] | .489 | 5.154, 535.996 | 0.790 | .005 |
| Block * Timepoint* | 1.234 | 5.154, 535.996 | 0.291 | .012 |

*[a] Greenhouse-Houser corrected*

The significant diagnosis-by-timepoint and block-by-timepoint interactions were further investigated with post-hoc pairwise comparisons. First, children responded significantly more accurately from one timepoint to the following one in the training blocks but not in the testing blocks, where their performance was almost unchanged over blocks at an asymptote of ~80% (**Figure 4.3B**). Second, children with dyslexia responded significantly less accurately than typical readers in the last two timepoints of each block of the artificial symbol-speech sound learning task (**Figure 4.3C**).

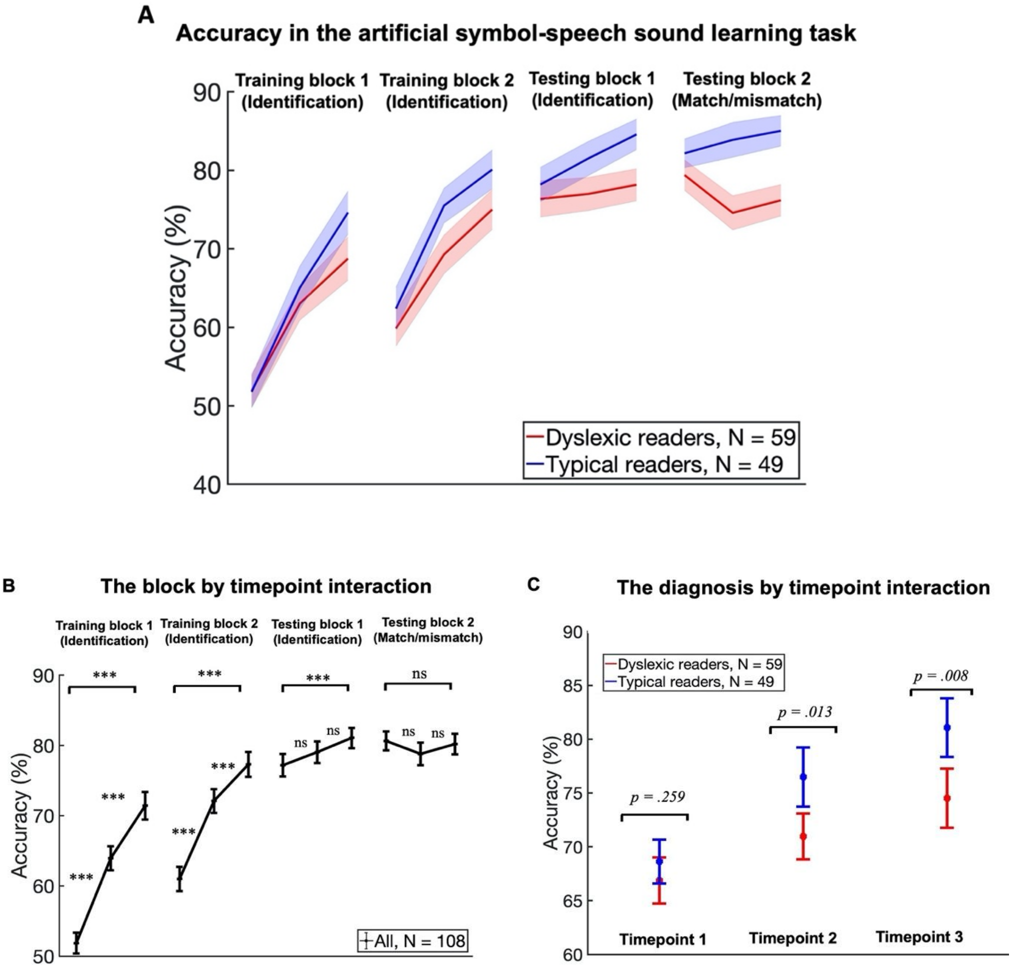

**Figure 4.3. A) Percentage of correct trials (accuracy) displayed per each block of the artificial symbol-speech sound learning for typical and dyslexic readers. For each block, trials were divided into 3 timepoints. B) Across the groups, in the testing blocks the accuracy increased from one timepoint to the following one, but not in the testing blocks. C) Dyslexic readers' performance diverged from typical readers in the second and third timepoints of each block.** *Error bars/shades: ±1 standard error. ***p < 0.001; *p < 0.05; ns = non-significant (p > 0.05)*

## Reaction times (RTs)

Ten participants' datapoints were removed from the model for having standardised residuals above 3 or below -3. Results of the Repeated Measures ANOVA are reported in **Table 4.5**.

**Table 4.5. Results of the Repeated Measures ANOVA on the RTs (log-transformed) values of the artificial symbol-speech sound learning task.**

| Effects | F | df | p-value | ηp2 |
|---|---|---|---|---|
| **Block[a]** | **29.977** | **1.641,** | **<0.001** | **.240** |
| Block * diagnosis[a] | .444 | 1.641, | 0.603 | .005 |
| **Block * age[a]** | **4.327** | **1.641,** | **0.021** | **.044** |
| Block * diagnosis * age[a] | .426 | 1.641, | 0.614 | .004 |
| **Timepoint[a]** | **26.161** | **1.682,** | **<0.001** | **.216** |
| Timepoint * diagnosis[a] | .562 | 1.682, | 0.542 | .006 |
| Timepoint * age[a] | .365 | 1.682, | 0.658 | .004 |
| Timepoint * diagnosis * age[a] | 2.242 | 1.682, | 0.118 | .023 |
| **Block * Timepoint[a]** | **11.023** | **4.524,** | **<0.001** | **.104** |
| Block * Timepoint* | 1.446 | 4.524, | 0.212 | .015 |
| Block * Timepoint* age[a] | .681 | 4.524, | 0.623 | .007 |
| Block * Timepoint* | .495 | 4.524, | 0.762 | .005 |

[a] *Greenhouse-Houser corrected*

No significant interaction was found with diagnosis (**Figure 4.4A).** We investigated further the significant block-by-timepoint and block-by-age interactions with post-hoc pairwise comparisons. These showed that children's reaction times dropped during the first and second timepoints of the training blocks, but in the last testing block, they slowed (**Figure 4.4C)**. Younger children were significantly slower in responding on the Match/Mismatch task in Testing Block 2 than were older children (**Figure 4.4B).**

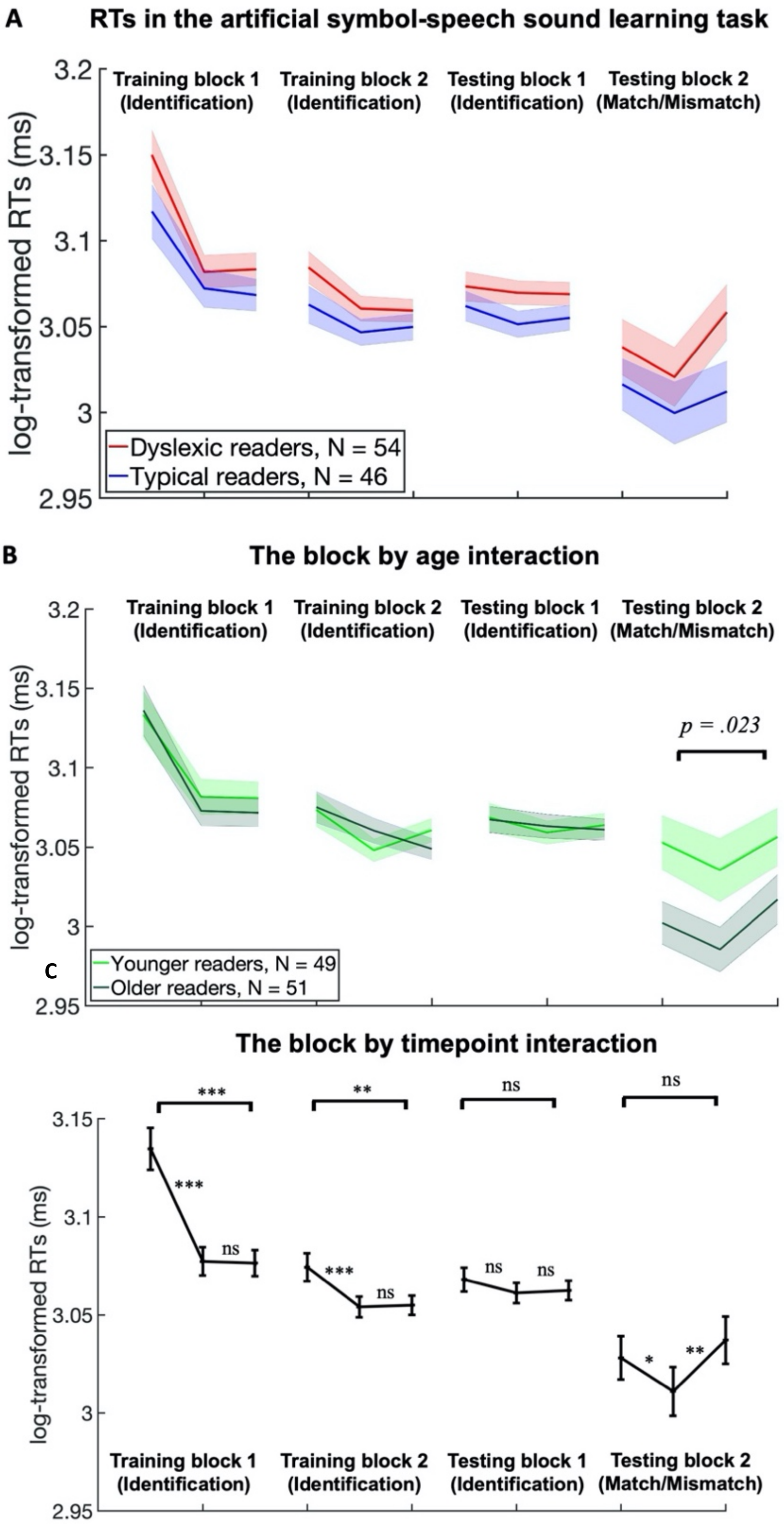

**Figure 4.4. A) Mean reaction times (log-transformed RTs) of the correct trials displayed per each task block divided in three timepoints for dyslexic and typical readers. B) Younger children gave slower responses in the match/mismatch task (Testing Block 2). C) Children's reaction times changed throughout the task. Error bars/shades: ±1 standard error ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; ns = non-significant ($p > 0.05$)**

### 4.4.1.3. Standardised letter-speech sound knowledge and relationship with artificial symbol-speech sound learning in dyslexic readers

After observing the lower response accuracy of children with dyslexia in the artificial symbol-speech task, we were interested in relating the learning task performance with their (alphabetic) letter-speech sound association skills. We compared standardised scores of the 3DM letter-speech sound association tasks with the normative population mean and correlated the 3DM raw scores with the artificial symbol-speech sound learning accuracy and RTs in the two testing blocks (controlling for age).

Compared to their same-age peers, children with dyslexia had deficits in identifying and discriminating (real) letter-speech sound correspondences (**Table 4.6**).

**Table 4.6. Alphabetic letter-speech sound association skills in dyslexic readers: comparison with normative population.**

| | M ± SD | t(54) | Percentage below normative range |
|---|---|---|---|
| **Accuracy identification** | 38.95 ±10.79 | -7.60*** | 51,8 |
| **Accuracy discrimination** | 41.04 ± 9.18 | -7.24*** | 54,5 |
| **RTs identification** | 39.65±9.12 | -8.41*** | 58,2 |
| **RTs discrimination** | 43.89±9.56 | -4.74*** | 38,2 |

*[a] Normative population: M = 50, SD = 10; ***p < 0.001*

Spearman partial correlation analyses revealed that artificial symbol-speech sound learning accuracy of Testing Block 1 was correlated with letter-speech sound accuracy of both identification and discrimination 3DM subtests (**Table 4.7.**).

**Table 4.7. Relationship between (alphabetic) letter-speech sound association measures and artificial symbol-speech sound learning measures in dyslexic readers.**

| | Artificial symbol-speech sound learning paradigm | | | |
|---|---|---|---|---|
| **Alphabetic letter-speech sound association (3DM tasks)** | **Acc. identification (Testing block 1)** | **Acc. match/mismatch (Testing block 2)** | **RTs identification (Testing block 1)** | **RTs match/mismatch (Testing block 2)** |
| **Accuracy identification** | **.338*** | .222 | .126 | .068 |
| **Accuracy discrimination** | **.376**** | .216 | .158 | .123 |
| RTs identification | -.086 | .058 | .038 | -.028 |
| RTs discrimination | .058 | -.038 | .059 | .106 |

*$p < 0.05$, **$p < 0.01$

We observed that (alphabetic) letter-speech sound association skills were only associated with the ability to identify the correct symbol in the artificial symbol-speech sound learning paradigm, suggesting that the latter task does not measure an overlapping construct and may thus provide additional information during diagnostic assessment.

#### 4.4.1.4. Dimensionality reduction of artificial symbol-speech sound learning task measures

To reduce the number of artificial symbol-speech sound learning task measures for the following analyses, a principal component analysis (PCA) was carried out with the accuracy and RTs values of Testing Block 1 (identification task) and Testing Block 2 (match/mismatch task).

Results yielded two factors with eigenvalues above 1, explaining cumulative variance of 85.84%. Factor loadings and proportion of variance accounted for by each of the components are presented in **Table 4.8**.

**Table 4.8. Factor loadings and proportion of variance explained by each component extracted.**

| Variables | Component 1 symbol-speech sound accuracy score 47.94% | Component 2 symbol-speech sound speed score 36.90 % |
|---|---|---|
| Accuracy identification (Testing block 1) | .926 | .121 |
| Accuracy match/mismatch (Testing block 2) | .956 | -.107 |
| RTs identification (Testing block 1) | .111 | .869 |
| RTs match/mismatch (Testing block 2) | -.099 | .903 |

The extracted PCA scores (hereafter referred to as the "accuracy and speed scores of artificial symbol-speech sound learning task") were used in some of the following analyses.

#### 4.4.1.5. Transfer of artificial symbol-speech sound learning to artificial orthography reading abilities

Here, we used multiple regression analyses to investigate whether artificial symbol-speech sound learning abilities during the task transferred to the ability to read aloud stimuli written in the artificial orthography, and whether this artificial reading performance was affected by diagnosis. Results are presented in **Table 4.9.**

**Table 4.9. Results of the multiple regression analyses: diagnosis, age and artificial symbol-speech sound learning accuracy and speed scores (PCA components) as predictors of word and pseudoword reading within artificial orthography.**

| Sum of word and pseudoword reading scores within artificial orthography | β | p | Lower CI | Upper CI |
|---|---|---|---|---|
| Diagnosis | .106 | 0.206 | -1.181 | 1.244 |
| Age (in months) | -.062 | 0.473 | -0.137 | 0.064 |
| **Symbol-sound learning accuracy** | **.617** | **<0.001** | **-3.932** | **7.050** |
| **Symbol-sound learning speed score** | **-.277** | **0.001** | **-3.781** | **-.993** |
|  | **$R^2$** | **df** | **F** | **p-value** |
| Model statistics | .373 | 4, 101 | 15.017 | <0.001 |

We observed that children's artificial symbol-speech sound learning abilities during the task predicted their ability to read words and pseudowords (**Figure 4.5**) written with the artificial symbols they had just learned. Children with dyslexia read correctly in one minute as many words and pseudowords as typical readers.

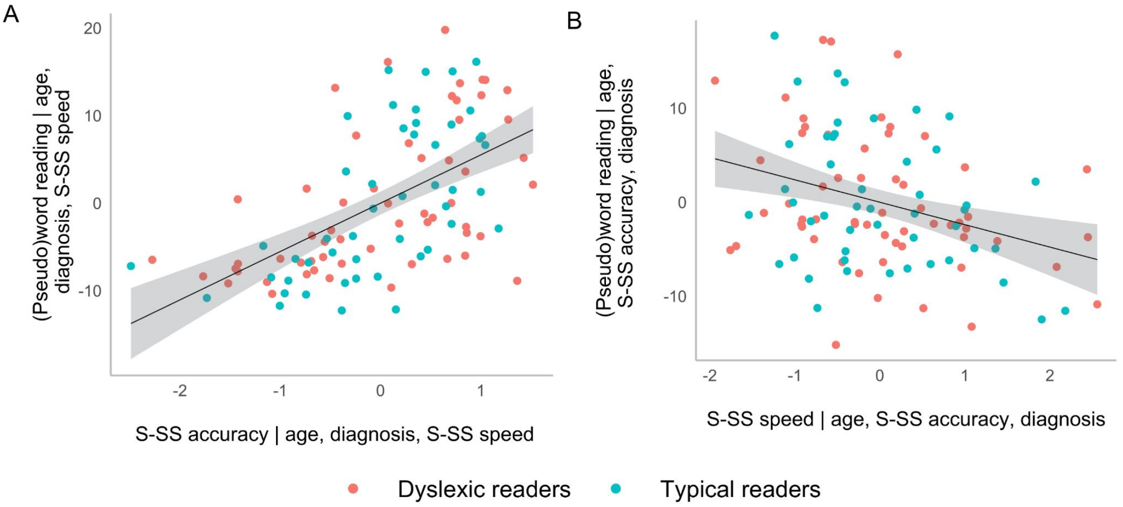

**Figure 4.5. Added variable plots showing that performance during the artificial symbol-speech sound learning task (symbol-speech sound A- accuracy and B- speed scores) predicted subsequent performance on a word and pseudoword reading tests within the artificial orthography, after controlling for the effects of the other predictors (age, diagnosis and either symbol-speech sound accuracy or speed score).** ***S-SS = symbol speech sound***

### 4.4.1.6. Predicting individual differences in reading fluency abilities

Here we examined whether artificial symbol-speech sound learning task performance and subsequent performance in the word and pseudoword reading tests within the artificial orthography predicted (alphabetic) reading fluency skills, measured with the 3DM reading task.

Results of the multiple regression analysis with symbol-speech sound learning accuracy and speed scores as predictors are reported in **Table 4.10**. One participant was removed from the model due to having standardised residuals above 3.

**Table 4.10. Results of the multiple regression analyses: artificial symbol-speech sound learning accuracy and speed scores (PCA components) as predictors of (alphabetic) reading fluency abilities (3DM battery reading task).**

| Step | Reading fluency | β | p | Lower CI | Upper CI |
|---|---|---|---|---|---|
| 1 | **Symbol-sound learning** | **.260** | **0.003** | **3.477** | **16.592** |
|  | **Symbol-sound learning** | **-.251** | **0.002** | **-15.596** | **-3.495** |
|  | **Age** | **.385** | **<0.001** | **.572** | **1.461** |
| 2 | Symbol-sound learning | .073 | 0.235 | -1.875 | 7.551 |
|  | Symbol-sound learning | -.094 | 0.104 | -7.883 | 0.750 |
|  | **Age** | **.454** | **<0.001** | **0.888** | **1.505** |
|  | **Diagnosis** | **-.628** | **<0.001** | **-28.212** | **-19.459** |

| Step | $R^2$ change | F(1,104) change | p | $R^2$ | df | F | p |
|---|---|---|---|---|---|---|---|
| 1 | - | - | - | .341 | 3, 105 | 18.093 | <0.001 |
| 2 | .348 | 116.646 | <0.001 | 0.689 | 4, 104 | 57.677 | <0.001 |

We found that more fluent readers were more accurate and faster in responding in the artificial symbol-speech sound learning task (**Figure 4.6A**). However, once we controlled for the effect of diagnosis of dyslexia, the artificial symbol-speech sound scores were no longer significantly associated with reading fluency **(Figure 4.6B**), suggesting that the relationship may be due to lower scores of dyslexic readers in both artificial symbol-speech sound learning and reading fluency.

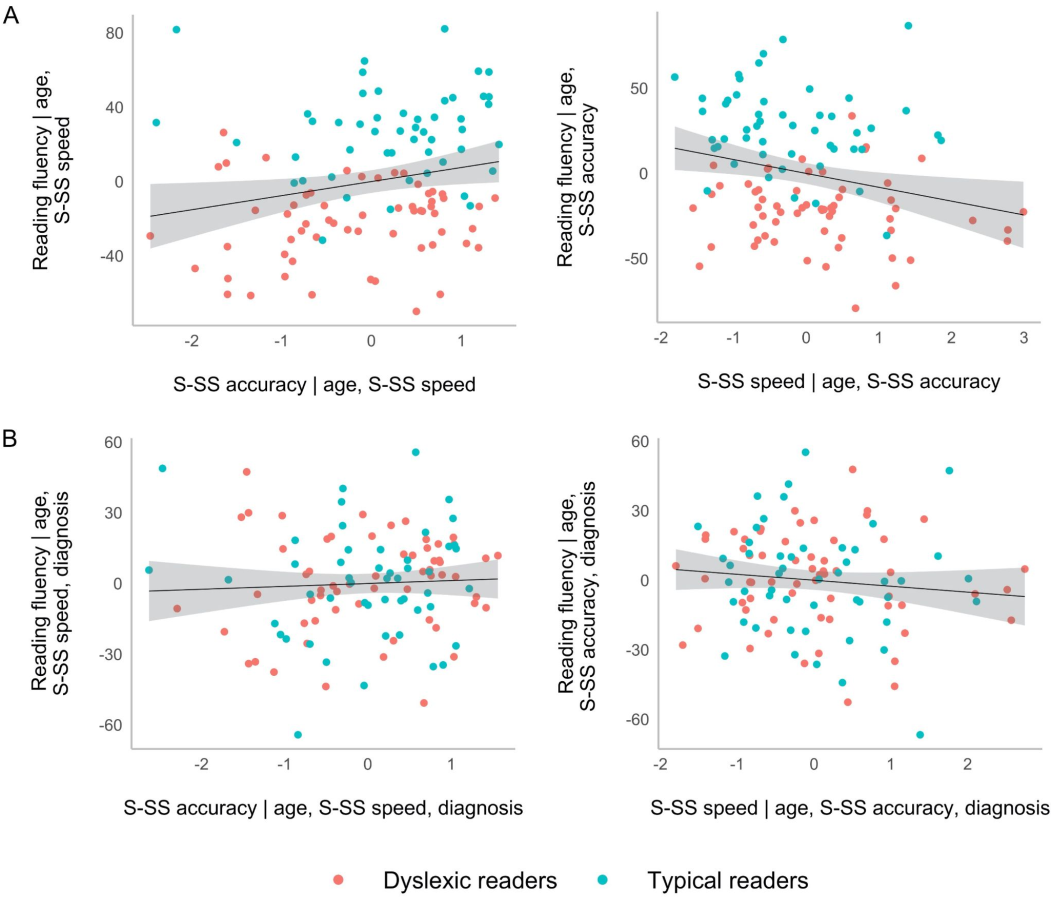

**Figure 4.6. Added variable plots showing that A) the performance during the artificial symbol-speech sound learning task (accuracy and speed) was related to (alphabetic) reading fluency abilities (raw scores of the 3DM task) but B) not once diagnosis was entered in the model.** ***S-SS = symbol speech sound***

Results of the multiple regression analysis with reading within the artificial orthography (sum of word and pseudoword reading test scores) as predictor of (alphabetic) reading fluency are reported in **Table 4.11.**

**Table 4.11. Results of the Multiple Regression analyses: word and pseudoword reading within artificial orthography as predictor of reading fluency.**

<table>
<tr><th>Step</th><th colspan="3">Reading fluency</th><th>β</th><th>p</th><th>Lower CI</th><th>Upper CI</th></tr>
<tr><td>1</td><td colspan="3">(Pseudo)word reading within artificial orthography</td><td>0.179</td><td>0.042</td><td>0.031</td><td>1.572</td></tr>
<tr><td></td><td colspan="3">Age</td><td>0.439</td><td><0.001</td><td>0.708</td><td>1.62</td></tr>
<tr><td>2</td><td colspan="3">(Pseudo)word reading within artificial orthography</td><td>0.123</td><td>0.031</td><td>0.05</td><td>1.052</td></tr>
<tr><td></td><td colspan="3">Age</td><td>0.458</td><td><0.001</td><td>0.92</td><td>1.511</td></tr>
<tr><td></td><td colspan="3">Diagnosis</td><td>-0.663</td><td><0.001</td><td>-29.807</td><td>-21.33</td></tr>
<tr><th>Step</th><th>R² change</th><th>F(1,102) change</th><th>p</th><th>R²</th><th>df</th><th>F</th><th>p</th></tr>
<tr><td>1</td><td>-</td><td>-</td><td>-</td><td>.252</td><td>2,103</td><td>17.375</td><td><0.001</td></tr>
<tr><td>2</td><td>.437</td><td>143.191</td><td><0.001</td><td>.689</td><td>3,102</td><td>75.304</td><td><0.001</td></tr>
</table>

We found that children who were more able to correctly read (pseudo)words written with the artificial symbols were also more fluent readers, as measured with a standardised word reading task (controlling for diagnosis; **Figure 4.7**).

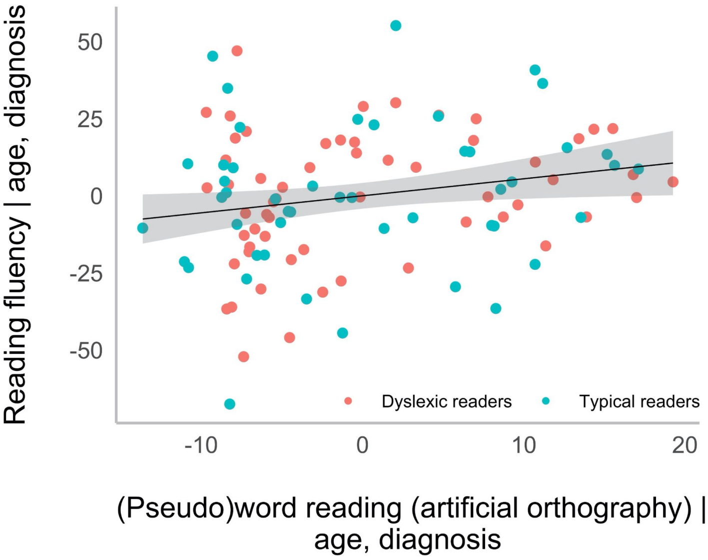

**Figure 4.7. Added variable (partial regression) plots showing that reading within the artificial orthography (sum of words and pseudowords) predicted (alphabetic) reading fluency (raw scores of 3DM battery) when the effects of age and diagnosis were partialed out.**

### 4.4.2. Interference control: Stroop effects and comparison of children with and without dyslexia

Here we tested incongruence (Stroop) effects on task accuracy and RTs (across children with and without dyslexia), and compare the magnitude of interference on children with and without dyslexia. Results revealed a significant Stroop effect on both accuracy (Z = -7.775, p < 0.001; **Figure 4.8A**) and RTs (t(108) = -4.542, p < 0.001; **Figure 4.8B**). Thus, interference control was indexed as both the difference in accuracy (incongruent-congruent; hereafter 'interference control accuracy') and the difference in median RTs (congruent - incongruent; hereafter 'interference control RTs'). Note that for both measures, more positive values indicate better interference control. Children with and without dyslexia did not show a significant difference on the two interference control measures (accuracy: t(107) = .302, p = 0.763; RTs: t(107) = .946, p = 0.346; **Figure 4.8C**).

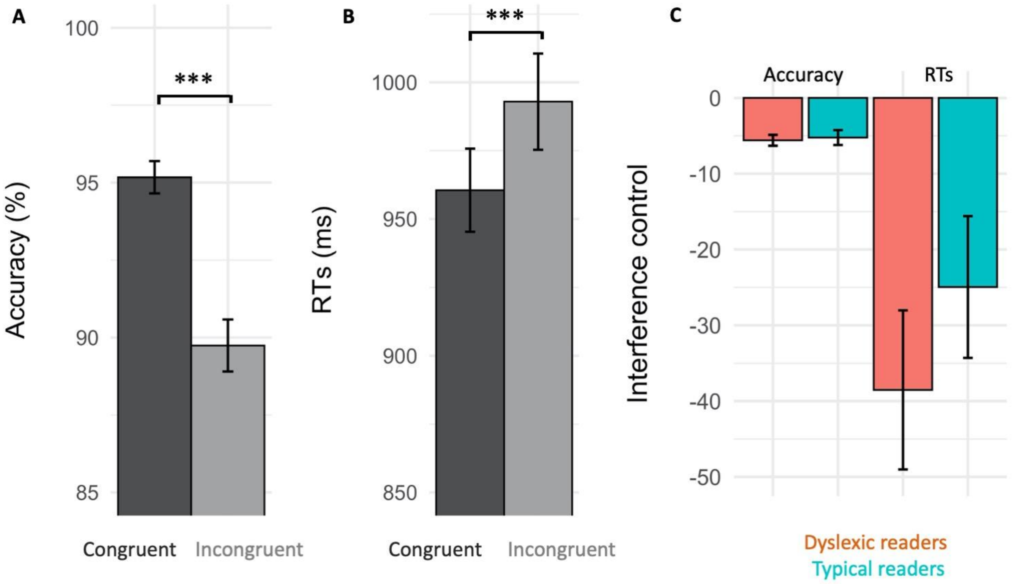

**Figure 4.8. A) Response accuracy was lower and B) responses were slower in the incongruent condition compared to the congruent condition. C) Both interference control in accuracy (incongruent-congruent) and in RTs (congruent - incongruent) did not significantly differ between children with and without dyslexia.**

### 4.4.3. Interference control and selective attention predict artificial symbol-speech sound learning abilities and artificial orthography reading

Here we examined the association between non-verbal sustained auditory selective attention, and interference control and artificial symbol-speech sound learning abilities (task and reading tests measures).

First, we carried out Spearman's partial correlation analyses (controlling for age) between each artificial symbol-speech sound paradigm measure and each auditory attentional control measure. Results are reported in **Table 4.12**.

**Table 4.12. Partial Spearman's correlations between measures of the artificial symbol-speech sound learning paradigm and auditory attentional measures controlling for age.**

| Artificial symbol-speech sound learning | Selective attention | Inhibitory control (Accuracy) | Inhibitory control (RTs) |
|---|---|---|---|
| **Accuracy identification (Testing block 1)** | **.319**** | **.211*** | -.046 |
| **Accuracy discrimination (Testing block 2)** | **.345**** | .206 | -.059 |
| **RTs identification (Testing block 1)** | .065 | .014 | -.050 |
| **RTs discrimination (Testing block 2)** | -.011 | -.034 | -.122 |
| **(Pseudo)word reading** | **.306**** | **.225*** | -.135 |

As we saw a significant relationship between non-verbal selective auditory sustained attention and the measures of the artificial symbol-speech sound learning task (accuracy, (pseudo)word reading), we also examined the correlation between these measures and the neural correlates of non-verbal selective attention (ITPC difference between active and passive conditions at 3 Hz or at 6 Hz) with channel-wise Spearman correlation (see **Chapter 3** for a complete rationale of the channel-wise method). Results are reported in the **Appendix of Chapter 4**.

We then used multiple regression to investigate the overall predictiveness of auditory attentional measures to artificial symbol-speech sound learning measures: symbol-speech sound accuracy score and (pseudo)words reading within the artificial orthography (sum of the word and pseudoword reading tests scores).

Results of the multiple regression analyses predicting symbol-speech sound response accuracy are reported in **Table 4.13.** One leverage value (influential point) was removed from the model (lev. = 0.27).

**Table 4.13. Results of the multiple regression analyses: non-verbal sustained auditory selective attention and interference control predicting response accuracy during the artificial symbol-speech sound task.**

| Symbol-speech sound learning | β | p | Lower CI | Upper CI |
|---|---|---|---|---|
| **Non-verbal selective attention** | **.265** | **0.010** | **0.088** | **0.630** |
| **Interference control accuracy** | **.197** | **0.049** | **0.000** | **0.072** |
| Interference control RTs | -.141 | 0.153 | -4.359 | .697 |
| **Age** | **.271** | **0.009** | **0.005** | **0.033** |
|  | $R^2$ | df | F | p |
|  | .250 | 4,82 | 6.833 | <0.001 |

We found that children with greater non-verbal selective sustained attention (**Figure 4.9A**) and interference control skills (**Figure 4.9B**) responded more accurately in the artificial symbol-speech sound learning task.

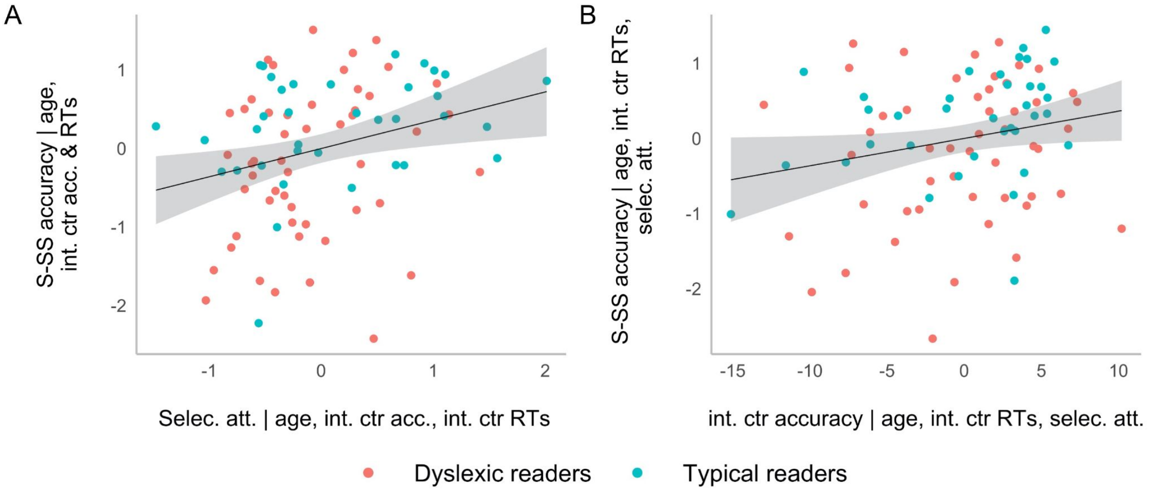

**Figure 4.9. Added variable (partial regression) plots displaying the relationship between sustained selective attention (A) and interference control accuracy (B) with response accuracy in the artificial symbol-speech sound learning task, while controlling for the effects of the other predictors (age, interference control RTs, and either selective attention or interference control RTs).** *Int. ctr = interference control, Acc. = accuracy; Selec. att. = selective attention; S-SS = symbol-speech sound*

We then investigated whether attentional control abilities scale with artificial symbol (pseudo)word-reading ability, independent of the contribution of attentional control to response accuracy of the artificial symbol-speech sound learning task. To accomplish this, the symbol-speech sound learning accuracy score was entered in the regression model predicting the sum of words and pseudowords scores, in addition to age and to the three attentional control measures. Results are presented in **Table 4.14**.

**Table 4.14. Results of the multiple regression analyses: non-verbal sustained selective attention and interference control predicting word and pseudoword reading within the artificial orthography.**

| (Pseudo)word reading | β | p | Lower CI | Upper CI |
|---|---|---|---|---|
| **Non-verbal selective attention** | **.222** | **0.027** | **0.304** | **5.032** |
| Interference control accuracy | .143 | 0.136 | -0.065 | 0.472 |
| Interference control RTs | -0.63 | 0.501 | -28.710 | 14.160 |
| Age | -.065 | 0.515 | -0.160 | 0.081 |
| **Symbol-speech sound learning** | **.443** | **<0.001** | **2.104** | **5.803** |
| | **$R^2$** | **df** | **F** | **p** |
| | 0.345 | 5,79 | 8.315 | <0.001 |

Thus, we found that children with better non-verbal selective attention skills were also more able to correctly read words and pseudowords written with the artificial symbol within one minute (**Figure 4.10**).

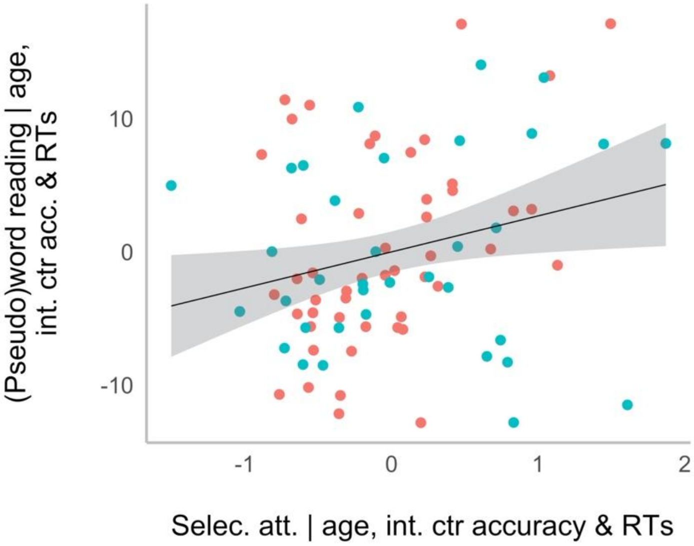

**Figure 4.10. Added variable (partial regression) plot showing that the number of words and pseudowords written with the artificial symbols that children read in one minute was predicted by sustained selective attention, also when controlling for the effect of response accuracy in the artificial-speech sound learning task (and of the other predictors).** ***Int. ctr = interference control, Selec. att. = selective attention; acc. = accuracy***

## 4.5. Discussion

In the current study, we used an artificial symbol-speech sound learning paradigm to investigate putative deficits in letter-speech sound association in children with dyslexia (e.g., Blomert, 2011; Žarić et al., 2014). In particular, we focused on the initial development of letter-speech sound associations, aiming at simulating the first crucial steps of reading development. To accomplish this, we asked 7-to-12-year-old children with and without dyslexia to learn to associate eight novel symbols with familiar native (Dutch) speech sounds. Then, the children read aloud words and pseudowords written with the artificial symbols. We also measured their non-verbal sustained auditory selective attention and interference control skills to examine whether these domain-general abilities were impaired in children with dyslexia and whether they predicted their ability to learn novel audio-visual correspondences. Compared to typical readers, we found that children with dyslexia showed more shallow learning curves in the symbol-speech sound learning task. However, they read aloud correctly as many words and pseudowords written within the artificial orthography as typical readers. We did not find that children with dyslexia had lower auditory interference control or non-verbal sustained auditory selective attention (**Chapter 3)** abilities compared to their peers. However, non-verbal auditory selective attention - and more marginally, interference control - were related to children's artificial symbol-speech sound learning abilities and to the ability to read within the artificial orthography.

### 4.5.1. Artificial symbol-speech sound learning is impaired in children with dyslexia

In our analyses of the artificial symbol-speech sound learning paradigm, we first focused on the last block of the task, where children were asked to determine whether a speech sound matched the previously presented symbol. First, we observed that overall, children were slower but more accurate when the symbol and the speech sound did not match (i.e., were incongruent). This different response pattern between the two conditions suggests that children could already discriminate the congruent versus the incongruent audio-visual pairs, possibly indicating that the novel pairs were starting to be processed as integrated units (Blomert, 2011). Second, in line with previous behavioural studies employing congruent and baseline real letters and speech sounds pairs (Clayton & Hulme, 2018; Nash et al., 2017), we did not find differences between typical and dyslexic readers in discriminating congruent and incongruent symbol-speech sounds pairs.

Replicating and extending results from previous behavioural studies that investigated the learning of novel audio-visual correspondences in children (Aravena et al., 2013, 2017), our findings revealed that the learning trajectories of children with dyslexia gradually diverged from those of typical readers. Specifically, their response accuracy was lower than that of typical readers in the last two-thirds of each block of the artificial symbol-speech sound learning task. The difference compared to typical readers was particularly pronounced in the last block of the learning paradigm, where the task design changed compared to previous blocks. This suggests that once children with dyslexia are required to adapt their learning and apply the (more poorly) learned pairs in a novel context, their difficulties become more evident. Another possibility is that the task tapped into a specific impairment of dyslexia in letter-speech sound association. In fact, in the match/mismatch task, children were first presented with the visual character and then with a matching/mismatching phoneme. This task may thus capture a difficulty in accessing the phonological information from print (Savill & Thierry, 2011) and/or reduced verbal short-term memory skills (Ramus & Szenkovits, 2008;

Menghini Finzi, Carlesimo, & Vicari, 2011). On the other hand, we cannot exclude the possibility that the greater divergence of the learning trajectory of dyslexic readers in this last part of the learning task is more simply due to reduced benefit from continued practice with the symbol-speech sound correspondences. In other words, the longer the children with and without dyslexia are exposed to the pairs, the larger the differences between typical and dyslexic readers.

In contrast to previous training studies, we did not observe a difference with typical readers in the speed of the responses (Aravena et al., 2017) or in subsequent reading tests within the artificial orthography (Aravena et al., 2017; Law et al., 2018). However, in our task, the training was shorter (6-7 minutes) than in the studies of Aravena et al. (2017) and Law et al. (2018), where training lasted 20 minutes. It is thus possible that extending the training duration may have increased response accuracy in both typical and dyslexic readers and instead may have revealed dissimilarities between the groups at the level of response speed or in making use of the learned correspondences to read words written with the artificial symbols. Future studies may clarify this point, for example, by employing a longer learning task or a task with no time limit (e.g., as in Karipidis et al., 2017) which allows children to move into the reading tests only once a predefined level of performance is achieved in the training task.

We also observed that younger children, both with and without dyslexia, gave slower responses across the match/mismatch task, but not during the identification task in the preceding blocks. This finding may relate to younger pupils' difficulty in task switching (e.g., Diamond, 2013), such that they require more time to respond correctly, despite being able to respond as accurately as the older participants. Alternatively, this result could be related to specific characteristics of the new task, for example, the interference created by the incongruence of the audio-visual units (Huizinga, Dolan & van der Molen, 2006).

Children’s performance in the letter-speech sound learning paradigm scaled with individual differences in reading fluency (measured with the standardised 3DM reading task). This may indicate that letter-speech sound integration may be specifically related to characteristic difficulties in dyslexia in automatising reading processes (Blomert, 2011). However, because artificial symbol-speech sound learning no longer predicted reading fluency when controlling for dyslexia diagnosis, we cannot rule out the possibility that the relationship is only due to the lower abilities of the dyslexic participants in both domains. We also found a significant relationship between reading fluency abilities and reading performance in the artificial orthography, which remained significant when diagnosis was entered in the model. Together, these findings suggest that learning new symbol-speech sound associations - and the subsequent application of these associations for reading - tap into fundamental processes to fluent reading development (e.g., Horbach et al., 2015; 2018).

### 4.5.2. Lack of evidence of interference control deficits in children with dyslexia

Our study did not provide evidence of interference control deficits in children with dyslexia, as the magnitude of their Stroop congruency effects (in accuracy and RTs) was not different from that of typical readers. This result is in line with a previous study measuring visual interference control using a Simon task in children with/without dyslexia (Bexkens et al., 2014) but not with a recent study reporting greater interference effects in an auditory (but not in a visual) Simon task in university students with dyslexia (Gabay et al., 2020). Aside from the difference between samples (children versus young adults), the inconsistency between Gabay's and our findings may also be attributed to the type of interference control processes engaged in each task. The auditory Simon task employed in Gabay's study requires inhibiting one type of perceptual information (the spatial location of a pure tone) while responding to another type of perceptual information (the pitch of a pure tone). In contrast, the auditory Stroop in our study requires inhibiting semantic information while responding on the basis of perceptual information. Therefore, we speculate that dyslexic readers may have specific difficulties in selecting relevant perceptual information while inhibiting irrelevant perceptual information and may not have generalised interference control difficulties. In future studies, it would be interesting to address this notion by employing a set of different interference control tasks requiring the suppression of different types of information. Moreover, including both auditory and visual modalities would also help ascertain whether also putative interference control deficits in children occur primarily in the auditory modality, as found by Gabay and colleagues in young adults.

### 4.5.3. Auditory attention control is associated with artificial symbol-speech sound learning abilities

As discussed above, we did not find that children with dyslexia have impaired interference control (or impaired non-verbal selective attention, see **Chapter 3**). However, we found that overall, children with better non-verbal sustained auditory selective attention and interference control abilities were better able to learn artificial symbol-speech sound associations. This result provides novel evidence supporting a potential role for top-down mechanisms such as attention control in children's letter-speech sound associative processes (as hypothesized by, e.g. Fraga González et al., 2017).

Our selective attention task required participants to direct attention to non-verbal sound streams by making use of the acoustic dimensions (temporal and spectral) that differentiated the to-be-attended and ignored tone melodies. The task also required participants to sustain attention over time and integrate information across the attended melody to successfully perform the target detection task. Better selective attention skills may thus facilitate attention towards relevant features of the audio and visual stimuli during letter-speech sound learning (Hämäläinen et al., 2019), resulting in better associative learning.

Alternatively, the relationship may be driven by the sustained attention component of the task; children who can maintain focus throughout the task may experience general benefits for learning across different domains. Non-verbal selective attention was also predictive of the ability to apply the learned symbol-speech sound correspondences in a subsequent reading tests, independently from attention contribution to the ability to learn these correspondences during the learning task. The observation that children with greater selective attentional resources were more able to read the novel orthography accurately and fluently supports previous findings demonstrating that selective attention to grapheme-phoneme mappings facilitates later word recognition (Yoncheva et al., 2015).

A weaker association was also found between symbol-speech sound task accuracy and interference control, as measured by the difference in response accuracy between the congruent and the incongruent conditions. This finding suggests that children may be required to suppress attention towards the incorrect audio-visual pairs while learning the associations. For example, in the identification task of the learning paradigm, attention toward the incorrect symbol may, in turn, activates the corresponding (incorrect) auditory information, which requires suppression. Having greater interference control skills may also help children resolve the incongruence between the presented audio and visual information (e.g. in the match/mismatch task).

## 4.6. Conclusions

Our study corroborates and extends findings from previous behavioural training studies (e.g., Aravena et al., 2017) showing symbol-speech sound learning deficits in children with dyslexia. Moreover, we showed that these deficits were independent of the ability to discriminate novel congruent versus incongruent audio-visual pairs, which was comparable to that of typical readers. These results may explain the contrasting findings of previous behavioural studies, which did not find dyslexia-related differences in discriminating congruent (real) letters-speech sound pairs (Clayton & Hulme, 2018; Nash et al., 2017) as compared to training studies which did find deficits in dyslexic readers' ability to learn novel correspondences (e.g., Aravena et al., 2013, 2017).

The learning paradigm allowed us to explore the factors related to the acquisition of novel audio-visual associations. Here, we focused on attentional control, revealing an association between non-verbal sustained selective auditory attention and interference control and children’s symbol-sound learning ability. This indicates that children with weaker attentional control may have increased difficulty associating letters with speech sounds during reading acquisition. In addition to attentional skills, other cognitive factors could have affected the effective learning of audio-visual associations. For example, the artificial orthography training may have placed high demands on working memory, a cognitive skill often found impaired in dyslexic readers (Swanson, Zheng, Jerman, 2009). In future studies, the inclusion of working memory measures may help clarify the independent contribution of attentional and working memory to audio-visual learning mechanisms relevant to reading acquisition.

Artificial symbol-speech sound learning paradigms such as the one employed in the present study may be a valuable and accessible tool for early screening and diagnostic assessment in clinical settings. Combining a dynamic assessment like our learning task with existing assessments of (alphabetic) letter-speech sound knowledge may provide more insight into the severity of learning impairments. Moreover, our findings highlight the need to define better the role of attention in the development of fundamental processes for successful reading acquisition, such as letter-speech sound learning.

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# Chapter 5

# Predicting individual reading and spelling gains after intervention for children with dyslexia: the role of reading-specific abilities and auditory attention

## 5.1. Abstract

Development of effective interventions for children with developmental dyslexia faces the challenge of identifying predictors explaining inter-individual variability in intervention outcome. In fact, it is still unclear whether domain-specific abilities associated with reading skills (e.g., phonological awareness, rapid naming, letter-speech sound association) explain this variability. In particular, little is known about whether domain-general abilities such as attentional control moderate response to intervention, for example by facilitating the development of reading-specific skills during intervention. In the present study we examined whether reading-specific and attentional abilities are predictive of reading fluency and spelling gains during an intensive intervention for children with dyslexia. The intervention was focused on the learning of letter–speech sound correspondences and of the use of these correspondences in reading and spelling. We found that selective attention to phonological information and selective attention during letter-speech sound learning were the best predictors of children's spelling and reading fluency gains during intervention. Thus, children's susceptibility to intervention may be influenced by domain-general and reading-specific abilities, and poor attention may hamper the success of interventions for children with dyslexia.

## 5.2. Introduction

According to the DSM, the persistence of reading impairments is one of the diagnostic criteria of developmental dyslexia (American Psychiatric Association, 2013). Longitudinal studies have demonstrated that reading difficulties of dyslexic readers do not spontaneously remit or improve (Shaywitz et al., 1999; Stein, Blum, & Barbaresi, 2011). In addition to the more direct effect on school attainments, dyslexia also affects children's (Carroll, Maughan, Goodman, & Meltzer, 2005; Livingston, Siegel, & Ribary, 2018) and adults' psychosocial functioning (Ghisi, Bottesi, Re, Cerea, & Mammarella, 2016), and decreases individuals' quality of life (Hakkaart-Van Roijen, Goettsch, Ekkebus, Gerretsen, & Stolk, 2011). It is thus of primary importance to develop and evaluate effective treatments to prevent a cascade of psychosocial and societal economic costs.

Phonics-related remediation programs have been identified as the most effective treatments, including interventions that systematically teach letter-speech sound correspondences and decoding strategies. These might involve blending or segmenting speech sounds, and the application of these strategies in reading and spelling (Galuschka, Ise, Krick, & Schulte-Körne, 2014; National reading panel, 2000). Nonetheless, studies have reported large inter-individual variability in response to intervention (Galuschka et al., 2014; Singleton, 2009) and the predictors of outcome remain unclear (Démonet, Taylor, & Chaix, 2004; Frijters et al., 2011; Stuebing et al., 2015; Tijms, 2011).

While reading-specific abilities such as rapid naming and phonological awareness were shown to predict early literacy intervention responsiveness for pupils at risk for reading problems (for reviews, see: al Otaiba & Fuchs, 2002; Nelson, Benner, & Gonzalez, 2003), it is not clear yet whether these skills act also as potential predictors of outcome of intensive intervention for pupils diagnosed with dyslexia. For example, some studies found a modest predictive value of rapid automatised naming (Tijms, 2011; Tilanus, Segers, & Verhoeven, 2019) and phonological memory on reading fluency gains (Tijms, 2011) or of phonological awareness on reading accuracy gains (Ring & Black, 2018). However, other studies did not find that phonological awareness and rapid automatised naming prior to treatment predicted reading fluency after intervention (Aravena, Tijms, Snellings, & van der Molen, 2016; Tilanus, Segers, & Verhoeven, 2016; Torgesen et al., 2001; van Rijthoven, Kleemans, Segers, & Verhoeven, 2021).

Although learning letter-speech sound associations is one of the fundamental processes underlying reading fluency development (Horbach et al., 2018; Karipidis et al., 2017; Ziegler & Goswami, 2005), its role in the context of reading intervention outcome has not been extensively examined. In a randomised controlled trial, Fraga Gonzáles and colleagues (2015) showed that in a group of children on a waiting-list for treatment for dyslexia, initial letter-speech sound association abilities were related to their reading fluency development. This association was not found in the treatment group who underwent the same training program examined in the present study, based on letter-speech sound associations with a focus on improving reading fluency (Fraga González et al., 2015). The modest or lack of relationship between treatment outcome and letter-speech sound association abilities (as well as other reading-specific skills) may be explained by the fact that treatments are designed to overcome initial weaknesses in these skills (Fraga González et al., 2015; Hatcher & Hulme, 1999).

Some studies employed a dynamic assessment which focuses on an individual's learning potential rather than on their present skill level (Gustafson, Svensson, & Fälth, 2014). Typically a dynamic assessment requires individuals to engage in training, and the effect of the training or the amount of training needed to complete the task is taken as an estimate of the individuals' learning potential (Grigorenko, 2009). This type of assessment was shown to help early identification of children at risk for reading impairments (e.g., Cho, Compton, & Josol, 2020) and was suggested as a viable approach for examining potential moderators of responsiveness to intervention. For example, in one study, children with dyslexia were asked to learn novel artificial symbol-speech sound associations before the start of the intervention (Aravena et al., 2016). They found that symbol-speech sound learning predicted reading improvements following the same intervention examined in Fraga-Ganzales et al. (2015) study (Aravena et al., 2016).

Recently, interest has grown in domain-general abilities as candidate moderators of response to intervention (Church et al., 2019), under the assumption that stronger domain-general cognitive abilities (such as executive functions and attentional control) may function as scaffold for the development of domain-specific abilities, such as reading and reading-specific skills (Aboud, Barquero, & Cutting, 2018). This hypothesis stems from the observation that executive functions (including attentional control) are predictive of school readiness and academic achievements (Blair & Peters Razza, 2007; St Clair-Thompson & Gathercole, 2006; Steele, Karmiloff-smith, Scerif, & Cornish, 2012; ten Braak, Kleemans, Størksena, Verhoeven & Segers, 2018). To date, little is known about whether attention facilitates improvements during intensive intervention for dyslexia. Torgesen et al. (2001) found an association between inattention ratings and reading growth during intervention. By contrast, Ring & Black (2018) did not find that clinically significant attentional deficits affected dyslexia treatment response. However, both of these studies included a high percentage of participants with a diagnosis of Attention Deficits Hyperactivity Disorder (ADHD) and employed inattention ratings as their primary measure of attention. Given the weak correlation between inattention ratings and cognitive measures of attentional control (e.g., Rezazadeh, Wilding, & Cornish, 2011; Sims & Lonigan, 2013; Steele et al., 2012), subjective observations of inattention may not be a reliable proxy of a child's attention. Compared to direct assessment of children's attentional abilities, inattention ratings may also be more susceptible to the characteristics of the intervention, for example the extent to which the remediation requires self-regulated activities. Thus, it is important to understand whether and how cognitive measures of attention interact with the learning processes during intervention, and whether they predict intervention outcomes in children with a sole diagnosis of dyslexia (i.e. children with no co-morbid diagnoses).

### 5.2.1. The current study

Currently, we have limited knowledge of the reading-specific and domain-general factors moderating response to intervention for children with dyslexia. Despite the great progress in the development of effective treatments (Galuschka et al., 2014), reading fluency generally remains less amenable to improvements compared to reading accuracy. For some children, reading fluency remains below the normative range even after intervention (Shaywitz et al., 2008; van Rijthoven et al., 2021). Moreover, although spelling deficits are associated with dyslexia (e.g., Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008) factors moderating growth in spelling abilities have not received much attention in intervention studies (but see e.g., van Rijthoven et al., 2021). The focus on spelling growth and on its predictors within remedial programs is also motivated by the observation that improvements in spelling can transfer to reading abilities (Conrad, 2008).

The goal of the present study is to identify the factors facilitating both reading fluency and spelling gains during an intervention for children with dyslexia that focuses on the learning of letter–speech sound correspondences, and on their use in reading and spelling. We examined the predictive value of both auditory attentional and reading-specific skills, including rapid automatised naming, phonological awareness and artificial symbol-speech sound learning, along with associations between these measures.

## 5.4. Materials and method

### 5.4.1. Participants

The participants of the current study were the children with dyslexia who participated in our EEG study, and who did not have hearing impairments (N = 60). None of the children were diagnosed with Attention Deficit and Hyperactivity Disorder (ADHD). All children were native Dutch speakers. Among these 60 children, 53 started the remediation at the Regional Institute for Dyslexia (RID). One child dropped out before intervention completion, and two children were still taking part in the treatment program at the time of data analysis.

At the RID, reading fluency and spelling abilities are assessed at three timepoints (pre-intervention, after 6 months, and at the end of the intervention). The reading fluency measure at all three timepoints was available for 48 children, and the spelling measure for 46 children. Of this group of children, 38 were included in the analyses aimed at identifying predictors of reading gains, and 37 included in the analyses identifying predictors of spelling gains. All these children had no missing values for phonological awareness and rapid naming tests (as extracted from the RID database), and all performed to criterion in the auditory attention and symbol-speech sound learning tasks (see the method sections of **Chapter 3** and **Chapter 4** for a detailed description). **Table 5.1** summarises participants' demographic characteristics, IQ, reading and spelling abilities.

**Table 5.1. Participants' gender, age, socio-economic status (parental education) and standardized IQ, reading fluency and spelling scores at the three timepoints (pre-intervention, after the first half of intervention and at the end of the intervention).**

| **Sex (m/f)** | 17/21 | | | | | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Range** | | | |
| **Age (years)** | **9.48** | 1.02 | 7.67-11.58 | | | |
| **Verbal IQ (Vocabulary)**[a] | 10.78 | 2.64 | 6-17 | | | |
| **Non-verbal IQ (Block design)** [a] | 9.78 | 3.31 | 3-19 | | | |
| | **Percentage (%)** | | | | | |
| **School grade (equivalent British grade level/entry age in years)** | **2nd / 6** | **3rd / 7** | **4th / 8** | **5th / 9** | **6th / 10** | **7th / 11** |
| | 2.6 | 18.4 | 52.6 | 15.8 | 5.3 | 5.3 |
| **Parental education**[b] | **Tertiary** | **Vocational** | **Secondary** | **Primary** | | |
| **Mother**[c] | 50 | 33.3 | 13.3 | 3.3 | | |
| **Father**[d] | 40.7 | 33.3 | 22.2 | 3.7 | | |
| **Reading fluency (Drie-minuten-test)** | **Percentage (%)** | | | | | |
| **List 1: percentiles** | **> 75** | **75 to 51** | **50 to 26** | **25 to 11** | **< 10** | |
| Timepoint 0 | 0 | 0 | 0 | 18.4 | 81.6 | |
| Timepoint 1 | 0 | 5.3 | 2.6 | 31.6 | 60.5 | |
| Timepoint 2 | 0 | 2.6 | 18.4 | 21.1 | 57.9 | |
| **List 2: percentiles** | **> 75** | **75 to 51** | **50 to 26** | **25 to 11** | **< 10** | |
| Timepoint 0 | 0 | 0 | 0 | 2.6 | 97.4 | |
| Timepoint 1 | 0 | 0 | 2.6 | 15.8 | 81.6 | |
| Timepoint 2 | 0 | 0 | 10.5 | 23.7 | 65.8 | |
| **List 3: percentiles** | **> 75** | **75 to 51** | **50 to 26** | **25 to 11** | **< 10** | |
| Timepoint 0 | 0 | 0 | 0 | 5.3 | 94.7 | |
| Timepoint 1 | 0 | 0 | 5.3 | 23.7 | 71.1 | |
| Timepoint 2 | 0 | 2.6 | 5.3 | 23.7 | 68.4 | |
| **Spelling (PI-DICTEE)**[e] | **Mean** | **SD** | **Range** | | | |
| Timepoint 0 | 26.84 | 6.90 | 23-48 | | | |
| Timepoint 1 | 30.13 | 9.09 | 23-52 | | | |
| Timepoint 2 | 35.34 | 11.62 | 23-71 | | | |

[a] *Standard scores (range 1-19, mean 10)*

[b] *Age at start and at end of each program of the Dutch educational system: Primary education: 4-12; Secondary education: PrO, 12-18; VMBO, 12-16; HAVO, 12-17; VWO, 12-18; Vocational education: MBO, start at 16; Tertiary education: HBO and WO, start at 18.*

[c] *Available in the RID database for 30 out of 38 participants*

[d] *Available in the RID database for 27 out of 38 participa*

[e] *T-scores (M = 50, SD = 10)*

## 5.4.2. Procedure

We contacted parents of children with dyslexia who were on a waiting list for RID treatment to ask whether their children would be interested in participating in our study. The study included both EEG (electroencephalography) and behavioural sessions. During the EEG session, non-verbal sustained auditory selective attention was assessed. During the behavioural session, children's speech-in-speech perception, interference control, and artificial symbol-speech sound learning abilities were assessed. Reading fluency and spelling abilities were tested at the RID during diagnostic assessment (T0), after about 6 months of intervention (T1) and at the end of the intervention, after about 12 months of intervention (T2). Rapid automatised naming and phonological awareness abilities were also assessed by RID during T0 diagnostic assessment.

#### 5.4.2.1. Intervention

The RID treatment is a phonics-based, tutor- and computer-assisted intervention programme focusing on the learning of Dutch letter–speech sound correspondences, and on the use of these correspondences in reading and spelling. The intervention is provided by a trained therapist on a one-to-one basis in weekly 45-minutes sessions in one of the RID locations. Participants receive approximately 12 months of treatment (~40 sessions). In addition to the in-person sessions, participants are required to practice at home three times a week for about 15 minutes.

The first half of the treatment mainly consists of direct instruction of phoneme–grapheme correspondences. Training is based on the mastery of learning principles and gradually progresses from simple, consistent correspondences to more complex and inconsistent ones. Letter-speech sound correspondences are trained in isolation, as well as in the context of reading and spelling exercises.

Whereas the first half of the intervention is more focused on accurate decoding, the second half of the intervention is more dedicated to skill automatization and developing fluency. Therefore, the goal of exercises is achieving automatic execution of the (previously mastered) reading and spelling skills, with practice at the word and text level. For a more detailed description of the characteristics of the treatment programme, see Fraga González et al. (2015).

#### 5.4.2.2. Outcome measures

**Reading fluency**

Reading fluency was measured with the standardised Dutch "Drie-minuten-test" (DMT; Three-minute-test; Verhoeven, 1995). This test consists of three lists: 1) a list of 150 vowel-consonant, consonant-vowel and consonant-vowel-consonant words; 2) a list of 150 more complex monosyllabic words that included consonant clusters;

and 3) a list of 150 multisyllabic words. For each list, children were asked to read correctly out loud as many words as possible in one minute. In this study, the number of words read correctly within the time limit (summed for the three lists) served as the raw reading fluency score. Age-standardised DMT scores are categorical values for each of the three word lists[2].

**Spelling**

Spelling abilities were measured with the PI-dictee test (Geelhoed & Reitsma, 2000). The test contains 135 words grouped in 9 blocks (15 words each) of increasing difficulty. On each trial, a sentence is presented orally, and one of the words is repeated. This repetition indicates the target word that the children are required to write down. The task terminates once the child makes six or more errors in one block, with the raw score calculated as the total number of correctly written words. Age-standardised scores are t-scores (M = 50, SD = 10).

#### 5.4.2.3. Predictor measures

The auditory attentional control and reading-specific measures examined in the current chapter are briefly summarised below. For a detailed description of the tasks, please refer to the previous chapters of the present dissertation.

##### 5.4.2.3.1. Auditory attentional control

**Non-verbal auditory sustained selective attention (Chapter 3)**

Non-verbal auditory sustained selective attention was assessed by asking the children to attend to one of two tone streams, and to detect occasional tone-sequences repeats within the attended stream. The task included three conditions: one in which children were asked to attend to the high-pitch tone stream, one in which they were asked to attend to the low-pitch tone stream and one in which they were passively listening to the stimuli without performing any task. EEG was recorded during the task. D-prime (Stanislaw & Todorv, 1999) was taken as a comprehensive measure of behavioural performance.

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[2] In previous studies, we used the reading fluency measure of the 3DM battery reading task (Blomert & Vaessen, 2009), where standardised scores are numerical (T-scores; M = 50, SD = 10). In this study, we used the reading fluency measure of the DMT test, because during the COVID-19 pandemic, some children were reassessed online, and the computerised 3DM battery subtests were not administered.

#### Speech-in-speech perception (Chapter 3)

During the speech-in-speech perception task, participants heard a male and a female voice, both simultaneously speaking a similar sentence: “Show the dog where the [colour] [number] is”. Participants were asked to selectively attend to the male voice in one condition, and to the female voice in the other condition. They report the target (a colour and a number) spoken by the attended talker by clicking on the appropriate colour/number combination using a mouse. The proportion of correct trials, averaged across both conditions, was used as a measure of performance.

#### Auditory interference control (Chapter 4)

Interference control was measured with an auditory version of the Stroop task, requiring the listener to ignore lexical information (the meaning of the words: boy/girl) and instead to respond on the basis of a perceptual feature (the gender of the speaker). In the congruent condition, the meaning of the word and the gender of the talker matched (e.g., 'boy' spoken by the male talker). In the incongruent condition, word meaning and talker gender did not match (e.g., 'boy' spoken by the female talker). Two measures of interference control were extracted: 1) ‘interference control accuracy', the difference in accuracy between incongruent minus congruent trials; and 2) ‘interference control RTs’ the difference in median RTs (congruent - incongruent). Note that for both measures, more positive values indicate better interference control.

### 5.4.2.3.2. Reading-specific skills

#### Artificial symbol-speech sound learning (Chapter 4)

Artificial symbol-speech sound learning was measured with a newly devised training task in which children were asked to learn eight novel artificial symbol-speech sound associations. The task consisted of four blocks. In the first block (Training Block 1), four artificial symbol-speech sound pairs were presented, and in the second block (Training Block 2), the remaining four pairs were presented. In the third and fourth blocks (Testing Block 1 and 2), all eight pairs were presented. In the first three blocks (Training Blocks and Testing Block 1) participants were asked to identify the correct symbol (identification task), while in the fourth block participants were asked to decide whether the spoken phoneme matched the previously presented symbol (match/mismatch task). Accuracy and RTs for Testing

Block 1 (identification task) and Testing Block 2 (match/mismatch task) were taken as a measure of performance[3].

**Phonological awareness (3DM battery; Chapter 3)**

Phonological awareness was measured with a phoneme deletion task (3DM battery, Blomert & Vaessen, 2009), where participants were asked to leave out a consonant from orally-presented pseudowords and to pronounce the remaining pseudoword (e.g., "/dauk/ – /d/, what is left?"). Accuracy scores were used as a measure of performance, as RTs scores are not generated by the software if the accuracy is below 21.8% (i.e. < 5 correct pseudowords), which occurred for 15 out of 38 participants.

**Alphanumeric rapid automatised naming (RAN, 3DM battery; Chapter 3)**

The rapid naming task of the 3DM battery consists of two subtasks: letter naming and digit naming (Blomert & Vaessen, 2009). In each subtask, 15 items (five letters or digits repeated three times) are presented on the screen. Each set of 15 items is presented two times on the screen, with the items presented in a different order. Performance is measured as response time obtained by averaging the response time of the two screen presentations.

### 5.4.3. Statistical analyses

We used repeated measures ANOVAs to test the overall effect of intervention on children's reading fluency and spelling abilities at three timepoints: before intervention (T0), after 6 months (T1), and after 12 months (T2) of intervention. We also used repeated measures ANOVAs to compared the magnitude of gains in the first and second halves of intervention. For both models, school grade was entered as a between-subject factor. Raw scores were used in these and in the following analyses because DMT reading fluency standardised scores are categorical, and thus less suitable for capturing inter-individual variability (see **Outcome measures** section). For consistency, we also used raw spelling scores. Because Mauchly's test indicated sphericity assumptions were violated, Greenhouse-Geisser corrections were used for reading fluency analyses.

Second, we carried out preliminary partial Spearman correlations (controlling for age) to explore the relationship between reading and spelling gains, and between

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[3] As we reported in Chapter 4, after the task, children were asked to read words and pseudowords written with the artificial symbols they have just learned. In the present study we did not include these measures to avoid excluding of additional two participants who did not complete these tests.

these gains and pre-intervention reading and spelling skills. Gains in the first half of intervention were computed as the difference between the raw scores at T1 and T0; second half gains were the raw scores at T2 minus T1.

Third, we evaluated whether auditory attentional control and reading-specific abilities were related to individuals' reading intervention outcomes. To accomplish this, we used principal component analysis with direct oblimin rotation to reduce the number of predictors, and to explore the association between predictors. The extracted principal components were then used in multiple regression analyses to examine whether attention and reading-specific abilities were in the first place associated with pre-intervention reading and spelling skills. Finally, we examined the predictiveness of attention and reading-specific abilities with respect to reading/spelling outcomes and growth between timepoints with four stepwise multiple regression analyses. To investigate growth in the first and second halves of intervention, reading and spelling abilities at T1 (first half) or T2 (second half) were used as dependent variables. Stepwise regressors were entered as follows: At Step 1, age in months was entered; at Step 2, extracted PCA components were entered; at Step 3, reading and spelling abilities at T0 (first half) or T1 (second half) were entered.

## 5.5. Results

### 5.5.1. Group effects of intervention

Here we investigated the group effect of intervention on reading fluency and spelling abilities during intervention. Reading fluency ($F(1.474, 47.161) = 27.118$, $p < 0.001$, $\eta p^2 = .459$; **Figure 5.1**) and spelling abilities ($F(2, 62) = 33.338$, $p < 0.001$, $\eta p^2 = .518$; **Figure 5.1**) differed across timepoints as anticipated. School grade did not account for significant variance in change across timepoints for either the reading ($F(7.361, 45.636) = .994$, $p = 0.450$, $\eta p^2 = .138$) or spelling model ($F(10, 62) = 1.322$, $p = 0.239$, $\eta p^2 = .176$).

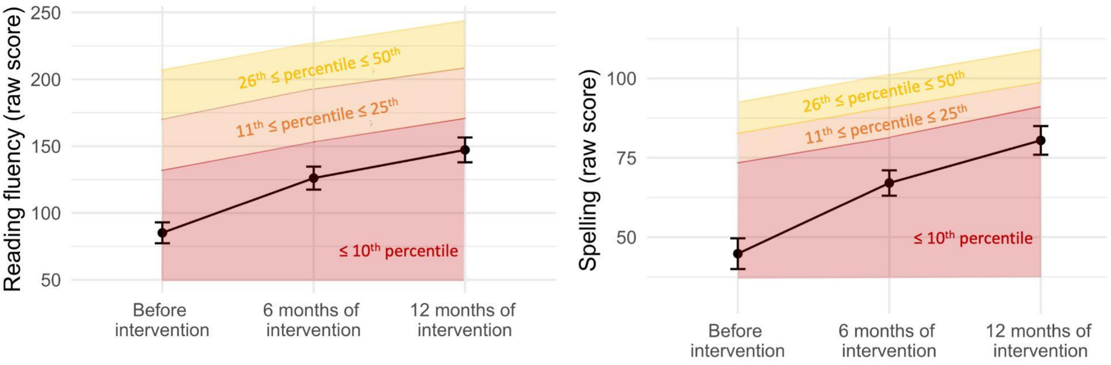

**Figure 5.1. Reading fluency and spelling abilities before RID intervention (T0) and after 6 months (T1) and 12 months (T2) of intervention. Despite the significant growth, on average both reading fluency and spelling abilities remained below normative range.** ***Error bars: ± 1 standard error. Reading fluency raw scores can range from 0 to 450; spelling raw scores can range from 0 to 135.***

Greater reading gains were observed in the first half compared to the second half of the intervention (F(1,32) = 6.027, p = 0.020, $\eta p^{2=}$ .158), and these differential gains were not modulated by school grade (F(5,32) =.581, p = 0.714, $\eta p^{2=}$ .083).

Similarly, greater spelling gains were observed in the first half than in the second half of the intervention (F(1,31) = 4.535, p = 0.041, $\eta p^{2=}$ .128), but as with reading, differential gains across intervention stages were not modulated by school grade (F(5,31) =.581, p = 0.728, $\eta p^{2}$= .105).

### 5.5.2. Individual differences in response to intervention

**Figure 5.2** shows the substantial individual differences in reading fluency and spelling growth during the intervention. Reading and spelling gains in the first half were not significantly correlated (rho = .311, p = 0.065), while reading and spelling gains in the second half were significantly if somewhat weakly correlated (rho = .331, p = 0.045).

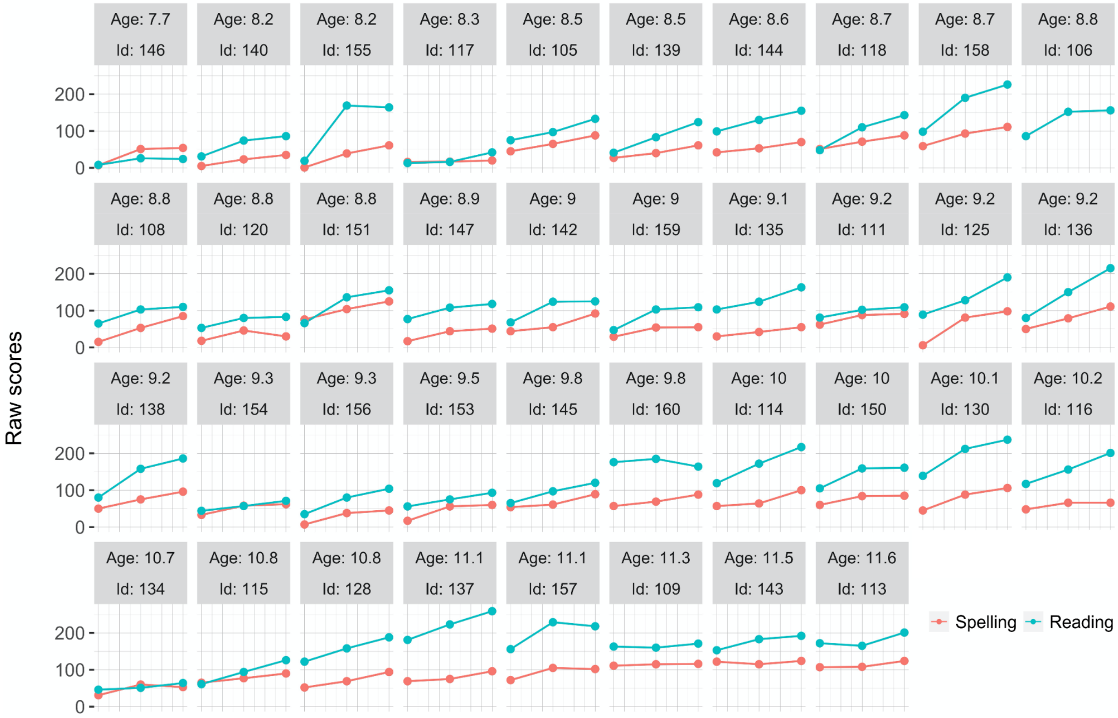

**Figure 5.2. Reading fluency and spelling abilities for each participant at three timepoints: before intervention (T0), after about 6 months of intervention (T1) and after about 12 months of intervention (T2). Participants are sorted by age.** *Note: spelling scores of participant 106 were not available for all three timepoints. Reading fluency raw scores can range from 0 to 450; spelling raw scores can range from 0 to 135.*

Children with lower pre-intervention spelling scores improved significantly more in spelling in the first half of intervention (**Table 5.2**). By contrast, neither pre-intervention either spelling or reading fluency abilities were significantly associated with reading fluency improvements (**Table 5.2**).

**Table 5.2. Partial Spearman's correlations between initial reading and spelling abilities, and subsequent spelling and reading fluency gains.**

| **Pre-intervention abilities** | **Spelling gains** | | **Reading fluency gains** | |
|---|---|---|---|---|
| | First half | Second half | First half | Second half |
| Reading fluency | -.191 | .311 | .174 | .132 |
| Spelling | **-.378*** | .225 | .183 | .040 |

**p* = 0.048. P-values were corrected for False Discovery Rate (Benjamini & Hochberg, 1995)*

#### 5.5.2.1. Shared variance among reading-specific and domain-general predictor variables

**Table 5.3** reports descriptive statistics of children's reading-specific skills and auditory attentional control skills.

**Table 5.3. Descriptive statistics of participants' reading-specific and auditory attentional control abilities.**

| N = 38 | Mean | SD | Range |
|---|---|---|---|
| **Reading-specific predictors** | | | |
| Phonological awareness (raw) | 40.6 | 24.2 | 0-87.0 |
| Phonological awareness (T-score) | 36.6 | 8.0 | 21-52 |
| RAN – Letters (raw) | 12.5 | 3.4 | 8-22 |
| RAN – Letters (T-score) | 33.5 | 8.2 | 20-51 |
| RAN – Digits (raw) | 9.9 | 2.9 | 7-24 |
| RAN – Digits (T-score) | 36.1 | 8.2 | 20-52 |
| S-SS learning accuracy (identification-Testing Block 1; %) | 77.3 | 15.8 | 41.1-98.2 |
| S-SS learning accuracy (match/mismatch-Testing Block 2; %) | 77.3 | 13.6 | 44.6-96.4 |
| S-SS learning RTs (identification-Testing Block 1; ms) | 1172.5 | 168.6 | 1005-1788 |
| S-SS learning RTs ( match/mismatch -Testing Block 2; ms) | 1081.2 | 326.7 | 628-207 |
| **Auditory attention predictors** | | | |
| Non-verbal selective attention (d-prime) | 0.84 | 0.59 | 0.1-2.3 |
| Interference control accuracy (incongruent-congruent; %) | -5.5 | 5.5 | -17.9-2.7 |
| Interference control RTs (congruent-incongruent; ms) | -33.3 | 81.4 | -246-107 |
| Speech-in-speech perception (accuracy, %) | 66.1 | 15.8 | 22-96 |

*S-SS = symbol speech sound; RAN = rapid automatised naming*

Results of the PCA yielded 5 components with eigenvalues above 1; these components explained a cumulative variance of 79.78%. **Figure 5.3** summarises the variance explained by each component and the rotated factor loadings.

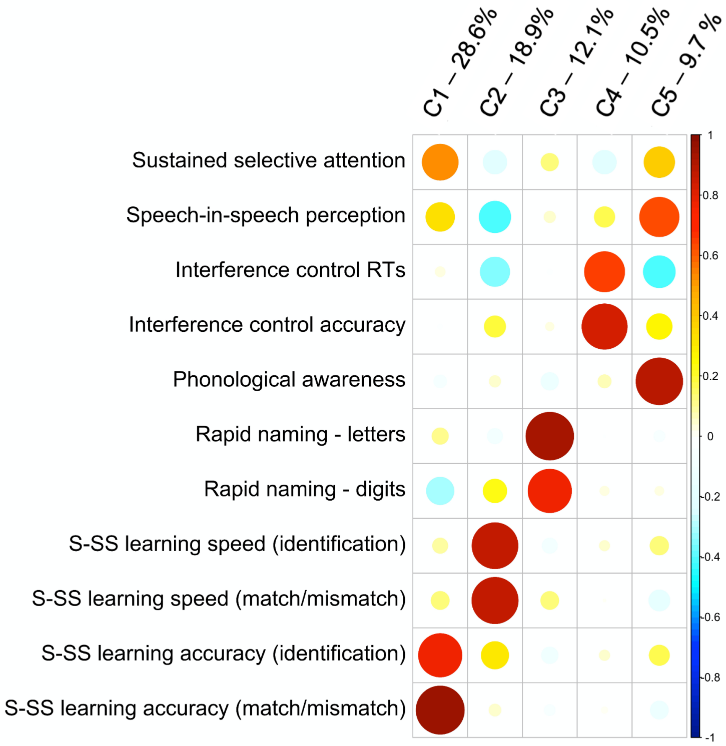

**Figure 5.3. Rotated factors loadings and variance explained by each component extracted with the PCA.** *S-SS = symbol-speech sound*

Non-verbal sustained selective attention (d-prime) and the accuracy measures of the artificial symbol-speech sound learning task loaded on the first component. Children's response speed (RTs) during the artificial symbol-speech sound learning task loaded on the second component. Alphanumeric rapid automatised naming loaded on the third component, and interference control (RTs and accuracy) on the fourth component. Phonological awareness (accuracy) and speech-in-speech perception accuracy loaded on the fifth component. Although less strongly, non-verbal sustained selective attention and interference control RTs also loaded on this last component. Surprisingly, interference control RTs loaded on this component with opposite polarity than the other variables (note that for both interference control measures, more positive values indicate greater interference control).

#### 5.5.2.3. Association between pre-intervention reading and spelling and attention and reading-specific predictors

The five components extracted with the PCA were used in multiple regression analyses to investigate the association between attentional and reading-specific predictors, and pre-intervention reading fluency and spelling abilities. Results of the multiple regression analyses are reported in **Table 5.4**.

**Table 5.4. Results of the multiple regression analyses predicting pre-intervention reading fluency and spelling abilities.**

| | Pre-intervention spelling | | | | Pre-intervention reading | | | |
|---|---|---|---|---|---|---|---|---|
| **Predictors** | **β** | **p** | **Lower CI** | **Upper CI** | **β** | **p** | **Lower CI** | **Upper CI** |
| Age | **0.563** | **<0.001** | **0.739** | **1.953** | 0.549 | **<0.001** | **1.092** | **3.115** |
| C1: Selective att./S-SS learning accuracy | 0.234 | 0.058 | -0.258 | 14.361 | 0.225 | 0.063 | -0.607 | 21.703 |
| C2: S-SS learning speed | 0.175 | 0.098 | -1.003 | 11.147 | 0.053 | 0.620 | -7.651 | 12.63 |
| C3: Alphanumeric rapid naming | 0.075 | 0.519 | -5.023 | 9.733 | -0.117 | 0.321 | -16.596 | 5.618 |
| C4: Interference control | -0.022 | 0.831 | -6.927 | 5.607 | 0.132 | 0.223 | -3.976 | 16.378 |
| C5: Phono aware/speech-in-speech | **0.253** | **0.031** | **0.73** | **13.976** | 0.132 | 0.262 | -4.857 | 17.206 |

| **Model statistics** | **$R^2$** | **F** | **df** | **p-value** |
|---|---|---|---|---|
| **Pre-intervention spelling** | .687 | 10.966 | 6,30 | <0.001 |
| **Pre-intervention reading** | .654 | 9.750 | 6,31 | <0.001 |

We observed that pre-intervention spelling skills were significantly predicted by the fifth component indexing speech-in-speech perception and phonological awareness. None of the other components significantly predicted pre-intervention reading and spelling skills, although for both skills a non-significant trend was observed for the first component indexing artificial symbol-speech learning accuracy and non-verbal sustained selective attention.

### 5.5.2.4. Predictiveness of auditory attentional and reading-specific abilities during intervention

The five components extracted with the PCA were used in multiple regression analyses to investigate the predictive value of attentional and reading-specific predictors with respect to reading fluency and spelling growth during intervention.

Results of the multiple regression analyses predicting spelling abilities after the first and after the second half of intervention are reported in **Table 5.5**.

**Table 5.5. Results of the multiple regression analyses predicting spelling abilities after the first part and after the second half of intervention.**

| | | Spelling (after first half of intervention) | | | | Spelling (after second half of intervention) | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Step** | **Predictors** | **β** | **p** | **Lower CI** | **Upper CI** | **β** | **p** | **Lower CI** | **Upper CI** |
| 1 | Age | **0.654** | **<0.001** | **0.778** | **1.801** | **0.53** | **0.001** | **0.539** | **1.807** |
| 2 | Age | **0.43** | **0.001** | **0.362** | **1.334** | **0.214** | **0.106** | **-0.106** | **1.053** |
| | C1: Selective att./S-SS learning accuracy | 0.229 | 0.056 | -0.147 | 11.556 | **0.312** | **0.011** | **2.056** | **14.844** |
| | C2: S-SS learning speed | 0.129 | 0.206 | -1.782 | 7.943 | 0.131 | 0.222 | -2.26 | 9.365 |
| | C3:Alphanumeric rapid naming | 0.135 | 0.234 | -2.392 | 9.42 | 0.021 | 0.859 | -5.807 | 6.926 |
| | C4: Interference control | 0.09 | 0.377 | -2.816 | 7.218 | 0.075 | 0.486 | -3.817 | 7.849 |
| | C5: Phonological aw./speech-in-speech | **0.448** | **<0.001** | **5.43** | **16.033** | **0.517** | **<0.001** | **7.666** | **20.313** |
| 3 | Age | 0.097 | 0.451 | -0.318 | 0.699 | -0.13 | 0.225 | -0.759 | 0.185 |
| | C1: Selective att./S-SS learning accuracy | 0.091 | 0.365 | -2.758 | 7.277 | **0.175** | **0.042** | **0.187** | **9.278** |
| | C2: S-SS learning speed | 0.025 | 0.766 | -3.507 | 4.712 | 0.03 | 0.689 | -3.273 | 4.885 |
| | C3:Alphanumeric rapid naming | 0.091 | 0.322 | -2.436 | 7.163 | -0.042 | 0.601 | -5.522 | 3.253 |
| | C4: Interference control | 0.103 | 0.213 | -1.528 | 6.575 | -0.02 | 0.784 | -4.633 | 3.526 |
| | C5: Phonological aw./speech-in-speech | **0.298** | **0.004** | **2.51** | **11.77** | 0.161 | 0.111 | -1.042 | 9.771 |
| | Spelling at T0 or T1 | **0.592** | **<0.001** | **0.248** | **0.729** | **0.782** | **<0.001** | **0.582** | **1.175** |

**Model statistics**

| **Step** | **$R^2$ change** | **F change** | **df** | **p** | **$R^2$** | **F** | **df** | **p** |
|---|---|---|---|---|---|---|---|---|
| **Spelling (first half)** | | | | | | | | |
| 1 | - | - | - | - | 0.428 | 26.178 | 1,35 | <0.001 |
| 2 | 0.277 | 5.634 | 5,30 | 0.001 | 0.705 | 11.946 | 6,30 | <0.001 |
| 3 | 0.11 | 17.21 | 1,29 | <0.001 | 0.815 | 18.231 | 7,29 | <0.001 |
| **Spelling (second half)** | | | | | | | | |
| 1 | - | - | - | - | 0.281 | 14.067 | 1,35 | 0.001 |
| 2 | 0.377 | 6.842 | 5,31 | <0.001 | 0.658 | 9.949 | 6,30 | <0.001 |
| 3 | 0.188 | 36.575 | 1,30 | <0.001 | 0.846 | 23.539 | 7,29 | <0.001 |

When controlling for pre-intervention spelling abilities, the fifth component indexing speech-in-speech perception and phonological awareness was significantly related to spelling growth in the first half of intervention (**Figure 5.4A**). When controlling for spelling abilities at T1, the first component indexing artificial symbol-speech learning accuracy and non-verbal sustained selective attention was significantly related to spelling growth in the second half of intervention (**Figure 5.4B**).

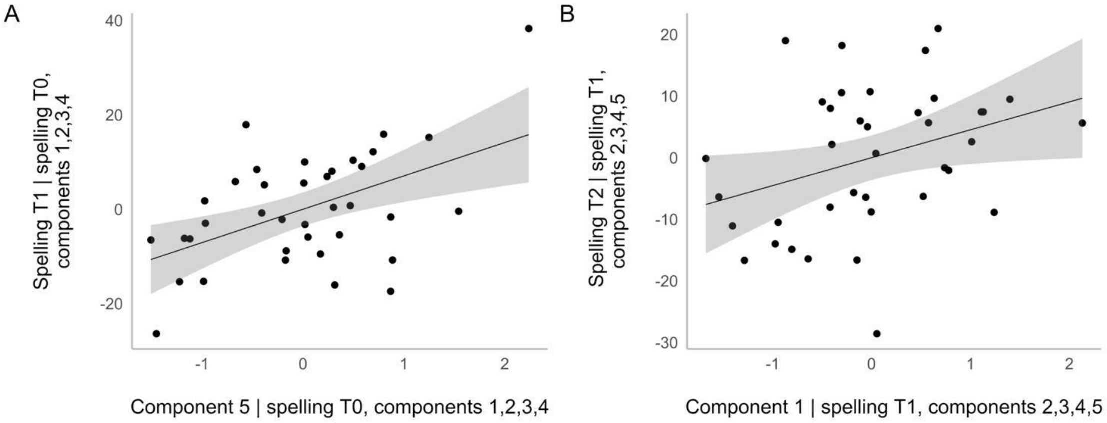

**Figure 5.4. Added variable (partial regression) plots displaying A) the relationship between spelling after the first half of the intervention with the fifth component indexing phonological awareness and speech-in-speech perception, once the effects of pre-intervention spelling abilities and of the other components were removed; B) the relationship between spelling after the second half of the intervention with the first component indexing artificial symbol-speech sound learning and non-verbal sustained selective attention, once the effects of spelling abilities at T1 and of the other components were removed.**

Results of the multiple regression analyses predicting reading fluency abilities after the first half and after the second half of intervention are reported in **Table 5.6**. One datapoint was removed from the model investigating gains in the first half for having standardised residuals above 3.

**Table 5.6. Results of the multiple regression analyses predicting reading fluency abilities after the first part and after the second half of intervention.**

| | | **Reading (after the first half of intervention)** | | | | **Reading (after the second half of intervention)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Step** | **Predictors** | **β** | **p** | **Lower CI** | **Upper CI** | **β** | **p** | **Lower CI** | **Upper CI** |
| **1** | Age | **0.561** | **<0.001** | **1.182** | **3.614** | **0.496** | **0.002** | **0.926** | 3.602 |
| **2** | Age | 0.262 | 0.089 | -0.18 | 2.426 | 0.158 | 0.319 | -0.731 | 2.175 |
| | C1: Selective att./S-SS learning accuracy | **0.297** | **0.037** | **0.999** | **29.733** | **0.368** | **0.014** | **4.511** | **36.556** |
| | C2: S-SS learning speed | 0.059 | 0.639 | -10.139 | 16.273 | -0.024 | 0.85 | -15.923 | 13.207 |
| | C3: Alphanumeric rapid naming | -0.234 | 0.095 | -26.33 | 2.229 | **-0.289** | **0.048** | **-32.094** | **-0.187** |
| | C4: Interference control | 0.173 | 0.180 | -4.727 | 24.179 | 0.049 | 0.704 | -11.871 | 17.364 |
| | C5: Phonological aw./speech-in-speech | 0.264 | 0.058 | -0.518 | 28.136 | 0.198 | 0.166 | -4.824 | 26.865 |
| **3** | Age | **-0.238** | **0.044** | **-2.005** | **-0.028** | -0.043 | 0.549 | -0.855 | 0.464 |
| | C1: Selective att./S-SS learning accuracy | 0.089 | 0.311 | -4.552 | 13.812 | **0.135** | **0.046** | **0.131** | **14.963** |
| | C2: S-SS learning speed | 0.01 | 0.897 | -7.497 | 8.519 | -0.028 | 0.623 | -7.959 | 4.848 |
| | C3: Alphanumeric rapid naming | -0.126 | 0.142 | -15.23 | 2.3 | -0.098 | 0.137 | -12.71 | 1.829 |
| | C4: Interference control | 0.059 | 0.448 | -5.56 | 12.259 | 0.025 | 0.658 | -5.024 | 7.838 |
| | C5: Phono aware/speech-in-speech | 0.144 | 0.093 | -1.324 | 16.338 | 0.016 | 0.803 | -6.309 | 8.085 |
| | Reading at T0 or T1 | **0.904** | **<0.001** | **0.732** | **1.301** | **0.851** | **<0.001** | **0.753** | **1.081** |

**Model statistics**

| **Step** | **$R^2$ change** | **F change** | **df** | **p** | **$R^2$** | **F** | **df** | **p** |
|---|---|---|---|---|---|---|---|---|
| **Reading (after the first half of intervention)** | | | | | | | | |
| **1** | - | - | - | - | 0.314 | 16.033 | 1,35 | <0.001 |
| **2** | 0.224 | 2.906 | 5,30 | 0.030 | 0.538 | 5.822 | 6,30 | <0.001 |
| **3** | 0.3 | 53.479 | 1,29 | <0.001 | 0.838 | 21.359 | 7,29 | <0.001 |
| **Reading (after the second half of intervention)** | | | | | | | | |
| **1** | - | - | - | - | 0.246 | 11.777 | 1,36 | 0.002 |
| **2** | 0.248 | 3.048 | 5,31 | 0.024 | 0.495 | 5.061 | 6,31 | 0.024 |
| **3** | 0.411 | 130.822 | 1,30 | <0.001 | 0.906 | 41.193 | 7,37 | <0.001 |

None of the predictors of interest were significantly associated with reading fluency gains in the first half of the intervention once variance associated with pre-intervention skills was partialed out. The first component indexing non-verbal selective sustained attention and artificial symbol-speech sound learning was significantly associated with reading fluency gains in the second half of the intervention, even when controlling for the reading fluency level after the first half of the intervention (**Figure 5.5**).

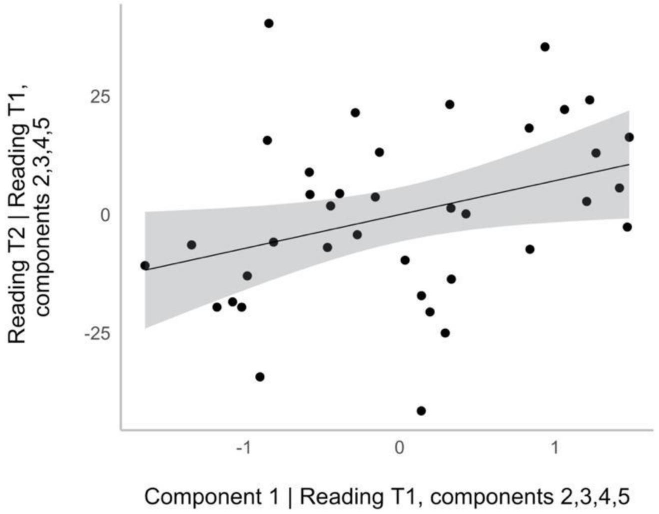

**Figure 5.5. Added variable (partial regression) plots displaying the relationship between reading fluency abilities after intervention with the first component indexing artificial symbol-speech sound learning and non-verbal sustained selective attention, once the effects of reading abilities at 6 months of intervention (T1) and of the other components were removed.**

### 5.5.2.5. Summary of multiple regression analyses results

In **Figure 5.6**, we present a summary of the results of the multiple regression analyses showing the predictiveness of auditory attentional and reading-specific abilities with respect to reading fluency and spelling abilities at the three timepoints, and to the growth of these skills during the intervention.

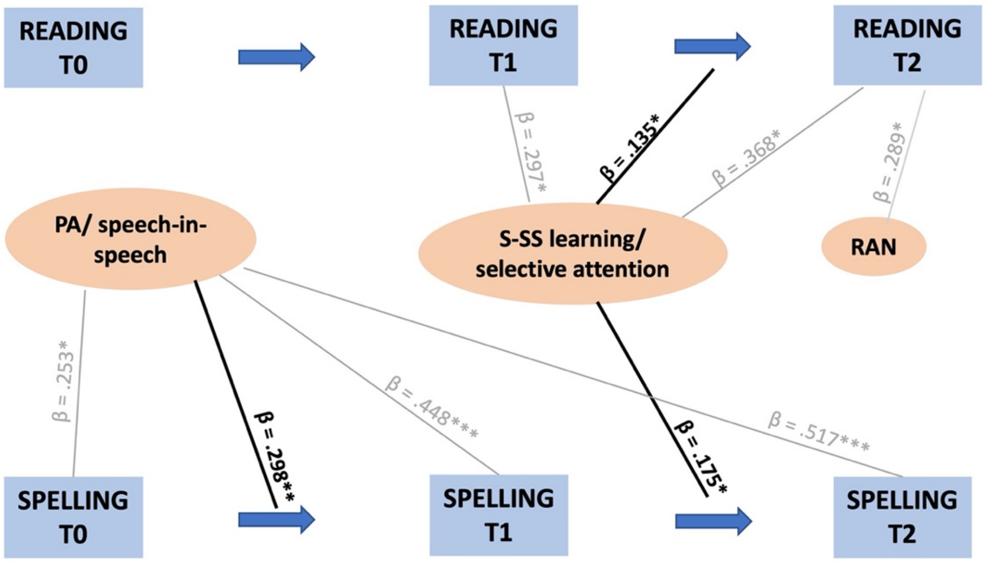

**Figure 5.6. Summary of the multiple regression analyses. The grey arrows refer to the association between predictors (in orange) and pre-intervention and outcome reading fluency and spelling skills. The arrows in black refer to the association between predictors and the growth of these abilities during intervention.** ***$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. PA = phonological awareness; S-SS = symbol-speech sound; RAN = rapid automatised naming.***

## 5.6. Discussion

Currently, there is limited knowledge on the potential predictors of response to intervention for children diagnosed with developmental dyslexia. The absence of consistent evidence for predictive factors may indicate the robustness of treatment effectiveness irrespective of inter-individual differences among children before treatment (e.g., Tijms, 2011; van Rijthoven et al., 2021). However, children do show great inter-individual variability in treatment outcome, with some children reaching reading fluency levels that are within the normative range for their age, while others continue to underperform after intervention. Improving our understanding of individual characteristics moderating treatment effects is therefore important for prognosis and for maximising a child's learning potential during treatment programs.

The present study aimed at identifying reading-specific and domain-general abilities that were predictive of reading fluency and spelling outcomes following intervention for children with dyslexia. Among candidate reading-specific predictors, here we focused on phonological awareness, rapid automatised naming, and letter-speech sound learning (assessed with an artificial symbol-speech sound learning paradigm). Among candidate domain-general predictors, we focused on auditory attentional control, and specifically on non-verbal sustained auditory selective attention, interference control and speech-in-speech perception. Children's reading-specific and auditory attentional control abilities were assessed prior to the start of the intervention programme. Reading fluency and spelling abilities were assessed at three timepoints: prior to the start of intervention, after about 6 months of intervention and at the end of intervention (after about 12 months). We examined associations among predictors with principal component analysis and whether the extracted components explained individual differences in response to intervention.

Children's reading fluency and spelling abilities improved during intervention, in line with previous reports investigating the effectiveness of this treatment program (Aravena et al., 2016; Fraga González et al., 2015; Tijms, 2007, 2011; Tijms & Hoeks, 2005). Nonetheless, on average the spelling and reading level of the children remained below normative range. We observed substantial inter-individual differences in response to intervention. Below we discuss the associations among predictor variables and their predictiveness with respect to reading fluency and spelling gains during the two parts of the intervention.

### 5.6.1. Associations among domain-general and domain-specific predictor variables

The results of the principal component analysis shed light on the relationships between the domain-general and reading-specific predictors of interest. In the context of intervention, this is relevant for a preliminary understanding of whether domain-general skills interact with reading-specific processes which are targeted during intervention, and whether these interactions engender more positive outcomes (Aboud et al., 2018).

Besides the expected shared variance among some of the variables measuring subcomponents of the same construct (e.g., alphabetic and numeric rapid automatised naming), we found that non-verbal auditory sustained selective attention and response accuracy in the artificial symbol-speech sound learning task loaded on one component. We also observed that speech-in-speech perception and phonological awareness measures (and to a lesser degree non-verbal auditory sustained selective attention) loaded on one component.

The observed shared variance between non-verbal selective attention and response accuracy in the artificial symbol-speech sound learning task is line with the results of our previous study (**Chapter 4**), in which in a large sample of children with and without dyslexia, we found that non-verbal sustained auditory selective attention predicted artificial symbol-speech sound learning abilities. The finding of the current study confirmed this link in a subset of children with dyslexia, indicating that the learning of the correspondences between graphemes and phonemes may be facilitated in children with (and without) dyslexia with stronger sustained auditory selective attention. These children may potentially have better abilities in directing and maintaining focus on relevant features of the audio-visual pairs during learning (Hämäläinen, Parviainen, Hsu, & Salmelin, 2019). Therefore, this component may reflect the ability to selectively direct and maintain attention during audio-visual learning.

The observed association between phonological awareness and speech-in-speech perception may be interpreted in light of the hypothesised mutual influence between phonological processes and speech perception in complex environments, which both tend to be impaired in dyslexic readers (Calcus, Hoonhorst, Colin, Deltenre, & Kolinsky, 2018). According to this hypothesis, weak or unspecified phonological representations in dyslexic readers may hamper their ability to compensate for the reduced reliability of acoustic cues in the speech signal in suboptimal listening conditions (Ziegler, Pech-Georgel, George, & Lorenzi, 2009). In addition, struggling with perceiving speech in noise may also impede the *development* of precise phonological representations prior to reading acquisition (Boets et al., 2011; Ziegler et al., 2009). We also found that non-verbal sustained auditory selective attention loaded on this component, albeit to a lesser extent. The shared variance between non-verbal selective attention and speech-in-speech perception aligns with the observation that speech perception with distracting speech in the background draws upon domain-general attention (Oberfeld & Klöckner-Nowotny, 2016; Strait & Kraus, 2011; Tierney, Rosen, & Dick, 2020; **Chapter 3**). It also fits with the notion that phonological awareness tasks are goal-directed acoustic tasks that require attention to some speech cues while suppressing other salient features in order to segment and manipulate sound segments (McCandliss & Yoncheva, 2011). Phonological processes may thus rely upon selective attention to sub-syllabic units (McCandliss & Yoncheva, 2011). Altogether, our data may reflect the interplay between linguistic and non-linguistic processes in speech perception, particularly in tasks with high selective attention demands. Therefore, this component may underlie the ability to effectively allocate attention to speech units during speech perception, or attention to phonology.

### 5.6.2. Predictiveness of pre-intervention reading-specific and domain-general skills

Our findings revealed that the component encompassing attention to phonology was predictive of spelling gains in the first half of intervention, while the component encompassing selective attention during audio-visual learning was predictive of spelling and reading gains in the second half of intervention.

This may indicate that being able to selectively attend to phonological information and to grapheme-phoneme mappings allows for developing greater access to orthographic representations (i.e. neural representations of letters' sequences that comprise a word) and thus leads to more positive outcomes. Spelling, as well as reading, draws upon phonological awareness and knowledge of letter-speech sound correspondences (Ehri, 2014). It has been argued that spelling - which requires production of a unique series of letters in a given order - relies on more detailed orthographic representations than those required for reading, which requires recognition of orthographical patterns (Perfetti, 1997). Selective attention to sub-lexical units may then be pivotal for strengthening phoneme-to-grapheme relations and for building rich and detailed orthographic representations. This notion is supported for example by Yoncheva and colleagues' study (2013) that investigated the effect of rhyming and orthographic similarity on behavioural and ERP measures. They showed that selective attention to sub-syllabic units within spoken words generated an enhanced positivity in the 400-500 ms window over parietal sites when rhyming versus non-rhyming words pairs were presented. When word pairs with similar versus different spelling were presented, they also found a later effect in the 700 ms window along with faster reaction times. These ERP and behavioural effects were absent when attention was diverted away from phonology, i.e. when the focus was directed to tone triplets embedded in words. These findings argue against the automaticity of orthographic engagement during auditory word processing (Yoncheva, Maurer, Zevin, & McCandliss, 2013) and suggest that efficient allocation of selective attention to phonological information may be critical for accessing orthographic information from spoken words.

In the current study, none of the components extracted from the principal component analysis predicted reading fluency gains during the first half of intervention. During the second half of the intervention, similar to spelling gains, reading fluency gains were predicted by the component encompassing selective attention during audio-visual learning. The second half of the intervention is focused primarily on developing automatic spelling and reading. Our results may reflect the relevance of being able to selectively direct and maintain attention during audio-visual learning for the development of skill automaticity during this part of the intervention. Attention during audio-visual learning may be essential for a learner's ability to develop automatic access to phonological information from print while reading (McCandliss & Yoncheva, 2011). The fact that the spelling improvement in the first half of the intervention is predicted by attention to phonology and in the second half by selective attention during audio-visual learning, may also reflect the two stages of spelling development addressed during intervention. Attention to phonology may be the first fundamental step for developing accurate spelling, while attention during audio-visual learning may facilitate the automatic use of phoneme-grapheme relations during spelling exercises.

Besides being associated with the growth of reading and spelling abilities, we observed that the two principal components, selective attention to phonology and during audio-visual learning, were also differentially associated with reading and spelling performance before and during the intervention. Spelling abilities at the three timepoints were consistently associated with the component encompassing attention to phonology, in line with the notion that phonological processes are particularly relevant for spelling development, possibly because spelling imposes higher demands on phonological awareness than reading (Furnes & Samuelsson, 2011; Landerl & Wimmer, 2008; Verhagen, Aarnoutse, & van Leeuwe, 2010). These studies have also shown that rapid naming is the best predictor of reading fluency development (Furnes et al., 2011; Landerl et al., 2008; Verhagen et al., 2010), however, our results showed only a significant association between rapid naming and fluency abilities after intervention. Instead, selective attention during audio-visual learning more consistently predicted reading abilities at the three timepoints. This finding concurs with previous evidence suggesting that deficits in the initial learning of letter–speech sound associations in children are a risk factor for reading difficulties (Gellert & Elbro, 2017; Horbach, Scharke, Cröll, Heim, & Günther, 2015; Horbach et al., 2018).

### 5.6.3. Conclusions and limitations

To conclude, our study identified an interplay between domain-specific and domain-general abilities that was predictive of outcomes in an intervention for children with dyslexia. Our data suggested that better selective attention to phonology and selective attention during audio-visual learning results in better spelling and reading fluency outcomes. These findings also suggest that dynamic assessments of children's learning potential may be suitable for investigating the factors that influence children's progress during intervention. Although establishing the effectiveness of the intervention was not the primary goal of the study, the lack of a control group of children with dyslexia who did not receive intervention within a randomised control trial (RCT) design limited considerably the clinical significance of our results. Reading instruction at school, and increased reading practise and exposure may also have significantly contributed to differences in participants' reading and spelling abilities across timepoints. Consequently, our study cannot determine the extent to which the identified abilities (e.g. selective attention to phonology) are predictive of individual responsiveness to intervention and increased reading practise and exposure. Reading development (in the absence of specialised reading intervention) may also depend upon the greater ability in directing and selecting the focus of attention to phonological information and phonological and orthographic relations. Previous longitudinal studies have in fact shown the contribution of attentional control to early reading development (Sims & Lonigan, 2013; ten Braak, Kleemans, Størksena, Verhoeven & Segers, 2018). Furthermore, our results cannot establish whether these abilities predict individual functional improvements, i.e., improvements in reading/spelling from a level below normative range to one expected from the child's age. Future studies may address this limitation by employing normative scores reflecting the inter-individual variability in reading and spelling with a larger sample of children with dyslexia and by including a control group of children with dyslexia receiving no intervention. In the current study, it was not possible to include the control group for ethical principles. The participants were already on a waiting list for treatment.

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# *Chapter 6*

# General Discussion

## 6.1. Introduction

Mastering proficient reading skills is essential for an individual's personal and professional development (UNESCO, 2006, 2015). There are large individual differences in reading skills among children and several potential environmental, genetic and cognitive factors underlying this variability (e.g., Landerl et al., 2019; Olson, Keenan, Byrne, & Samuelsson, 2014; van Bergen, van der Leij, & de Jong, 2014).

The overarching aim of this thesis was to establish whether auditory attention is among the factors explaining school-age children's differences in reading abilities and whether auditory attention is impaired in dyslexic readers.

In the four studies presented in the previous chapters, I examined whether:

> i) auditory attention (non-verbal sustained selective attention and interference control) is impaired in children with dyslexia
>
> ii) auditory attention modulates a child's susceptibility to distracting speech while performing listening and reading tasks
>
> iii) auditory attention (non-verbal sustained selective attention and interference control) facilitates critical processes for reading acquisition, such as letter-speech sound learning, and whether the latter is impaired in children with dyslexia
>
> iv) auditory attentional abilities, as well as reading-specific abilities, are predictive of individual outcomes of intensive intervention for children with dyslexia

This chapter summarises experimental findings and discusses them according to the research goals described above. Theoretical and practical implications as well as the limitations and potential directions for future research are considered.

## 6.2. Summary of findings

In the study detailed in **Chapter 2**, we observed that background speech affected school-age children's reading performance. We found that manipulating two characteristics of background speech led to different effects on reading performance: higher speech intensity slowed down text reading while speech intelligibility affected the accuracy of reading comprehension. Children with lower auditory interference control abilities responded less accurately to reading comprehension questions when intelligible background speech was presented but did not take more time to read the text when louder speech was presented. Surprisingly, we found that more fluent readers, as measured with a standardised word reading task, slowed down relatively more with the louder speech in the background.

**Chapter 3** examined non-verbal sustained auditory selective attention and its neural (EEG) correlates in children with and without dyslexia. Sustained selective attention was assessed by asking the children to attend to one of two sound streams and to detect occasional tone sequence repeats. First, we found that directing attention to one of two tone-streams resulted in greater inter-trial-phase-coherence (ITPC) at the attended tone stream rate (3 Hz) in fronto-central sites of the scalp. Unexpectedly, we also found differences in ITPC between active and passive conditions at the cross-band frequency rate (6 Hz). The strongest effect was a decreased phase consistency in posterior regions of the scalp and a smaller effect was found in two fronto-central channels, where ITPC was higher when children were attending. However, we only found a significant relationship between task performance (detection of tone-triplets repeats) and phase consistency at the attended frequency (3 Hz), suggesting that increased phase entrainment at the attended band serves as a reliable index of the ability of the children of directing focus to a target stream and sustaining it over time. Behavioural and neural correlates of selective attention did not differ between children with and without dyslexia, but the data suggested a trend, with dyslexic readers showing lower modulation of neural entrainment at some fronto-central electrodes compared to typical readers. Children with dyslexia showed significantly lower speech-in-speech perception abilities. Last, the behavioural measure of non-verbal sustained selective attention (d-prime) was predictive of both reading fluency and speech-in-speech perception abilities.

**Chapter 4** focused on one of the fundamental processes underlying reading acquisition: letter-speech sound learning. We investigated putative deficits in letter-speech sound learning in children with dyslexia with an artificial symbol-speech sound learning paradigm. Both children with and without dyslexia had no previous knowledge of the correspondences, but after a short time (~6-7 minutes of training), the paradigm revealed that dyslexic readers responded less accurately than typical readers. The subsequent ability to read words and pseudowords written with the artificial symbols was not affected by a diagnosis of dyslexia but was strongly predicted by learning task performance (response accuracy and RTs). Auditory interference control abilities of children with dyslexia were comparable to those of typical readers. Overall, reading fluency abilities scaled with the artificial symbol-speech sound learning paradigm measures (response accuracy and reading within the artificial orthography), although the association between response accuracy and reading fluency did not remain significant when variance associated with dyslexia diagnosis was partialed out. Children's ability to learn the novel correspondences and to read (pseudo)words written with the artificial symbols was predicted by their auditory attention control skills (non-verbal selective sustained attention and interference control).

**Chapter 5** aimed at identifying pre-intervention abilities predictive of reading fluency and spelling gains during an intensive intervention for children with dyslexia focused on the learning of letter-speech sound associations. In this study, we included the attentional measures examined in the previous studies (non-verbal sustained selective attention, speech-in-speech perception, interference control) and reading-specific skills (letter-speech sound learning, rapid naming, phonological awareness). Results of a principal component analysis revealed shared variance among attentional and reading-specific abilities. Two components were subsequently found to be associated with intervention gains. One component indicated an association between non-verbal selective attention and response accuracy during the letter-speech sound learning task. The other component indicated an association between speech-in-speech perception, phonological awareness and, to a lesser extent, non-verbal sustained selective attention. Therefore, we interpreted these components as encompassing the ability to selectively direct attention during audio-visual learning and selectively direct attention to phonological information. The component encompassing selective attention to phonology was related to spelling growth during the first half of intervention, which focused on the acquisition of accurate decoding skills. The component encompassing selective attention during audio-visual learning was related to reading fluency and spelling growth during the second half of the intervention, which was dedicated to skill automatization and fluency development.

## 6.3. Synthesis of the results, theoretical and practical implications

### 6.3.1. Do children with dyslexia have impaired auditory attention abilities?

Previous studies reported non-verbal deficits in several attentional components (e.g., selective attention, inhibitory control of attention, attention shifting) in individuals with dyslexia in the auditory and visual modality (e.g., Facoetti et al., 2010; Gabay, Gabay, Schiff, & Henik, 2020; Roach & Hogben, 2007, 2008; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014; Ruffino et al., 2010), although they examined more extensively the latter. These studies largely employed behavioural paradigms with small sample sizes, limiting our understanding of whether attentional difficulties are widespread in the population with dyslexia, their underlying neural mechanisms and whether they are associated with impaired reading.

In this project, we assessed two components of auditory attention control in children with and without dyslexia: non-verbal sustained selective attention and interference control. EEG was recorded during the selective attention task to understand the neural mechanisms of attentional selection in 7-to-12-years-old children. At the group level, children with dyslexia did not show a significant difference with typical readers in either the selective attention (**Chapter 3**) or the interference control task (**Chapter 4**), although their performance in the selective attention task was marginally lower and the amount of Stroop interference in response speed, i.e., RTs, was slightly higher.

The EEG group analyses did not reveal significant group differences, although children with dyslexia showed less evident increased phase entrainment at the attended band (difference between inter-trial-phase-coherence (ITPC) at 3 Hz in active versus passive conditions) in fronto-central sites of the scalp. We also examined whether the observed attentional modulation of neural entrainment in dyslexic and typical readers was independent of the more general ability to phase-lock neural activity to sound of each group. According to the temporal sampling theory (Goswami, 2011), impaired auditory entrainment at lower frequencies (< 10 Hz) in individuals with dyslexia would cause difficulties in encoding the prosodic and syllabic structure of speech, and in turn, reading impairments (Goswami, 2011; Power, Mead, Barnes, & Goswami, 2013; Soltész, Szucs, Leong, White, & Goswami, 2013). In **Appendix of Chapter 3**, we showed that across conditions (attend high band, attend low band and passive listening), ITPC at 3 and 6 Hz in children with dyslexia was comparable to one of their peers, which thus does not provide support for the hypothesis of impaired auditory phase-locking mechanisms in dyslexic readers (Goswami, 2011).

The observed lower performance of children with dyslexia on attentional measures, which did not reach statistical significance, may indicate that attentional difficulties are more prevalent in dyslexic readers but are characteristic of only some individuals with dyslexia. This interpretation is in line with a risk factor model of neurodevelopmental disorders, proposing that no single deficit is either necessary or sufficient to lead to (reading) deficits but rather several interacting factors (e.g., Astle & Fletcher-Watson, 2020; Pennington, 2006; van Bergen, van der Leij, & de Jong, 2014). Difficulties in auditory attention might be among these risk factors. Given the significant relationship between sustained selective attention and reading fluency abilities, it is possible that although some children may not demonstrate attentional impairments reaching clinically significant cut-offs, yet mildly compromised attentional skills may still be related to their reading difficulties (Ring & Black, 2018). Possibly, poor attentional skills might represent a risk for more severe reading disfluency, rather than for reading impairments per se. In fact, selective attention scaled with reading fluency within the group of children with dyslexia (and across groups) but not of typical readers (**Chapter 3**). However, these speculations need further investigations, as the lack of association in typical readers may be simply due to the smaller sample size and thus to lack of statistical power.

When children were required to select one speech stream over a similar one and identify familiar words (colours/numbers), children with dyslexia performed worse than typical readers. Furthermore, non-verbal selective attention was predictive of speech-in-speech perception abilities (**Chapter 3**), extending to children with and without dyslexia the notion that domain-general skills are predictive of speech perception in suboptimal listening conditions (Laffere, Dick, Holt, & Tierney, 2020; Oberfeld & Klöckner-Nowotny, 2016; Strait & Kraus, 2011; Tierney, Rosen, & Dick, 2020). For the first time, our findings provide evidence for the hypothesis that auditory attention is one of the underlying factors of difficulties with perceiving speech in complex environments and reading in dyslexic readers (Calcus, Hoonhorst, Colin, Deltenre, & Kolinsky, 2018; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). However, selective attention might be less engaged in speech-in-noise tasks, according to the employed target (e.g., identification of consonants in vowel-consonant-vowel streams versus of keywords in sentences) and masker (e.g., speech-shaped noise versus two-talkers babble). Accordingly, the inconsistency of speech-in-noise deficits in children with dyslexia across different tasks may also be related to the differential engagement of attention. Employing different speech-in-noise tasks (e.g. Messaoud-Galusi, Hazan, & Rosen, 2011) would help understanding to what extent auditory attention in children with dyslexia contributes to specific difficulties in perceiving speech in complex environments. Children's speech-in-noise abilities are thought to be explained by an interplay of language and cognitive (domain-general) abilities (Klatte, Bergström, & Lachmann, 2013; Thompson et al., 2019). In this work, we found evidence of this interplay in the results of the principal component analysis including a selection of children with dyslexia (**Chapter 5),** whereby measures of speech-in-speech perception, phonological awareness and (to a lesser extent) non-verbal selective attention loaded on one component. Difficulties in dyslexia in speech-in-noise/speech-in-speech perception may therefore be closely linked to phonological deficits (Boets et al., 2011) and poor auditory attentional abilities in some individuals with dyslexia are likely to aggravate these difficulties (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009).

To summarise, our data are not conclusive concerning a non-linguistic auditory attention deficit in children with dyslexia. The non-significant trends in group comparison analyses of attentional measures and the association between attentional measures and reading fluency and speech-in-speech perception may indicate that poor auditory attention in some individuals with dyslexia may represent a risk for more severe reading disfluency and speech-in-speech perception difficulties. In classrooms or other educational settings, children with dyslexia are likely to struggle in the presence of distracting voices. If background noise or speech partly mask the message conveyed by the teacher, it can result in a cumulative loss of educational information and thus constitute an additional risk or burden. Therefore, educational practices should target the level of noise within classrooms to provide an optimal learning environment and prevent potential additional learning difficulties in children with dyslexia.

### 6.3.2. Does auditory attention modulate children's susceptibility to background speech during listening and reading tasks?

In everyday life, children often perform various tasks in noisy surroundings. In the classroom, children's activities involve listening to the teacher and performing tasks alone or in a group, such as reading silently a science textbook or solving a math problem. Sound like traffic noise from the road or children's voices from the corridor is irrelevant for these activities, can distract pupils from their tasks and makes it difficult to focus on teaching instructions. Therefore, environmental noise and background speech can affect both children's listening and non-listening activities (Klatte et al., 2013).

Children have more difficulties than adults in perceiving speech in unfavourable listening conditions (Klatte, Lachmann, & Meis, 2010; Valente, Plevinsky, Franco, Heinrichs-Graham, & Lewis, 2012; vander Ghinst et al., 2019). Children's greater challenges in noise were attributed to lower language abilities such as less specified phonological representations and domain-general abilities such as attention (Klatte et al., 2013). As we have discussed in the previous section, there are also differences among children in the ability to single out a voice when another talker is speaking, and auditory attention is predictive of these differences.

We know much less about whether children are differentially affected by background noise or speech while performing non-listening tasks. In this project, we investigated whether background speech can disrupt reading performance and whether and why some school-age children are more affected than others (**Chapter 2)**. Although usually children are surrounded by a mixture of different sounds and voices (Woolner & Hall, 2010), in this project we focused on the effects of background speech to isolate the effects of two of its characteristics: intensity and intelligibility. In line with previous adults' studies (Martin, Wogalter, & Forlano, 1988; Vasilev, Liversedge, Rowan, Kirkby, & Angele, 2019; see for a review: Vasilev, Kirkby, & Angele, 2018), we found that children's reading comprehension was disrupted by the intelligibility of background speech. We also found that louder background speech resulted in slower text reading. Among the pupils' characteristics or abilities modulating these effects, interference control influenced speech intelligibility effect on reading comprehension while word reading fluency (assessed in quiet) modulated loudness effect on reading speed.

This study provided some insight into the potential mechanisms through which background speech influences children's reading performance. Moreover, the study identified sources of individual differences in the susceptibility to the effects of background speech on reading. First, results indicated that when children read and try to understand a text, intelligible speech activates automatic semantic processes. These automatic processes elicited by background speech need active suppression to avoid interference with the ongoing semantic processes to understand the text (interference-by-process; Hughes, 2014; Marsh, Hughes, & Jones, 2008, 2009).

Previous studies hypothesised that top-down control does not modulate the interference generated by a conflict between similar ongoing processes (e.g., Hughes, 2014). This hypothesis was indirectly derived by the observation that the amount of interference did not differ between adults and children and by the notion that children have poorer attentional control than adults. However, our results suggested that top-down attentional control (in our study, auditory interference control) could be exerted to suppress the interference generated by semantic processes activated by intelligible background speech.

By contrast, interference control did not modulate the individual susceptibility to the effect of loudness on reading speed. Therefore, we speculated that disruption caused by louder sounds may generate interference at the perceptual level, for example by interfering with the automatic access to phonological code from print. Following this interpretation, it will be interesting to test whether a selective attention measure that taps into the suppression of perceptual irrelevant information (rather than semantic information as in the interference control task employed in **Chapter 2**), is related to an individual's susceptibility to loudness effect on reading speed.

Unexpectedly, we found that pupils with better reading fluency (assessed in quiet with a standardised word reading aloud test) slowed down relatively more when background speech was louder. In the literature, the greater susceptibility to noise of younger children compared to older children and adults was argued to be due to weaker attention but also to lower abilities in performing the main task (in our case, reading) (Elliott & Briganti, 2012; Klatte et al., 2010). Following this rationale, we expected more fluent children to be less affected by speech loudness. We hypothesised that more skilled readers are more able to regulate their reading behaviour as a function of the environment. For example, they may slow down more to preserve text comprehension (e.g., Vasilev, 2018). Alternatively, if louder background speech specifically affects the automaticity of reading decoding processes, less fluent readers might be less affected by loud background noise relative to more fluent readers. Future studies including typical as well as dyslexic readers may help test this hypothesis. Reading disfluency is the core and most persistent difficulty of dyslexic readers, and indicates a decreased automaticity of reading decoding processes. If background speech loudness slows down reading by affecting the automaticity of reading decoding processes, dyslexic readers' reading fluency should be less affected by background speech loudness relative to typical readers' reading fluency. More generally, broadening the investigations on the harmful effects of background noise to participants with diverse neurodevelopment disorders would benefit the identification of vulnerable groups and encourage practices to reduce noise exposures in educational settings. In the case of dyslexia, given the existing evidence showing difficulties in perceiving speech in challenging acoustic settings, potential evidence showing greater susceptibility of reading skills to specific background speech or noise conditions would further indicate the implementation of noise reduction policies in classrooms. As mentioned in **Chapter 2**, in the current PhD project, it was not possible to address this question, for example, by including the reading under distracting speech paradigm among the measures of the study presented in **Chapters 3 and 4** with dyslexic and typical readers due to the already long testing sessions.

To summarise, we observed that interference control modulated the effect of background speech intelligibility on reading comprehension (**Chapter 2)**. Moreover, children with poorer selective auditory attention found it harder to perceive speech with distracting speech in the background (**Chapter 3**). Therefore, we conclude that auditory attention may act as a protective factor in noisy surroundings by modulating the harmful effects of irrelevant speech on speech perception and reading comprehension. Conversely, lower auditory attentional skills (as well as the level of noise in the classroom) should be accounted for in educational practices as a risk factor for general learning outcomes as educational information is usually conveyed orally and reading becomes, after the first years of primary education, a privileged tool for learning. Altogether, these findings point to a complex view of background sound effects on children’s performance, in which sound characteristics, general cognitive abilities and skill level on the main task (e.g. reading) interact with each other.

### 6.3.3. Simulation of first steps of reading acquisition: behavioural evidence of letter-speech sound learning deficits in children with dyslexia and the relationship with auditory attention

Longitudinal studies demonstrated that the ability to learn grapheme-phoneme correspondences is integral to future reading fluency development in relatively transparent alphabetic languages (Gellert & Elbro, 2017; Horbach, Scharke, Cröll, Heim, & Günther, 2015; Horbach et al., 2018).

Although existing neuroimaging evidence supports the hypothesis of a letter-speech sound integration deficit in children with dyslexia (Froyen, Willems, & Blomert, 2011; Romanovska, Janssen, & Bonte, 2021; Žarić et al., 2014), only a few studies focused on audio-visual learning processes. These behavioural studies employed training paradigms showing deficits in learning symbol-speech sound correspondences (Aravena, Tijms, Snellings, & van der Molen, 2017) and in making use of these correspondences in a subsequent word reading task (Aravena, Snellings, Tijms, & van der Molen, 2013; Aravena et al., 2017; Law et al., 2018). Some of these studies found that symbol-speech sound learning was predictive of reading skills (e.g., Aravena et al., 2017), but other studies did not (Law et al., 2018).

In this project, we took a similar training approach and developed an artificial symbol-speech sound learning paradigm (**Chapter 4**). The project benefited from the collaboration with the Regional Institute for Dyslexia in the Netherlands, which provides diagnosis and treatment for children with dyslexia. Motivated by close contact with the clinical practice, we were interested in developing an experimental tool that could potentially be introduced in diagnostic assessments, i.e. relatively short and accessible.

We focused our analyses on the learning trajectories of children with and without dyslexia. Despite its brevity, the learning task uncovered shallower learning trajectories of children with dyslexia, who, however, performed similarly in subsequent reading tasks within the artificial orthography. Our results partially contrast with previous findings from training studies which all found a decreased ability to read within the artificial orthography (Aravena et al., 2013, 2017; Law et al., 2018), but did not consistently find a deficit in acquiring the knowledge of the correspondences (Aravena et al., 2017). The observed shallower learning trajectories support the hypothesis of letter-speech sound learning deficits in dyslexia (Aravena et al., 2013, 2017). They also suggest that it is likely that the previously found lower ability to read the novel orthography indicates lower letter-speech sound learning abilities (Aravena et al., 2013, 2017) rather than mainly be the result of reduced reading experience of dyslexic readers (Law et al., 2018)

However, the data of our study were not conclusive concerning the association between letter-speech sound learning and (alphabetic) reading fluency abilities, as the relationship did not remain significant within each group (i.e. when the binary diagnosis was entered in the regression model). Interestingly, a component underlying symbol-speech sound learning and non-verbal selective attention predicted reading fluency (and spelling) gains of dyslexic readers during the intervention (**Chapter 5)**. The same construct was also related to pre-intervention reading fluency but only with a non-significant trend. The greater predictiveness of letter-speech sound learning measures for longitudinal rather than concurrent reading proficiency may be partly due to the dynamic nature of these measures (Horbach et al., 2018). In other words, the fact that these measures capture individual learning potential rather than established knowledge may be reflected in greater predictiveness of future reading fluency development.

The dynamic nature of this dynamic assessment also allowed us to hone in on factors that may influence children's learning. In line with the overarching goal of this thesis, we investigated whether children with greater auditory attentional abilities were also more able to learn audio-visual associations. Recent models of multisensory integration emphasised that top-down attention influence multisensory integration, particularly when multiple stimuli within each unisensory modality are present and thus compete for further processing (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010), which is the case during reading acquisition, when readers are rarely presented with graphemes and phonemes in isolation (Lallier et al., 2012). In **Chapter 4**, we found that non-verbal selective attention and interference control predicted response accuracy in the learning task. Non-verbal selective attention, as well as EEG correlates, i.e. ITPC difference between active and passive conditions at the attended frequency (3 Hz), also predicted the ability of decoding words and pseudowords written with the newly learned correspondences (**Appendix of Chapter 4**). This finding was confirmed by principal component analysis results of **Chapter 5**, showing shared variance between learning task response accuracy and non-verbal selective attention in a smaller sample of children with dyslexia. Thus, children with greater ability to selectively direct and sustain attentional focus were more able to learn to associate novel visual characters with familiar spoken language units. Although with the limitations of a correlational design, these findings denote that poor attentional skills may constitute a risk in the early stages of reading acquisition, given that poor attention may influence one of the fundamental processes for learning to read, the learning of grapheme-phonemes associations.

### 6.3.4. Individual differences in response to intervention for dyslexia: does auditory attention play a role?

Despite the demonstrated benefits of phonics-based treatments involving phonological and letter-speech sound mapping instructional elements, reading fluency (the ability to read words correctly but also fast and effortlessly; National reading panel, 2000) remains less susceptible to intervention, even after systematic and intensive treatments (Singleton, 2009; Snowling & Hulme, 2011; Torgesen et al., 2001). In addition, there are substantial inter-individual differences in reading fluency outcome after intervention (Galuschka, Ise, Krick, & Schulte-Körne, 2014; Singleton, 2009; Snowling & Hulme, 2011; Tijms, 2011). Thus, the identification of individual factors predicting treatment outcomes has become a relevant focus of research.

It is still unclear whether reading-specific abilities, i.e. abilities explaining significant variance in reading such as phonological awareness, rapid naming and letter-speech sound processes (e.g., Caravolas et al., 2012), are also predictive of benefits during reading interventions. Existing findings are inconsistent (e.g., Tilanus, Segers, & Verhoeven, 2019 cf. Tilanus, Segers, & Verhoeven, 2016), possibly because treatments specifically target weakness in these reading-specific abilities and thus the initial level in these reading-specific abilities is not associate with treatment outcome (Fraga et al., 2015; Hatcher and Hulme, 1999). The lack of significant relationships between initial abilities and outcomes may also indicate that interventions are effective regardless of a child's initial profile (e.g., Tijms, 2011; van Rijthoven, Kleemans, Segers, & Verhoeven, 2021). Nonetheless, a large proportion of variance in treatment outcome remains unexplained. Although studies showed that executive and attentional abilities influence the development of literacy abilities (e.g., Blair & Peters Razza, 2007; St Clair-Thompson & Gathercole, 2006; Welsh, Nix, Blair, Bierman, & Nelson, 2010), it is unknown whether these skills interact with learning processes during intervention for dyslexic readers.

It is plausible that better responders to intervention may have a more efficient executive and attentional scaffold supporting the development of reading-specific abilities (Aboud, Barquero, & Cutting, 2018). In **Chapter 5**, we examined this hypothesis asking whether reading-specific and attentional abilities were predictive of reading fluency and spelling gains during a reading intervention. The intervention was focused on the learning of letter–speech sound correspondences and on the use of these correspondences in reading and spelling. We found that a component encompassing selective attention to phonological information (extracted with a principal component analysis) was predictive of the spelling gains in the first half of the intervention program, focused on the development of accurate knowledge of the correspondences. We hypothesised that efficient allocation of selective attention to phonological information might be critical for developing access to orthographic information from spoken words. Another component encompassing selective attention during letter-speech sound learning was predictive of both spelling and reading fluency gains during the second half of the intervention, focused on the development of skill automaticity and fluent reading. These results demonstrated that taking an interactive approach, i.e., an approach that considers the interrelation of domain-general and reading-specific abilities, may be informative in understanding how variation in these abilities affects an individual's reading/spelling development.

Should auditory attention be targeted in interventions for dyslexia? Results of our studies do not support the hypothesis that auditory deficits are a common characteristic of children with dyslexia, suggesting that not all individuals may require or benefit from an auditory attention training. Auditory attentional deficits may occur only in some individuals, possibly in children with more severe reading fluency impairments. In fact, we did not find significant group-level deficits in non-verbal sustained selective attention (**Chapter 3**) or auditory interference control (**Chapter 4**), although the group performance was generally lower than that of typical readers. Within the group of children with dyslexia (and across groups), non-verbal selective attention scaled with reading fluency abilities (**Chapter 3**). The observation that greater ability in directing attention to phonological information and during audio-visual learning resulted in better intervention outcomes (**Chapter 5**) may also suggest that attentional deficits in dyslexic readers may be a risk for disorder severity, given that a child's response to evidence-based interventions is thought to indicate the severity of reading impairments (Fuchs & Fuchs, 2006; Rose, 2009; Snowling & Hulme, 2011). To conclude, the evidence reported in the present work suggests that improving auditory attention (before or during intervention targeting reading-specific deficits) could be beneficial for some children, particularly those with more severe disfluency.

## 6.4. Limitations and future directions of the current work

The study in **Chapter 2** reported novel findings showing that different properties of background speech (loudness and intelligibility) can differentially affect children's reading. However, we inferred the mechanisms through which background speech disrupts children's reading performance from the differential effect of loudness and intelligibility of background speech and the predictiveness of individual characteristics to these effects. In future studies, the use of eye-tracking and/or electroencephalography

(EEG) might help to track background speech processing and to detect subtle effects on children's reading performance that may not be captured by behavioural measures. The limitation of behavioural measures was shown, for example, in previous eye-tracking studies with adult participants, reporting that speech intelligibility affected reading comprehension processes, although behavioural performance remained unaffected (e.g., Vasilev et al., 2019). Follow-up studies may also include different speech conditions, for example, by varying the degree of engagement for children or including conversational speech. Our single-talker background speech featured content not particularly engaging for children (i.e., an article on migration history). Although this choice helped isolate the effects of different properties of background speech and to potentially limit disrupting effects solely due to attentional capture (i.e., when attention is momentarily disengaged from the relevant task; Hughes et al., 2014), everyday life contexts present children with a variety of sounds, linguistic and non-linguistic, rarely continuous, and potentially attractive. Although mimicking naturalistic environments may reveal methodological challenges, it would potentially provide a real-world image of challenges children face in educational settings. Finally, future studies may include participants with atypical development, including children with dyslexia. These studies may be able to clarify further the mechanisms through which background speech disrupts children's reading performance, as well as identifying vulnerable groups.

In **Chapter 3**, we found that inter-trial-phase-coherence (ITPC) at the attended band (3 Hz) increased in frontal areas and decreased in the temporal areas of the scalp when children were selectively attending to one of the two tone-streams. This increased phase entrainment at other scalp locations than the ones where phase consistency was found to be greatest during passive listening was not found in previous in-lab studies with adults (Laffere, Dick, & Tierney, 2020) and older children with and without ADHD (Laffere, Dick, Holt, et al., 2020), using the same non-verbal selective attention paradigm. In a follow-up study, it will be interesting to investigate the possibility that this finding reflects a developmental change in neural mechanisms underlying auditory attentional selection. This type of study would also fill a gap in the literature, as there is some evidence of developmental changes in neural entrainment in response to speech (e.g., Ríos-López, Molinaro, Bourguignon, & Lallier, 2020) but, to date, no previous studies investigated longitudinal changes in selective attention-driven neural entrainment.

A longitudinal study may also be particularly informative for clarifying the extent to which auditory attention is causally linked to reading acquisition and reading deficits in children with dyslexia (e.g., Goswami, Power, Lallier, & Facoetti, 2014). Exploring the interaction between attentional and reading and reading-specific skills over time may reveal, for example, that the contribution of attention is more pronounced in certain stages of reading acquisition, as some authors previously proposed for the influence of visual attention in the early stages of reading acquisition (e.g., Bosse & Valdois, 2009). Concerning the influence of attention on fundamental processes underlying early reading acquisition, in **Chapter 4,** we examined children's ability to learn novel audio-visual correspondences, as a model mimicking one of the first steps in reading acquisition, and the relationship between this ability and auditory attentional skills, which was found significant. However, the correlational and cross-sectional design of the study cannot allow us to draw strong conclusions about whether auditory attention is causally linked to (un)successful reading fluency development. In follow-up studies, the use of learning paradigms that manipulate attentional demands, supported by neuroimaging methods (e.g. Hämäläinen, Parviainen, Hsu, & Salmelin, 2019; Yoncheva, Blau, Maurer, & McCandliss, 2010) may help to clarify to which extent attentional mechanisms support audio-visual learning processes of children with and without dyslexia.

**Chapter 5** showed how domain-general (i.e. attentional) and reading-specific abilities were interrelated and that this interrelation was predictive of individual intervention benefits. The exploratory nature of this study was informative as a starting point to understand whether attentional abilities interact with learning processes during interventions but the lack of a control group in a randomised-controlled trial limited critically the clinical significance of the results. In future studies, including a control group and training attentional skills before intensive specialised interventions targeting reading-specific deficits and tracking the underlying neural changes between pre-and post-attentional training could clarify whether improvements in attention demonstrate significant larger benefits during subsequent reading-specific interventions.

In addition, the studies reported in **Chapters 3-5** included a broad age range group of children to ensure the recruitment of a large clinical (and non-clinical) sample. The large sample size enabled to investigate individual differences in auditory attention and letter-speech sound learning relevant to reading skills. I observed age-related increases in tasks' performance, which did not reach ceiling effects in older participants in any of the experimental tasks. However, it is also possible that at a different age, the same task may have tapped into different mechanisms (e.g. Schleepen & Jonkman, 2010), due for example to the application of different strategies to solve the same task (Stiles, Moses, Passarotti, Dick & Buxton, 2003). In the study illustrated in **Chapter 5**, differences across age groups in the exact nature of task demands may limit our understanding of the mechanisms supporting learning during dyslexia intervention.

Finally, as previously mentioned in **Chapters 3 and 4**, individual differences in working memory abilities may have affected children's performance in the artificial symbol-speech sound learning task and in the selective sustained attention task. In future studies, it would be important to determine the independent contribution of auditory attention and working memory to typical and atypical reading development.

## 6.5. Concluding remarks

This thesis examined auditory attention as a potential contributor to children's reading abilities. We examined interference control, behavioural and neural (EEG) correlates of non-verbal sustained selective attention in typical and dyslexic readers. The non-significant trends in group comparison analyses of attentional measures and the association between attentional and reading fluency abilities suggested that auditory attention deficits may be among the multiple risk factors leading to reading difficulties in dyslexia. As a model mimicking one of the first steps of reading acquisition, we asked children to learn novel audio-visual associations, providing evidence of letter-speech sound learning deficits in children with dyslexia and predictiveness of auditory attention to letter-speech sound learning abilities. Furthermore, we investigated factors moderating the individual response to intensive intervention for children with dyslexia. We found that the ability to direct attention to phonological and grapheme-phoneme relations was predictive of reading fluency and spelling gains, indicating that attention may interact with and facilitate learning processes during interventions. Finally, we examined the effects of background speech on children's reading and speech perception abilities, showing that auditory attention could modulate the harmful effects of background speech. The novel findings presented in the four studies represent a starting point for future investigations into a deeper understanding of the relationship between auditory attention and reading abilities during development. The findings also emphasised that broadening the focus of our investigations to domain-general processes and their relationship with language-specific skills can improve our understanding of the multiple factors influencing the development of reading abilities. Ultimately, this deeper understanding will allow for individualising interventions based on a child's characteristics.

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# Appendix of Chapter 3

## A. Statistics

**Table A3.1. Post-hoc pairwise comparisons of ITPC at 3 and 6 Hz in the active conditions versus in the passive condition.**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **t(88)** | **p** | **FDR-corrected p** | **t(88)** | **p-values** | **FDR-corrected p** |
| Fp1 | 0.578 | 0.565 | 0.757 | -0.056 | 0.956 | 0.983 |
| Fz | **4.081** | **<0.001** | **0.006** | 2.566 | 0.012 | 0.061 |
| F3 | 1.744 | 0.085 | 0.254 | 1.956 | 0.054 | 0.130 |
| F7 | 1.184 | 0.239 | 0.487 | 0.198 | 0.843 | 0.896 |
| FT9 | -2.827 | 0.006 | 0.050 | -2.216 | 0.029 | 0.092 |
| FC5 | 1.242 | 0.218 | 0.457 | 1.483 | 0.142 | 0.262 |
| FC1 | 1.907 | 0.060 | 0.222 | -0.006 | 0.995 | 0.995 |
| C3 | 1.129 | 0.262 | 0.504 | -0.361 | 0.719 | 0.824 |
| T7 | -0.868 | 0.388 | 0.555 | -1.488 | 0.140 | 0.262 |
| TP9 | -1.848 | 0.068 | 0.225 | **-4.329** | **0.000** | **0.002** |
| CP5 | -0.975 | 0.332 | 0.538 | -2.456 | 0.016 | 0.064 |
| CP1 | 0.939 | 0.350 | 0.538 | -1.101 | 0.274 | 0.392 |
| Pz | 0.753 | 0.453 | 0.621 | -1.545 | 0.126 | 0.248 |
| P3 | 0.504 | 0.615 | 0.779 | -1.287 | 0.202 | 0.318 |
| P7 | 0.130 | 0.897 | 0.958 | **-3.014** | **0.003** | **0.027** |
| O1 | 0.524 | 0.602 | 0.779 | **-3.545** | **0.001** | **0.007** |
| Oz | 0.913 | 0.364 | 0.546 | **-2.688** | **0.009** | **0.049** |
| O2 | 0.050 | 0.960 | 0.960 | **-2.861** | **0.005** | **0.034** |
| P4 | -0.776 | 0.440 | 0.616 | -1.632 | 0.106 | 0.216 |
| P8 | -2.042 | 0.044 | 0.186 | **-3.679** | **0.000** | **0.006** |
| TP10 | **-2.955** | **0.004** | **0.042** | -2.194 | 0.031 | 0.092 |
| CP6 | -1.120 | 0.266 | 0.504 | -1.381 | 0.171 | 0.297 |
| CP2 | 0.445 | 0.657 | 0.812 | 0.328 | 0.744 | 0.835 |
| Cz | 1.635 | 0.106 | 0.279 | 1.336 | 0.185 | 0.299 |
| C4 | 1.458 | 0.148 | 0.346 | 2.176 | 0.032 | 0.092 |
| T8 | -2.370 | 0.020 | 0.105 | -1.234 | 0.221 | 0.331 |
| FT10 | -2.449 | 0.016 | 0.093 | -1.345 | 0.182 | 0.299 |
| FC6 | 0.185 | 0.853 | 0.958 | 1.416 | 0.160 | 0.288 |
| FC2 | 1.810 | 0.074 | 0.232 | 0.940 | 0.350 | 0.459 |
| F4 | 2.120 | 0.037 | 0.166 | 2.408 | 0.018 | 0.064 |
| F8 | -0.238 | 0.813 | 0.931 | 0.312 | 0.756 | 0.835 |
| Fp2 | 1.951 | 0.054 | 0.214 | 0.443 | 0.659 | 0.769 |
| AF7 | 1.858 | 0.067 | 0.225 | -0.622 | 0.535 | 0.649 |
| AF3 | 2.610 | 0.011 | 0.075 | 2.235 | 0.028 | 0.092 |
| AFz | 2.793 | 0.006 | 0.050 | **3.325** | **0.001** | **0.012** |
| F1 | 2.149 | 0.034 | 0.166 | 1.734 | 0.087 | 0.182 |
| F5 | **3.063** | **0.003** | **0.037** | 0.774 | 0.441 | 0.545 |
| FT7 | -1.406 | 0.163 | 0.362 | -0.814 | 0.418 | 0.537 |
| FC3 | **3.367** | **0.001** | **0.035** | 1.015 | 0.313 | 0.438 |
| C1 | 0.873 | 0.385 | 0.555 | 0.963 | 0.338 | 0.459 |
| C5 | -0.500 | 0.619 | 0.779 | -0.791 | 0.431 | 0.543 |
| TP7 | -1.710 | 0.091 | 0.260 | **-3.856** | **0.000** | **0.006** |
| CP3 | 0.353 | 0.725 | 0.862 | -2.433 | 0.017 | 0.064 |
| P1 | 0.364 | 0.717 | 0.862 | -0.568 | 0.571 | 0.679 |
| P5 | -0.057 | 0.954 | 0.960 | -1.871 | 0.065 | 0.145 |
| PO7 | -0.136 | 0.892 | 0.958 | **-3.793** | **0.000** | **0.006** |
| PO3 | 0.067 | 0.947 | 0.960 | -2.128 | 0.036 | 0.095 |
| POz | 0.983 | 0.328 | 0.538 | -1.934 | 0.056 | 0.132 |
| PO4 | -0.056 | 0.956 | 0.960 | -2.129 | 0.036 | 0.095 |
| PO8 | -0.291 | 0.772 | 0.901 | **-3.594** | **0.001** | **0.007** |
| P6 | -1.079 | 0.283 | 0.510 | -2.548 | 0.013 | 0.061 |
| P2 | 0.964 | 0.338 | 0.538 | -1.370 | 0.174 | 0.297 |
| CPz | 1.611 | 0.111 | 0.279 | -0.042 | 0.967 | 0.983 |
| CP4 | -0.133 | 0.895 | 0.958 | 0.186 | 0.853 | 0.896 |
| TP8 | **-3.151** | **0.002** | **0.035** | -2.406 | 0.018 | 0.064 |
| C6 | 1.061 | 0.292 | 0.510 | 1.104 | 0.273 | 0.392 |
| C2 | 1.534 | 0.129 | 0.312 | 2.055 | 0.043 | 0.108 |
| FC4 | 1.106 | 0.272 | 0.504 | 1.266 | 0.209 | 0.321 |
| FT8 | -1.394 | 0.167 | 0.362 | -0.948 | 0.346 | 0.459 |
| F6 | 1.617 | 0.110 | 0.279 | 1.761 | 0.082 | 0.178 |
| AF8 | 0.949 | 0.345 | 0.538 | -0.266 | 0.791 | 0.859 |
| AF4 | **3.210** | **0.002** | **0.035** | **2.853** | **0.005** | **0.034** |
| F2 | 2.498 | 0.014 | 0.090 | 2.470 | 0.015 | 0.064 |

**Table A3.2. Channel-wise correlations between ITPC (active-passive) at 3 and 6 Hz and sustained auditory selective attention task performance (d-prime).**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **rho** | **p** | **FDR-corrected p** | **rho** | **p** | **FDR-corrected p** |
| Fp1 | **0.363** | **<0.001** | **0.010** | -0.027 | 0.800 | 0.884 |
| Fz | **0.291** | **0.006** | **0.033** | 0.128 | 0.234 | 0.431 |
| F3 | **0.324** | **0.002** | **0.015** | 0.107 | 0.317 | 0.499 |
| F7 | **0.297** | **0.005** | **0.030** | -0.043 | 0.687 | 0.817 |
| FT9 | 0.193 | 0.070 | 0.209 | -0.011 | 0.920 | 0.950 |
| FC5 | 0.176 | 0.098 | 0.229 | 0.019 | 0.862 | 0.920 |
| FC1 | 0.171 | 0.108 | 0.243 | 0.062 | 0.567 | 0.776 |
| C3 | 0.039 | 0.719 | 0.795 | -0.087 | 0.420 | 0.630 |
| T7 | 0.157 | 0.142 | 0.308 | -0.056 | 0.602 | 0.776 |
| TP9 | 0.141 | 0.188 | 0.370 | -0.282 | 0.007 | 0.071 |
| CP5 | 0.094 | 0.380 | 0.641 | -0.200 | 0.061 | 0.182 |
| CP1 | 0.011 | 0.920 | 0.935 | -0.025 | 0.814 | 0.884 |
| Pz | -0.048 | 0.654 | 0.790 | -0.121 | 0.257 | 0.436 |
| P3 | -0.061 | 0.569 | 0.753 | -0.174 | 0.103 | 0.241 |
| P7 | 0.071 | 0.508 | 0.702 | -0.322 | 0.002 | 0.068 |
| O1 | 0.053 | 0.624 | 0.786 | -0.240 | 0.023 | 0.114 |
| Oz | 0.047 | 0.665 | 0.790 | -0.312 | 0.003 | 0.068 |
| O2 | 0.136 | 0.205 | 0.391 | -0.264 | 0.012 | 0.087 |
| P4 | 0.060 | 0.574 | 0.753 | -0.245 | 0.021 | 0.108 |
| P8 | 0.199 | 0.062 | 0.204 | -0.213 | 0.045 | 0.167 |
| TP10 | 0.181 | 0.090 | 0.229 | -0.231 | 0.030 | 0.133 |
| CP6 | 0.043 | 0.692 | 0.795 | -0.175 | 0.101 | 0.241 |
| CP2 | 0.070 | 0.513 | 0.702 | -0.006 | 0.957 | 0.972 |
| Cz | -0.072 | 0.501 | 0.702 | 0.049 | 0.648 | 0.785 |
| C4 | 0.036 | 0.735 | 0.799 | -0.053 | 0.624 | 0.785 |
| T8 | 0.204 | 0.055 | 0.193 | -0.220 | 0.038 | 0.151 |
| FT10 | 0.177 | 0.097 | 0.229 | -0.252 | 0.017 | 0.101 |
| FC6 | **0.282** | **0.008** | **0.036** | 0.030 | 0.779 | 0.876 |
| FC2 | **0.315** | **0.003** | **0.018** | 0.014 | 0.894 | 0.939 |
| F4 | **0.279** | **0.008** | **0.036** | 0.167 | 0.118 | 0.265 |
| F8 | **0.354** | **0.001** | **0.010** | -0.057 | 0.593 | 0.776 |
| Fp2 | 0.221 | 0.037 | 0.146 | 0.051 | 0.638 | 0.785 |
| AF7 | **0.325** | **0.002** | **0.015** | -0.034 | 0.753 | 0.862 |
| AF3 | **0.389** | **<0.001** | **0.010** | -0.004 | 0.972 | 0.972 |
| AFz | **0.281** | **0.008** | **0.036** | 0.189 | 0.076 | 0.218 |
| F1 | 0.196 | 0.066 | 0.208 | 0.120 | 0.263 | 0.436 |
| F5 | **0.372** | **<0.001** | **0.010** | -0.056 | 0.601 | 0.776 |
| FT7 | 0.183 | 0.086 | 0.229 | -0.125 | 0.243 | 0.431 |
| FC3 | 0.080 | 0.454 | 0.665 | 0.134 | 0.209 | 0.400 |
| C1 | 0.099 | 0.355 | 0.621 | -0.056 | 0.603 | 0.776 |
| C5 | 0.088 | 0.410 | 0.645 | -0.200 | 0.060 | 0.182 |
| TP7 | 0.083 | 0.439 | 0.659 | -0.200 | 0.061 | 0.182 |
| CP3 | 0.055 | 0.608 | 0.781 | -0.111 | 0.301 | 0.487 |
| P1 | -0.093 | 0.387 | 0.641 | -0.149 | 0.164 | 0.345 |
| P5 | 0.008 | 0.938 | 0.938 | -0.302 | 0.004 | 0.068 |
| PO7 | 0.040 | 0.708 | 0.795 | -0.300 | 0.004 | 0.068 |
| PO3 | -0.031 | 0.775 | 0.823 | -0.251 | 0.018 | 0.101 |
| POz | -0.030 | 0.783 | 0.823 | -0.274 | 0.009 | 0.074 |
| PO4 | 0.040 | 0.712 | 0.795 | -0.289 | 0.006 | 0.071 |
| PO8 | 0.177 | 0.097 | 0.229 | -0.176 | 0.100 | 0.241 |
| P6 | 0.114 | 0.289 | 0.536 | -0.280 | 0.008 | 0.071 |
| P2 | 0.024 | 0.821 | 0.848 | -0.186 | 0.080 | 0.220 |
| CPz | 0.090 | 0.399 | 0.645 | -0.066 | 0.537 | 0.769 |
| CP4 | 0.049 | 0.652 | 0.790 | -0.103 | 0.335 | 0.515 |
| TP8 | 0.149 | 0.163 | 0.343 | -0.223 | 0.036 | 0.151 |
| C6 | 0.110 | 0.305 | 0.548 | -0.149 | 0.164 | 0.345 |
| C2 | 0.084 | 0.436 | 0.659 | 0.078 | 0.470 | 0.689 |
| FC4 | 0.145 | 0.176 | 0.358 | 0.124 | 0.246 | 0.431 |
| FT8 | 0.191 | 0.073 | 0.209 | -0.137 | 0.201 | 0.395 |
| F6 | **0.330** | **0.002** | **0.015** | 0.201 | 0.059 | 0.182 |
| AF8 | 0.259 | 0.014 | 0.060 | 0.039 | 0.717 | 0.836 |
| AF4 | **0.336** | **0.001** | **0.015** | 0.176 | 0.100 | 0.241 |
| F2 | 0.219 | 0.039 | 0.146 | 0.147 | 0.170 | 0.346 |

**Table A3.3. Channel-wise correlations between ITPC (active-passive) at 3 and 6 Hz and age (in months).**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **rho** | **p** | **FDR-corrected p** | **rho** | **p** | **FDR-corrected p** |
| Fp1 | -0.063 | 0.557 | 0.938 | 0.035 | 0.744 | 0.951 |
| Fz | 0.070 | 0.512 | 0.938 | 0.096 | 0.370 | 0.951 |
| F3 | 0.172 | 0.106 | 0.938 | 0.056 | 0.604 | 0.951 |
| F7 | -0.044 | 0.684 | 0.938 | 0.157 | 0.142 | 0.951 |
| FT9 | 0.070 | 0.513 | 0.938 | 0.112 | 0.298 | 0.951 |
| FC5 | 0.085 | 0.427 | 0.938 | 0.032 | 0.765 | 0.951 |
| FC1 | 0.058 | 0.591 | 0.938 | 0.019 | 0.863 | 0.951 |
| C3 | 0.165 | 0.123 | 0.938 | 0.123 | 0.253 | 0.951 |
| T7 | 0.031 | 0.775 | 0.938 | 0.115 | 0.283 | 0.951 |
| TP9 | 0.022 | 0.839 | 0.938 | -0.007 | 0.950 | 0.969 |
| CP5 | 0.051 | 0.638 | 0.938 | 0.052 | 0.629 | 0.951 |
| CP1 | 0.082 | 0.444 | 0.938 | 0.046 | 0.666 | 0.951 |
| Pz | -0.146 | 0.171 | 0.938 | 0.056 | 0.600 | 0.951 |
| P3 | -0.038 | 0.724 | 0.938 | 0.019 | 0.862 | 0.951 |
| P7 | 0.011 | 0.918 | 0.938 | 0.015 | 0.891 | 0.951 |
| O1 | 0.010 | 0.923 | 0.938 | 0.038 | 0.725 | 0.951 |
| Oz | -0.026 | 0.812 | 0.938 | -0.015 | 0.889 | 0.951 |
| O2 | -0.057 | 0.596 | 0.938 | 0.074 | 0.490 | 0.951 |
| P4 | -0.114 | 0.286 | 0.938 | 0.061 | 0.568 | 0.951 |
| P8 | -0.044 | 0.685 | 0.938 | 0.064 | 0.554 | 0.951 |
| TP10 | -0.069 | 0.519 | 0.938 | -0.043 | 0.692 | 0.951 |
| CP6 | -0.128 | 0.231 | 0.938 | 0.048 | 0.653 | 0.951 |
| CP2 | -0.061 | 0.571 | 0.938 | 0.216 | 0.042 | 0.951 |
| Cz | 0.029 | 0.787 | 0.938 | 0.090 | 0.401 | 0.951 |
| C4 | -0.001 | 0.989 | 0.989 | 0.002 | 0.986 | 0.986 |
| T8 | -0.110 | 0.303 | 0.938 | -0.022 | 0.836 | 0.951 |
| FT10 | -0.012 | 0.910 | 0.938 | -0.064 | 0.548 | 0.951 |
| FC6 | -0.030 | 0.779 | 0.938 | -0.131 | 0.220 | 0.951 |
| **FC2** | 0.164 | 0.125 | 0.938 | 0.047 | 0.664 | 0.951 |
| **F4** | 0.152 | 0.156 | 0.938 | 0.158 | 0.140 | 0.951 |
| **F8** | 0.050 | 0.645 | 0.938 | -0.079 | 0.465 | 0.951 |
| Fp2 | 0.060 | 0.574 | 0.938 | -0.061 | 0.572 | 0.951 |
| AF7 | -0.114 | 0.286 | 0.938 | 0.159 | 0.137 | 0.951 |
| **AF3** | 0.108 | 0.315 | 0.938 | 0.120 | 0.265 | 0.951 |
| **AFz** | -0.011 | 0.916 | 0.938 | 0.070 | 0.514 | 0.951 |
| F1 | 0.187 | 0.080 | 0.938 | 0.072 | 0.503 | 0.951 |
| F5 | 0.032 | 0.766 | 0.938 | 0.033 | 0.757 | 0.951 |
| FT7 | 0.039 | 0.718 | 0.938 | 0.159 | 0.136 | 0.951 |
| FC3 | 0.131 | 0.222 | 0.938 | 0.015 | 0.889 | 0.951 |
| C1 | 0.155 | 0.147 | 0.938 | 0.124 | 0.248 | 0.951 |
| C5 | -0.017 | 0.872 | 0.938 | -0.053 | 0.624 | 0.951 |
| TP7 | 0.030 | 0.782 | 0.938 | 0.056 | 0.600 | 0.951 |
| CP3 | 0.075 | 0.487 | 0.938 | -0.040 | 0.713 | 0.951 |
| P1 | -0.106 | 0.322 | 0.938 | 0.052 | 0.626 | 0.951 |
| P5 | 0.027 | 0.800 | 0.938 | -0.010 | 0.923 | 0.969 |
| PO7 | -0.015 | 0.891 | 0.938 | 0.006 | 0.954 | 0.969 |
| PO3 | -0.048 | 0.655 | 0.938 | 0.015 | 0.886 | 0.951 |
| POz | -0.082 | 0.443 | 0.938 | 0.019 | 0.858 | 0.951 |
| PO4 | -0.166 | 0.121 | 0.938 | 0.066 | 0.538 | 0.951 |
| PO8 | -0.064 | 0.552 | 0.938 | 0.061 | 0.567 | 0.951 |
| P6 | -0.064 | 0.549 | 0.938 | 0.056 | 0.599 | 0.951 |
| P2 | -0.140 | 0.191 | 0.938 | 0.087 | 0.416 | 0.951 |
| CPz | 0.113 | 0.291 | 0.938 | 0.126 | 0.238 | 0.951 |
| CP4 | -0.119 | 0.267 | 0.938 | 0.101 | 0.345 | 0.951 |
| TP8 | -0.051 | 0.635 | 0.938 | -0.025 | 0.820 | 0.951 |
| C6 | -0.103 | 0.335 | 0.938 | -0.067 | 0.534 | 0.951 |
| C2 | -0.013 | 0.901 | 0.938 | 0.126 | 0.239 | 0.951 |
| FC4 | 0.095 | 0.374 | 0.938 | 0.021 | 0.844 | 0.951 |
| FT8 | -0.102 | 0.342 | 0.938 | -0.074 | 0.491 | 0.951 |
| F6 | 0.114 | 0.287 | 0.938 | 0.035 | 0.747 | 0.951 |
| AF8 | 0.078 | 0.466 | 0.938 | -0.054 | 0.612 | 0.951 |
| AF4 | 0.156 | 0.144 | 0.938 | 0.024 | 0.824 | 0.951 |
| F2 | 0.112 | 0.295 | 0.938 | 0.170 | 0.112 | 0.951 |

**Table A3.4. Channel-wise group comparisons (dyslexic versus typical readers) of ITPC difference (active-passive) at 3 Hz and 6 Hz.**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **Z** | **p** | **FDR-corrected p** | **Z** | **p** | **FDR-corrected p** |
| Fp1 | -0.046 | 0.964 | 0.990 | -0.618 | 0.537 | 0.961 |
| Fz | -0.344 | 0.731 | 0.990 | -0.245 | 0.807 | 0.990 |
| F3 | -1.447 | 0.148 | 0.660 | -0.875 | 0.382 | 0.961 |
| F7 | -0.941 | 0.346 | 0.839 | -1.481 | 0.139 | 0.961 |
| FT9 | 0.858 | 0.391 | 0.849 | -2.003 | 0.045 | 0.961 |
| FC5 | -2.177 | 0.029 | 0.633 | -0.377 | 0.706 | 0.990 |
| FC1 | -1.663 | 0.096 | 0.651 | 0.203 | 0.839 | 0.990 |
| C3 | -2.401 | 0.016 | 0.633 | 0.568 | 0.570 | 0.961 |
| T7 | 1.132 | 0.258 | 0.773 | -0.643 | 0.520 | 0.961 |
| TP9 | 0.311 | 0.756 | 0.990 | -0.203 | 0.839 | 0.990 |
| CP5 | -0.668 | 0.504 | 0.908 | 0.635 | 0.526 | 0.961 |
| CP1 | -0.120 | 0.904 | 0.990 | 0.535 | 0.593 | 0.961 |
| Pz | 0.095 | 0.924 | 0.990 | 0.867 | 0.386 | 0.961 |
| P3 | 0.137 | 0.891 | 0.990 | 0.635 | 0.526 | 0.961 |
| P7 | 0.012 | 0.990 | 0.990 | 0.784 | 0.433 | 0.961 |
| O1 | -0.129 | 0.898 | 0.990 | 0.966 | 0.334 | 0.961 |
| Oz | 0.261 | 0.794 | 0.990 | 1.580 | 0.114 | 0.961 |
| O2 | 0.311 | 0.756 | 0.990 | 0.361 | 0.718 | 0.990 |
| P4 | -0.618 | 0.537 | 0.939 | 0.187 | 0.852 | 0.990 |
| P8 | -0.278 | 0.781 | 0.990 | 0.012 | 0.990 | 0.990 |
| TP10 | -0.178 | 0.858 | 0.990 | 0.369 | 0.712 | 0.990 |
| CP6 | -0.734 | 0.463 | 0.905 | -1.423 | 0.155 | 0.961 |
| CP2 | -0.469 | 0.639 | 0.990 | 0.021 | 0.983 | 0.990 |
| Cz | -1.340 | 0.180 | 0.660 | -0.552 | 0.581 | 0.961 |
| C4 | -0.751 | 0.453 | 0.905 | -0.825 | 0.409 | 0.961 |
| T8 | -1.381 | 0.167 | 0.660 | -1.024 | 0.306 | 0.961 |
| FT10 | -1.248 | 0.212 | 0.703 | -0.751 | 0.453 | 0.961 |
| FC6 | -0.867 | 0.386 | 0.849 | 0.112 | 0.911 | 0.990 |
| FC2 | -1.912 | 0.056 | 0.633 | -0.286 | 0.775 | 0.990 |
| F4 | -2.069 | 0.039 | 0.633 | -0.618 | 0.537 | 0.961 |
| F8 | -0.435 | 0.663 | 0.990 | -0.021 | 0.983 | 0.990 |
| Fp2 | -1.497 | 0.134 | 0.651 | -0.991 | 0.322 | 0.961 |
| AF7 | -0.966 | 0.334 | 0.839 | -1.431 | 0.152 | 0.961 |
| AF3 | -0.145 | 0.885 | 0.990 | -0.054 | 0.957 | 0.990 |
| AFz | -1.215 | 0.224 | 0.707 | -1.315 | 0.189 | 0.961 |
| F1 | 0.917 | 0.359 | 0.839 | -0.883 | 0.377 | 0.961 |
| F5 | -1.879 | 0.060 | 0.633 | -0.411 | 0.681 | 0.990 |
| FT7 | -0.178 | 0.858 | 0.990 | -1.472 | 0.141 | 0.961 |
| FC3 | -1.630 | 0.103 | 0.651 | 0.294 | 0.768 | 0.990 |
| C1 | -1.539 | 0.124 | 0.651 | 0.245 | 0.807 | 0.990 |
| C5 | -1.315 | 0.189 | 0.660 | -0.071 | 0.944 | 0.990 |
| TP7 | 0.693 | 0.489 | 0.905 | 0.311 | 0.756 | 0.990 |
| CP3 | -0.336 | 0.737 | 0.990 | 0.975 | 0.330 | 0.961 |
| P1 | -0.046 | 0.964 | 0.990 | 0.759 | 0.448 | 0.961 |
| P5 | -0.402 | 0.687 | 0.990 | 0.659 | 0.510 | 0.961 |
| PO7 | -0.054 | 0.957 | 0.990 | 0.784 | 0.433 | 0.961 |
| PO3 | 0.319 | 0.749 | 0.990 | 0.792 | 0.428 | 0.961 |
| POz | 0.494 | 0.622 | 0.990 | 1.497 | 0.134 | 0.961 |
| PO4 | -0.245 | 0.807 | 0.990 | 0.601 | 0.548 | 0.961 |
| PO8 | 0.353 | 0.724 | 0.990 | 0.212 | 0.832 | 0.990 |
| P6 | -0.435 | 0.663 | 0.990 | -0.120 | 0.904 | 0.990 |
| P2 | -0.029 | 0.977 | 0.990 | 0.510 | 0.610 | 0.961 |
| CPz | -1.024 | 0.306 | 0.839 | 0.054 | 0.957 | 0.990 |
| CP4 | -0.709 | 0.478 | 0.905 | -0.742 | 0.458 | 0.961 |
| TP8 | -0.560 | 0.576 | 0.980 | -0.510 | 0.610 | 0.961 |
| C6 | -0.966 | 0.334 | 0.839 | -1.016 | 0.310 | 0.961 |
| C2 | -1.597 | 0.110 | 0.651 | -0.543 | 0.587 | 0.961 |
| FC4 | -0.817 | 0.414 | 0.869 | 0.319 | 0.749 | 0.990 |
| FT8 | -1.555 | 0.120 | 0.651 | -0.817 | 0.414 | 0.961 |
| F6 | -1.364 | 0.172 | 0.660 | -0.079 | 0.937 | 0.990 |
| AF8 | -1.016 | 0.310 | 0.839 | -0.709 | 0.478 | 0.961 |
| AF4 | -1.920 | 0.055 | 0.633 | -0.784 | 0.433 | 0.961 |
| F2 | -1.522 | 0.128 | 0.651 | -0.867 | 0.386 | 0.961 |

**Table A3.5. Channel-wise correlations between ITPC (active-passive) at 3 and 6 Hz and reading fluency (3DM reading task – raw score).**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **rho** | **p** | **FDR-corrected p** | **rho** | **p** | **FDR-corrected p** |
| Fp1 | -0.102 | 0.342 | 0.941 | 0.071 | 0.506 | 0.983 |
| Fz | 0.025 | 0.814 | 0.977 | -0.049 | 0.648 | 0.983 |
| F3 | 0.197 | 0.065 | 0.582 | 0.078 | 0.469 | 0.983 |
| F7 | 0.061 | 0.568 | 0.977 | 0.139 | 0.194 | 0.983 |
| FT9 | -0.093 | 0.385 | 0.941 | 0.165 | 0.122 | 0.983 |
| FC5 | 0.202 | 0.058 | 0.582 | 0.072 | 0.499 | 0.983 |
| FC1 | 0.129 | 0.227 | 0.873 | 0.035 | 0.743 | 0.983 |
| C3 | 0.248 | 0.019 | 0.582 | 0.051 | 0.634 | 0.983 |
| T7 | -0.134 | 0.209 | 0.873 | 0.084 | 0.432 | 0.983 |
| TP9 | -0.088 | 0.410 | 0.941 | 0.073 | 0.496 | 0.983 |
| CP5 | 0.081 | 0.448 | 0.941 | 0.060 | 0.575 | 0.983 |
| CP1 | 0.051 | 0.632 | 0.977 | 0.028 | 0.794 | 0.983 |
| Pz | 0.031 | 0.775 | 0.977 | -0.030 | 0.778 | 0.983 |
| P3 | 0.002 | 0.986 | 0.986 | -0.002 | 0.983 | 0.983 |
| P7 | 0.005 | 0.966 | 0.984 | 0.006 | 0.954 | 0.983 |
| O1 | -0.019 | 0.858 | 0.982 | -0.085 | 0.430 | 0.983 |
| Oz | -0.031 | 0.774 | 0.977 | -0.090 | 0.399 | 0.983 |
| O2 | -0.084 | 0.434 | 0.941 | 0.015 | 0.886 | 0.983 |
| P4 | 0.046 | 0.670 | 0.977 | 0.013 | 0.906 | 0.983 |
| P8 | 0.004 | 0.969 | 0.984 | 0.005 | 0.966 | 0.983 |
| TP10 | -0.022 | 0.837 | 0.977 | -0.040 | 0.706 | 0.983 |
| CP6 | 0.048 | 0.652 | 0.977 | 0.159 | 0.137 | 0.983 |
| CP2 | 0.035 | 0.741 | 0.977 | 0.071 | 0.509 | 0.983 |
| Cz | 0.129 | 0.228 | 0.873 | 0.098 | 0.358 | 0.983 |
| C4 | 0.025 | 0.814 | 0.977 | 0.066 | 0.538 | 0.983 |
| T8 | 0.125 | 0.244 | 0.873 | 0.079 | 0.461 | 0.983 |
| FT10 | 0.134 | 0.211 | 0.873 | 0.041 | 0.706 | 0.983 |
| FC6 | 0.049 | 0.650 | 0.977 | -0.144 | 0.177 | 0.983 |
| FC2 | 0.144 | 0.178 | 0.873 | -0.047 | 0.663 | 0.983 |
| F4 | 0.209 | 0.050 | 0.582 | 0.009 | 0.930 | 0.983 |
| F8 | 0.023 | 0.828 | 0.977 | -0.002 | 0.983 | 0.983 |
| Fp2 | 0.097 | 0.366 | 0.941 | 0.107 | 0.318 | 0.983 |
| AF7 | 0.016 | 0.885 | 0.984 | 0.150 | 0.160 | 0.983 |
| AF3 | 0.007 | 0.947 | 0.984 | -0.026 | 0.811 | 0.983 |
| AFz | 0.126 | 0.238 | 0.873 | 0.097 | 0.363 | 0.983 |
| F1 | -0.108 | 0.314 | 0.941 | 0.029 | 0.786 | 0.983 |
| F5 | 0.214 | 0.044 | 0.582 | 0.056 | 0.604 | 0.983 |
| FT7 | 0.007 | 0.946 | 0.984 | 0.137 | 0.199 | 0.983 |
| FC3 | 0.213 | 0.045 | 0.582 | 0.019 | 0.857 | 0.983 |
| C1 | 0.154 | 0.148 | 0.873 | 0.124 | 0.245 | 0.983 |
| C5 | 0.120 | 0.263 | 0.873 | 0.066 | 0.537 | 0.983 |
| TP7 | -0.082 | 0.443 | 0.941 | 0.057 | 0.597 | 0.983 |
| CP3 | 0.044 | 0.684 | 0.977 | 0.015 | 0.892 | 0.983 |
| P1 | 0.056 | 0.604 | 0.977 | -0.025 | 0.818 | 0.983 |
| P5 | 0.030 | 0.777 | 0.977 | -0.009 | 0.931 | 0.983 |
| PO7 | -0.007 | 0.945 | 0.984 | -0.040 | 0.707 | 0.983 |
| PO3 | -0.046 | 0.666 | 0.977 | -0.048 | 0.654 | 0.983 |
| POz | -0.037 | 0.732 | 0.977 | -0.111 | 0.301 | 0.983 |
| PO4 | -0.031 | 0.772 | 0.977 | -0.020 | 0.856 | 0.983 |
| PO8 | -0.083 | 0.440 | 0.941 | 0.006 | 0.957 | 0.983 |
| P6 | -0.011 | 0.917 | 0.984 | 0.022 | 0.836 | 0.983 |
| P2 | 0.029 | 0.787 | 0.977 | -0.009 | 0.932 | 0.983 |
| CPz | 0.109 | 0.307 | 0.941 | 0.060 | 0.578 | 0.983 |
| CP4 | 0.060 | 0.575 | 0.977 | 0.109 | 0.307 | 0.983 |
| TP8 | 0.074 | 0.491 | 0.966 | 0.041 | 0.700 | 0.983 |
| C6 | 0.068 | 0.525 | 0.977 | 0.066 | 0.535 | 0.983 |
| C2 | 0.120 | 0.261 | 0.873 | 0.058 | 0.589 | 0.983 |
| FC4 | 0.076 | 0.479 | 0.966 | -0.097 | 0.364 | 0.983 |
| FT8 | 0.126 | 0.238 | 0.873 | 0.017 | 0.873 | 0.983 |
| F6 | 0.088 | 0.414 | 0.941 | -0.043 | 0.686 | 0.983 |
| AF8 | 0.044 | 0.679 | 0.977 | 0.041 | 0.705 | 0.983 |
| AF4 | 0.197 | 0.065 | 0.582 | 0.047 | 0.659 | 0.983 |
| F2 | 0.166 | 0.119 | 0.873 | 0.006 | 0.956 | 0.983 |

**Table A3.6. Model statistics of the multiple regressions with channel-wise ITPC difference(active-passive) at 3 and 6 Hz, age and diagnosis as predictors of speech-in-speech perception abilities.**

| | 3 Hz | | | | 6 Hz | | | |
|---|---|---|---|---|---|---|---|---|
| **Channel** | **$R^2$** | **F(3,83)** | **p** | **FDR-corrected p** | **$R^2$** | **F(3,83)** | **p** | **FDR-corrected p** |
| Fp1 | 0.246 | 9.003 | <0.001 | <0.001 | 0.246 | 9.047 | <0.001 | <0.001 |
| Fz | 0.247 | 9.085 | <0.001 | <0.001 | 0.256 | 9.524 | <0.001 | <0.001 |
| F3 | 0.249 | 9.182 | <0.001 | <0.001 | 0.245 | 8.995 | <0.001 | <0.001 |
| F7 | 0.252 | 9.322 | <0.001 | <0.001 | 0.269 | 10.174 | <0.001 | <0.001 |
| FT9 | 0.257 | 9.556 | <0.001 | <0.001 | 0.257 | 9.545 | <0.001 | <0.001 |
| FC5 | 0.254 | 9.402 | <0.001 | <0.001 | 0.251 | 9.276 | <0.001 | <0.001 |
| FC1 | 0.248 | 9.104 | <0.001 | <0.001 | 0.245 | 8.994 | <0.001 | <0.001 |
| C3 | 0.257 | 9.555 | <0.001 | <0.001 | 0.245 | 8.995 | <0.001 | <0.001 |
| T7 | 0.255 | 9.457 | <0.001 | <0.001 | 0.250 | 9.233 | <0.001 | <0.001 |
| TP9 | 0.250 | 9.210 | <0.001 | <0.001 | 0.294 | 11.495 | <0.001 | <0.001 |
| CP5 | 0.252 | 9.319 | <0.001 | <0.001 | 0.267 | 10.055 | <0.001 | <0.001 |
| CP1 | 0.246 | 9.036 | <0.001 | <0.001 | 0.255 | 9.452 | <0.001 | <0.001 |
| Pz | 0.246 | 9.006 | <0.001 | <0.001 | 0.246 | 9.008 | <0.001 | <0.001 |
| P3 | 0.246 | 9.004 | <0.001 | <0.001 | 0.249 | 9.172 | <0.001 | <0.001 |
| P7 | 0.274 | 10.416 | <0.001 | <0.001 | 0.260 | 9.743 | <0.001 | <0.001 |
| O1 | 0.251 | 9.280 | <0.001 | <0.001 | 0.253 | 9.369 | <0.001 | <0.001 |
| Oz | 0.246 | 9.025 | <0.001 | <0.001 | 0.252 | 9.342 | <0.001 | <0.001 |
| O2 | 0.248 | 9.121 | <0.001 | <0.001 | 0.258 | 9.624 | <0.001 | <0.001 |
| P4 | 0.260 | 9.735 | <0.001 | <0.001 | 0.258 | 9.596 | <0.001 | <0.001 |
| P8 | 0.250 | 9.239 | <0.001 | <0.001 | 0.251 | 9.262 | <0.001 | <0.001 |
| TP10 | 0.246 | 9.036 | <0.001 | <0.001 | 0.268 | 10.140 | <0.001 | <0.001 |
| CP6 | 0.266 | 10.047 | <0.001 | <0.001 | 0.280 | 10.766 | <0.001 | <0.001 |
| CP2 | 0.260 | 9.712 | <0.001 | <0.001 | 0.250 | 9.220 | <0.001 | <0.001 |
| Cz | 0.246 | 9.010 | <0.001 | <0.001 | 0.245 | 8.996 | <0.001 | <0.001 |
| C4 | 0.255 | 9.475 | <0.001 | <0.001 | 0.259 | 9.683 | <0.001 | <0.001 |
| T8 | 0.247 | 9.078 | <0.001 | <0.001 | 0.268 | 10.114 | <0.001 | <0.001 |
| FT10 | 0.248 | 9.112 | <0.001 | <0.001 | 0.267 | 10.053 | <0.001 | <0.001 |
| FC6 | 0.277 | 10.604 | <0.001 | <0.001 | 0.246 | 9.027 | <0.001 | <0.001 |
| FC2 | 0.260 | 9.725 | <0.001 | <0.001 | 0.245 | 8.997 | <0.001 | <0.001 |
| F4 | 0.285 | 11.013 | <0.001 | <0.001 | 0.248 | 9.111 | <0.001 | <0.001 |
| F8 | 0.260 | 9.703 | <0.001 | <0.001 | 0.262 | 9.820 | <0.001 | <0.001 |
| Fp2 | 0.246 | 9.003 | <0.001 | <0.001 | 0.245 | 8.994 | <0.001 | <0.001 |
| AF7 | 0.247 | 9.071 | <0.001 | <0.001 | 0.264 | 9.905 | <0.001 | <0.001 |
| AF3 | 0.245 | 9.000 | <0.001 | <0.001 | 0.251 | 9.290 | <0.001 | <0.001 |
| AFz | 0.248 | 9.147 | <0.001 | <0.001 | 0.276 | 10.554 | <0.001 | <0.001 |
| F1 | 0.246 | 9.006 | <0.001 | <0.001 | 0.245 | 8.997 | <0.001 | <0.001 |
| F5 | 0.251 | 9.295 | <0.001 | <0.001 | 0.247 | 9.094 | <0.001 | <0.001 |
| FT7 | 0.250 | 9.208 | <0.001 | <0.001 | 0.258 | 9.627 | <0.001 | <0.001 |
| FC3 | 0.248 | 9.128 | <0.001 | <0.001 | 0.246 | 9.040 | <0.001 | <0.001 |
| C1 | 0.246 | 9.015 | <0.001 | <0.001 | 0.256 | 9.541 | <0.001 | <0.001 |
| C5 | 0.260 | 9.714 | <0.001 | <0.001 | 0.246 | 9.013 | <0.001 | <0.001 |
| TP7 | 0.259 | 9.695 | <0.001 | <0.001 | 0.275 | 10.511 | <0.001 | <0.001 |
| CP3 | 0.245 | 8.994 | <0.001 | <0.001 | 0.259 | 9.679 | <0.001 | <0.001 |
| P1 | 0.246 | 9.020 | <0.001 | <0.001 | 0.250 | 9.221 | <0.001 | <0.001 |
| P5 | 0.269 | 10.169 | <0.001 | <0.001 | 0.254 | 9.397 | <0.001 | <0.001 |
| PO7 | 0.268 | 10.145 | <0.001 | <0.001 | 0.259 | 9.687 | <0.001 | <0.001 |
| PO3 | 0.250 | 9.243 | <0.001 | <0.001 | 0.253 | 9.356 | <0.001 | <0.001 |
| POz | 0.245 | 8.997 | <0.001 | <0.001 | 0.248 | 9.146 | <0.001 | <0.001 |
| PO4 | 0.248 | 9.140 | <0.001 | <0.001 | 0.254 | 9.401 | <0.001 | <0.001 |
| PO8 | 0.246 | 9.028 | <0.001 | <0.001 | 0.252 | 9.308 | <0.001 | <0.001 |
| P6 | 0.263 | 9.880 | <0.001 | <0.001 | 0.253 | 9.393 | <0.001 | <0.001 |
| P2 | 0.259 | 9.660 | <0.001 | <0.001 | 0.250 | 9.222 | <0.001 | <0.001 |
| CPz | 0.254 | 9.409 | <0.001 | <0.001 | 0.250 | 9.208 | <0.001 | <0.001 |
| CP4 | 0.276 | 10.541 | <0.001 | <0.001 | 0.258 | 9.610 | <0.001 | <0.001 |
| TP8 | 0.250 | 9.205 | <0.001 | <0.001 | 0.269 | 10.187 | <0.001 | <0.001 |
| C6 | 0.279 | 10.684 | <0.001 | <0.001 | 0.319 | 12.948 | <0.001 | <0.001 |
| C2 | 0.259 | 9.652 | <0.001 | <0.001 | 0.245 | 8.999 | <0.001 | <0.001 |
| FC4 | 0.260 | 9.743 | <0.001 | <0.001 | 0.247 | 9.081 | <0.001 | <0.001 |
| FT8 | 0.248 | 9.133 | <0.001 | <0.001 | 0.268 | 10.134 | <0.001 | <0.001 |
| F6 | 0.262 | 9.827 | <0.001 | <0.001 | 0.245 | 8.999 | <0.001 | <0.001 |
| AF8 | 0.253 | 9.394 | <0.001 | <0.001 | 0.277 | 10.623 | <0.001 | <0.001 |
| AF4 | 0.253 | 9.360 | <0.001 | <0.001 | 0.247 | 9.099 | <0.001 | <0.001 |
| F2 | 0.256 | 9.543 | <0.001 | <0.001 | 0.254 | 9.403 | <0.001 | <0.001 |

### Table A3.7. Coefficients statistics of the multiple regressions with channel-wise ITPC difference (active-passive) at 3 and 6 Hz, age and diagnosis as predictors of speech-in-speech perception abilities.

| | | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|---|
| **Channel** | **Predictor** | **β** | **p** | **FDR-corrected p** | **β** | **p** | **FDR-corrected p** |
| **Fp1** | **ITPC** | 0.014 | 0.886 | 0.933 | -0.033 | 0.730 | 0.920 |
| | **Age** | **0.446** | **<0.001** | **<0.001** | **0.448** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.215** | **0.027** | **0.041** | **-0.218** | **0.025** | **0.041** |
| **Fz** | **ITPC** | 0.043 | 0.652 | 0.889 | 0.105 | 0.276 | 0.670 |
| | **Age** | **0.442** | **<0.001** | **<0.001** | **0.433** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.214** | **0.027** | **0.041** | **-0.210** | **0.030** | **0.041** |
| **F3** | **ITPC** | 0.064 | 0.516 | 0.856 | 0.003 | 0.975 | 0.983 |
| | **Age** | **0.434** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.205** | **0.037** | **0.042** | **-0.215** | **0.027** | **0.041** |
| **F7** | **ITPC** | -0.083 | 0.392 | 0.826 | -0.157 | 0.106 | 0.607 |
| | **Age** | **0.444** | **<0.001** | **<0.001** | **0.467** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.227** | **0.020** | **0.041** | **-0.241** | **0.013** | **0.041** |
| **FT9** | **ITPC** | -0.107 | 0.263 | 0.768 | -0.108 | 0.267 | 0.670 |
| | **Age** | **0.451** | **<0.001** | **<0.001** | **0.457** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.211** | **0.028** | **0.041** | **-0.236** | **0.016** | **0.041** |
| **FC5** | **ITPC** | -0.094 | 0.339 | 0.803 | 0.076 | 0.426 | 0.715 |
| | **Age** | **0.457** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.236** | **0.017** | **0.041** | **-0.211** | **0.029** | **0.041** |
| **FC1** | **ITPC** | 0.048 | 0.620 | 0.868 | -0.002 | 0.983 | 0.983 |
| | **Age** | **0.445** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.207** | **0.035** | **0.041** | **-0.215** | **0.027** | **0.041** |
| **C3** | **ITPC** | -0.111 | 0.263 | 0.768 | -0.003 | 0.974 | 0.983 |
| | **Age** | **0.463** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.240** | **0.016** | **0.041** | **-0.215** | **0.027** | **0.041** |
| **T7** | **ITPC** | -0.098 | 0.309 | 0.803 | -0.070 | 0.464 | 0.715 |
| | **Age** | **0.452** | **<0.001** | **<0.001** | **0.453** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.205** | **0.034** | **0.041** | **-0.221** | **0.023** | **0.041** |
| **TP9** | **ITPC** | -0.067 | 0.487 | 0.837 | -0.220 | 0.020 | 0.607 |
| | **Age** | **0.448** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.210** | **0.030** | **0.041** | **-0.222** | **0.018** | **0.041** |
| **CP5** | **ITPC** | -0.082 | 0.393 | 0.826 | -0.147 | 0.125 | 0.607 |
| | **Age** | **0.450** | **<0.001** | **<0.001** | **0.448** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.219** | **0.024** | **0.041** | **-0.198** | **0.040** | **0.041** |
| **CP1** | **ITPC** | 0.029 | 0.760 | 0.933 | -0.097 | 0.312 | 0.700 |
| | **Age** | **0.444** | **<0.001** | **<0.001** | **0.451** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.215** | **0.027** | **0.041** | **-0.206** | **0.033** | **0.041** |
| **Pz** | **ITPC** | 0.016 | 0.871 | 0.933 | -0.017 | 0.861 | 0.983 |
| | **Age** | **0.447** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.216** | **0.026** | **0.041** | **-0.213** | **0.029** | **0.041** |
| **P3** | **ITPC** | -0.014 | 0.883 | 0.933 | -0.061 | 0.528 | 0.756 |
| | **Age** | **0.445** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.215** | **0.027** | **0.041** | **-0.209** | **0.032** | **0.041** |
| **P7** | **ITPC** | -0.168 | 0.076 | 0.748 | -0.124 | 0.197 | 0.670 |
| | **Age** | **0.441** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.204** | **0.033** | **0.041** | **-0.201** | **0.037** | **0.041** |
| **O1** | **ITPC** | -0.076 | 0.423 | 0.833 | -0.089 | 0.359 | 0.700 |
| | **Age** | **0.447** | **<0.001** | **<0.001** | **0.450** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.214** | **0.027** | **0.041** | **-0.201** | **0.039** | **0.041** |
| **Oz** | **ITPC** | -0.025 | 0.794 | 0.933 | -0.086 | 0.378 | 0.700 |
| | **Age** | **0.446** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.215** | **0.027** | **0.041** | **-0.199** | **0.043** | **0.043** |
| **O2** | **ITPC** | 0.051 | 0.593 | 0.868 | -0.114 | 0.236 | 0.670 |
| | **Age** | **0.445** | **<0.001** | **<0.001** | **0.452** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.216** | **0.026** | **0.041** | **-0.203** | **0.036** | **0.041** |
| **P4** | **ITPC** | 0.123 | 0.199 | 0.748 | -0.111 | 0.247 | 0.670 |
| | **Age** | **0.457** | **<0.001** | **<0.001** | **0.456** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.206** | **0.032** | **0.041** | **-0.205** | **0.033** | **0.041** |
| **P8** | **ITPC** | 0.071 | 0.458 | 0.837 | -0.074 | 0.439 | 0.715 |
| | **Age** | **0.447** | **<0.001** | **<0.001** | **0.449** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.212** | **0.028** | **0.041** | **-0.209** | **0.031** | **0.041** |
| **TP10** | **ITPC** | -0.029 | 0.759 | 0.933 | -0.151 | 0.111 | 0.607 |
| | **Age** | **0.446** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.216** | **0.026** | **0.041** | **-0.206** | **0.031** | **0.041** |
| **CP6** | **ITPC** | 0.146 | 0.126 | 0.748 | -0.187 | 0.048 | 0.607 |
| | **Age** | **0.461** | **<0.001** | **<0.001** | **0.452** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.205** | **0.032** | **0.041** | **-0.232** | **0.015** | **0.041** |
| **CP2** | **ITPC** | 0.121 | 0.206 | 0.748 | -0.069 | 0.477 | 0.715 |
| | **Age** | **0.450** | **<0.001** | **<0.001** | **0.460** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.210** | **0.029** | **0.041** | **-0.213** | **0.028** | **0.041** |
| **Cz** | **ITPC** | -0.018 | 0.851 | 0.933 | -0.005 | 0.956 | 0.983 |
| | **Age** | **0.446** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | **Diagnosis** | **-0.218** | **0.026** | **0.041** | **-0.215** | **0.027** | **0.041** |
| **C4** | **ITPC** | 0.099 | 0.300 | 0.803 | -0.119 | 0.215 | 0.670 |
| | **Age** | **0.442** | **<0.001** | **<0.001** | **0.454** | **<0.001** | **<0.001** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Diagnosis | **-0.205** | **0.034** | **0.041** | **-0.231** | **0.017** | **0.041** |
| T8 | ITPC | 0.042 | 0.663 | 0.889 | -0.150 | 0.115 | 0.607 |
| | Age | **0.448** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.209** | **0.032** | **0.041** | **-0.232** | **0.016** | **0.041** |
| FT10 | ITPC | 0.049 | 0.607 | 0.868 | -0.146 | 0.125 | 0.607 |
| | Age | **0.447** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.210** | **0.031** | **0.041** | **-0.230** | **0.017** | **0.041** |
| FC6 | ITPC | 0.179 | 0.060 | 0.748 | -0.026 | 0.786 | 0.952 |
| | Age | **0.452** | **<0.001** | **<0.001** | **0.444** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.198** | **0.038** | **0.042** | **-0.215** | **0.027** | **0.041** |
| FC2 | ITPC | 0.127 | 0.202 | 0.748 | -0.007 | 0.938 | 0.983 |
| | Age | **0.427** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.185** | **0.061** | **0.062** | **-0.215** | **0.027** | **0.041** |
| F4 | ITPC | 0.206 | 0.035 | 0.748 | 0.049 | 0.609 | 0.833 |
| | Age | **0.415** | **<0.001** | **<0.001** | **0.438** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.169** | **0.079** | **0.079** | **-0.214** | **0.027** | **0.041** |
| F8 | ITPC | 0.120 | 0.209 | 0.748 | -0.129 | 0.175 | 0.670 |
| | Age | **0.442** | **<0.001** | **<0.001** | **0.440** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.213** | **0.027** | **0.041** | **-0.217** | **0.024** | **0.041** |
| Fp2 | ITPC | -0.014 | 0.889 | 0.933 | -0.002 | 0.981 | 0.983 |
| | Age | **0.447** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.217** | **0.027** | **0.041** | **-0.215** | **0.027** | **0.041** |
| AF7 | ITPC | -0.040 | 0.678 | 0.890 | -0.139 | 0.155 | 0.670 |
| | Age | **0.442** | **<0.001** | **<0.001** | **0.467** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.221** | **0.024** | **0.041** | **-0.238** | **0.015** | **0.041** |
| AF3 | ITPC | -0.011 | 0.908 | 0.937 | 0.079 | 0.415 | 0.715 |
| | Age | **0.447** | **<0.001** | **<0.001** | **0.432** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.216** | **0.026** | **0.041** | **-0.212** | **0.029** | **0.041** |
| AFz | ITPC | 0.056 | 0.559 | 0.868 | 0.177 | 0.064 | 0.607 |
| | Age | **0.444** | **<0.001** | **<0.001** | **0.438** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.208** | **0.033** | **0.041** | **-0.194** | **0.043** | **0.043** |
| F1 | ITPC | 0.016 | 0.869 | 0.933 | -0.007 | 0.941 | 0.983 |
| | Age | **0.442** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.216** | **0.026** | **0.041** | **-0.216** | **0.027** | **0.041** |
| F5 | ITPC | -0.080 | 0.412 | 0.833 | -0.046 | 0.635 | 0.833 |
| | Age | **0.453** | **<0.001** | **<0.001** | **0.448** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.232** | **0.019** | **0.041** | **-0.220** | **0.024** | **0.041** |
| FT7 | ITPC | -0.066 | 0.489 | 0.837 | -0.116 | 0.235 | 0.670 |
| | Age | **0.451** | **<0.001** | **<0.001** | **0.463** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.218** | **0.024** | **0.041** | **-0.231** | **0.018** | **0.041** |
| FC3 | ITPC | -0.054 | 0.583 | 0.868 | 0.031 | 0.749 | 0.925 |
| | Age | **0.453** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.224** | **0.023** | **0.041** | **-0.216** | **0.026** | **0.041** |
| C1 | ITPC | -0.021 | 0.830 | 0.933 | -0.106 | 0.269 | 0.670 |
| | Age | **0.450** | **<0.001** | **<0.001** | **0.458** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.219** | **0.026** | **0.041** | **-0.212** | **0.028** | **0.041** |
| C5 | ITPC | -0.121 | 0.205 | 0.748 | 0.020 | 0.838 | 0.983 |
| | Age | **0.446** | **<0.001** | **<0.001** | **0.448** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.226** | **0.019** | **0.041** | **-0.215** | **0.027** | **0.041** |
| TP7 | ITPC | -0.119 | 0.211 | 0.748 | -0.174 | 0.067 | 0.607 |
| | Age | **0.448** | **<0.001** | **<0.001** | **0.455** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.205** | **0.033** | **0.041** | **-0.210** | **0.027** | **0.041** |
| CP3 | ITPC | 0.001 | 0.989 | 0.989 | -0.119 | 0.217 | 0.670 |
| | Age | **0.446** | **<0.001** | **<0.001** | **0.442** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.215** | **0.027** | **0.041** | **-0.200** | **0.039** | **0.041** |
| P1 | ITPC | 0.023 | 0.810 | 0.933 | -0.069 | 0.476 | 0.715 |
| | Age | **0.447** | **<0.001** | **<0.001** | **0.449** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.215** | **0.027** | **0.041** | **-0.208** | **0.033** | **0.041** |
| P5 | ITPC | -0.153 | 0.107 | 0.748 | -0.091 | 0.342 | 0.700 |
| | Age | **0.444** | **<0.001** | **<0.001** | **0.444** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.213** | **0.026** | **0.041** | **-0.204** | **0.035** | **0.041** |
| PO7 | ITPC | -0.152 | 0.110 | 0.748 | -0.119 | 0.214 | 0.670 |
| | Age | **0.443** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.210** | **0.028** | **0.041** | **-0.200** | **0.039** | **0.041** |
| PO3 | ITPC | -0.071 | 0.455 | 0.837 | -0.087 | 0.368 | 0.700 |
| | Age | **0.445** | **<0.001** | **<0.001** | **0.446** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.214** | **0.027** | **0.041** | **-0.203** | **0.037** | **0.041** |
| POz | ITPC | -0.008 | 0.934 | 0.949 | -0.057 | 0.560 | 0.783 |
| | Age | **0.445** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.215** | **0.027** | **0.041** | **-0.204** | **0.038** | **0.041** |
| PO4 | ITPC | 0.055 | 0.567 | 0.868 | -0.092 | 0.340 | 0.700 |
| | Age | **0.452** | **<0.001** | **<0.001** | **0.452** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.214** | **0.027** | **0.041** | **-0.204** | **0.036** | **0.041** |
| PO8 | ITPC | 0.026 | 0.783 | 0.933 | -0.081 | 0.402 | 0.715 |
| | Age | **0.446** | **<0.001** | **<0.001** | **0.450** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.215** | **0.027** | **0.041** | **-0.206** | **0.034** | **0.041** |
| P6 | ITPC | 0.134 | 0.160 | 0.748 | -0.090 | 0.345 | 0.700 |
| | Age | **0.451** | **<0.001** | **<0.001** | **0.449** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.208** | **0.030** | **0.041** | **-0.208** | **0.031** | **0.041** |
| P2 | ITPC | 0.117 | 0.223 | 0.748 | -0.069 | 0.475 | 0.715 |
| | Age | **0.458** | **<0.001** | **<0.001** | **0.452** | **<0.001** | **<0.001** |
| | Diagnosis | **-0.212** | **0.027** | **0.041** | **-0.209** | **0.031** | **0.041** |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| **CPz** | **ITPC** | 0.093 | 0.336 | 0.803 | -0.067 | 0.489 | 0.716 |
|  | **Age** | **0.437** | **<0.001** | **<0.001** | **0.455** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.206** | **0.034** | **0.041** | **-0.211** | **0.029** | **0.041** |
| **CP4** | **ITPC** | 0.176 | 0.065 | 0.748 | -0.112 | 0.241 | 0.670 |
|  | **Age** | **0.458** | **<0.001** | **<0.001** | **0.457** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.199** | **0.037** | **0.042** | **-0.221** | **0.022** | **0.041** |
| **TP8** | **ITPC** | 0.066 | 0.491 | 0.837 | -0.154 | 0.104 | 0.607 |
|  | **Age** | **0.445** | **<0.001** | **<0.001** | **0.449** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.212** | **0.029** | **0.041** | **-0.222** | **0.020** | **0.041** |
| **C6** | **ITPC** | 0.184 | 0.054 | 0.748 | -0.275 | 0.004 | 0.230 |
|  | **Age** | **0.466** | **<0.001** | **<0.001** | **0.443** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.201** | **0.035** | **0.041** | **-0.260** | **0.006** | **0.041** |
| **C2** | **ITPC** | 0.117 | 0.226 | 0.748 | -0.010 | 0.919 | 0.983 |
|  | **Age** | **0.451** | **<0.001** | **<0.001** | **0.447** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.195** | **0.045** | **0.047** | **-0.216** | **0.027** | **0.041** |
| **FC4** | **ITPC** | 0.123 | 0.197 | 0.748 | 0.042 | 0.659 | 0.847 |
|  | **Age** | **0.436** | **<0.001** | **<0.001** | **0.442** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.209** | **0.030** | **0.041** | **-0.217** | **0.025** | **0.041** |
| **FT8** | **ITPC** | 0.054 | 0.576 | 0.868 | -0.152 | 0.112 | 0.607 |
|  | **Age** | **0.449** | **<0.001** | **<0.001** | **0.442** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.207** | **0.035** | **0.041** | **-0.233** | **0.016** | **0.041** |
| **F6** | **ITPC** | 0.131 | 0.173 | 0.748 | 0.009 | 0.921 | 0.983 |
|  | **Age** | **0.432** | **<0.001** | **<0.001** | **0.445** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.199** | **0.039** | **0.042** | **-0.216** | **0.026** | **0.041** |
| **AF8** | **ITPC** | 0.091 | 0.344 | 0.803 | -0.180 | 0.058 | 0.607 |
|  | **Age** | **0.441** | **<0.001** | **<0.001** | **0.433** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.206** | **0.033** | **0.041** | **-0.230** | **0.016** | **0.041** |
| **AF4** | **ITPC** | 0.090 | 0.365 | 0.822 | 0.046 | 0.627 | 0.833 |
|  | **Age** | **0.427** | **<0.001** | **<0.001** | **0.444** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.197** | **0.046** | **0.047** | **-0.213** | **0.028** | **0.041** |
| **F2** | **ITPC** | 0.108 | 0.268 | 0.768 | 0.092 | 0.339 | 0.700 |
|  | **Age** | **0.431** | **<0.001** | **<0.001** | **0.431** | **<0.001** | **<0.001** |
|  | **Diagnosis** | **-0.196** | **0.044** | **0.047** | **-0.212** | **0.028** | **0.041** |

## B. Supplementary analyses

According to the temporal sampling theory (Goswami, 2011), impaired auditory entrainment at lower frequencies (< 10 Hz) in individuals with dyslexia would cause difficulties in encoding the prosodic and syllabic structure of speech, and in turn, reading impairments (Goswami, 2011; Power, Mead, Barnes, & Goswami, 2013; Soltész, Szucs, Leong, White, & Goswami, 2013). To exclude the possibility that the results of analyses investigating the influence of dyslexia diagnosis on neural correlates of sustained selective attention (i.e. group comparison of ITPC difference at 3 Hz and 6 Hz between active and passive conditions) were cofounded by group differences in the more general ability to entrain neural activity to sounds at low frequencies, we compared ITPC at 3 Hz and 6 Hz, averaged across conditions (attend high band, attend low band and passive listening) between dyslexic and typical readers. We did not observe any significant difference between groups in either averaged ITPC at 3 Hz (**Figure A3.1A; Table A3.8**) or at 6 Hz (**Figure A3.1B; Table A3.8**). Thus, these results do not provide support for the hypothesis of impaired auditory phase-locking mechanisms in dyslexic readers (Goswami, 2011).

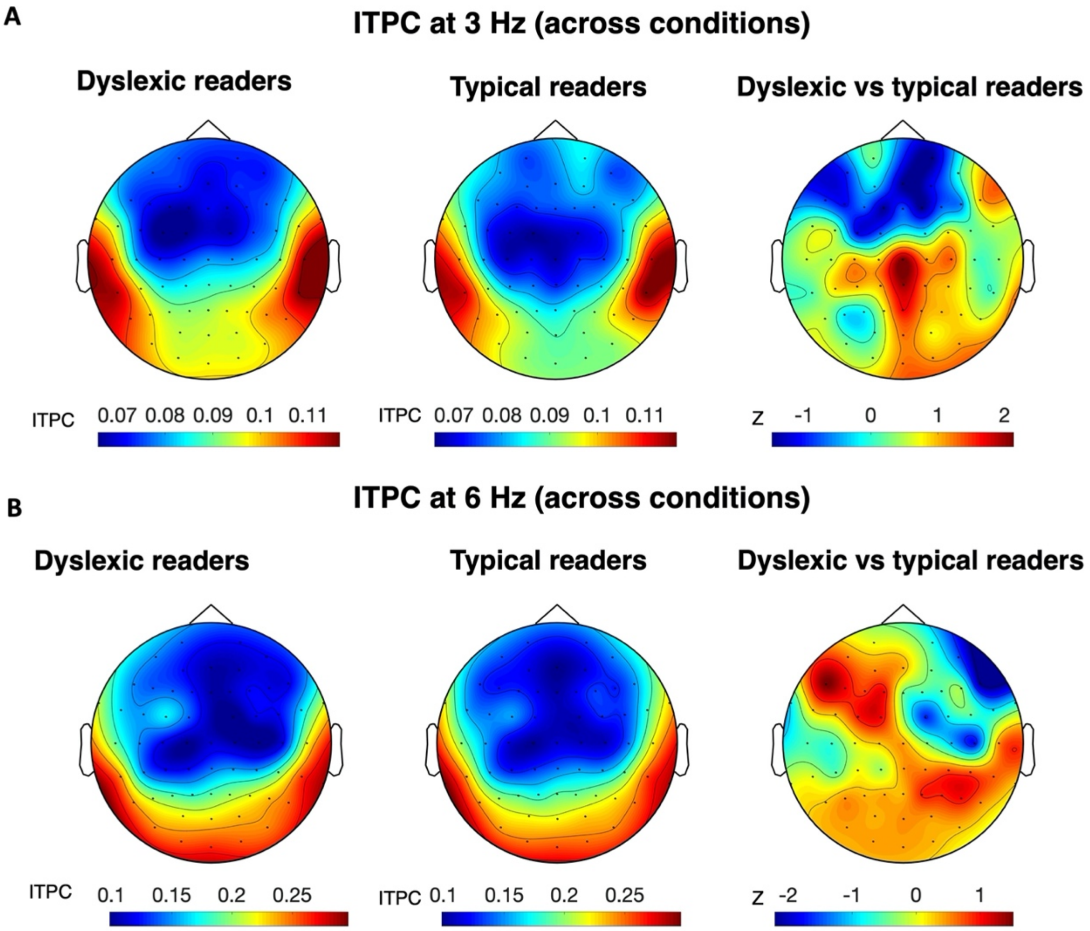

**Figure A3.1 A) ITPC at 3 Hz and B) at 6 Hz (averaged across conditions) for the group of children with and without dyslexia and the z values of the pairwise comparisons. No significant group differences were found at any channels after FDR-correction was applied.**

**Table A3.8. Channel-wise group comparisons (dyslexic versus typical readers) of ITPC values across conditions (attend high, attend low, passive listening) at 3 Hz and 6 Hz.**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **Z** | **p** | **FDR-corrected p** | **Z** | **p** | **FDR-corrected p** |
| Fp1 | 0.245 | 0.807 | 0.946 | 0.012 | 0.990 | 0.990 |
| Fz | -0.767 | 0.443 | 0.850 | -0.411 | 0.681 | 0.863 |
| F3 | -0.684 | 0.494 | 0.850 | 0.809 | 0.419 | 0.863 |
| F7 | -0.883 | 0.377 | 0.830 | 1.514 | 0.130 | 0.863 |
| FT9 | -0.253 | 0.800 | 0.946 | -0.917 | 0.359 | 0.863 |
| FC5 | 0.435 | 0.663 | 0.870 | 0.328 | 0.743 | 0.863 |
| FC1 | -0.676 | 0.499 | 0.850 | 1.049 | 0.294 | 0.863 |
| C3 | 1.016 | 0.310 | 0.830 | 0.037 | 0.970 | 0.990 |
| T7 | 0.535 | 0.593 | 0.870 | -0.576 | 0.564 | 0.863 |
| TP9 | 0.071 | 0.944 | 0.959 | -0.029 | 0.977 | 0.990 |
| CP5 | 0.875 | 0.382 | 0.830 | -0.527 | 0.598 | 0.863 |
| CP1 | 1.049 | 0.294 | 0.830 | -0.245 | 0.807 | 0.876 |
| Pz | 1.671 | 0.095 | 0.830 | 0.353 | 0.724 | 0.863 |
| P3 | -0.145 | 0.885 | 0.956 | 0.353 | 0.724 | 0.863 |
| P7 | 0.485 | 0.628 | 0.870 | 0.286 | 0.775 | 0.863 |
| O1 | 0.452 | 0.651 | 0.870 | 0.435 | 0.663 | 0.863 |
| Oz | 1.248 | 0.212 | 0.830 | 0.435 | 0.663 | 0.863 |
| O2 | 1.091 | 0.275 | 0.830 | 0.361 | 0.718 | 0.863 |
| P4 | 0.983 | 0.326 | 0.830 | 0.900 | 0.368 | 0.863 |
| P8 | 0.610 | 0.542 | 0.870 | 0.543 | 0.587 | 0.863 |
| TP10 | 1.323 | 0.186 | 0.830 | 0.286 | 0.775 | 0.863 |
| CP6 | 0.502 | 0.616 | 0.870 | 0.709 | 0.478 | 0.863 |
| CP2 | 1.190 | 0.234 | 0.830 | 0.527 | 0.598 | 0.863 |
| Cz | 2.128 | 0.033 | 0.830 | 0.435 | 0.663 | 0.863 |
| C4 | 1.331 | 0.183 | 0.830 | -1.074 | 0.283 | 0.863 |
| T8 | 0.344 | 0.731 | 0.939 | 0.502 | 0.616 | 0.863 |
| FT10 | 0.518 | 0.604 | 0.870 | -0.792 | 0.428 | 0.863 |
| FC6 | 0.220 | 0.826 | 0.946 | -0.518 | 0.604 | 0.863 |
| FC2 | -0.153 | 0.878 | 0.956 | -1.622 | 0.105 | 0.863 |
| F4 | -0.726 | 0.468 | 0.850 | -0.576 | 0.564 | 0.863 |
| F8 | 0.991 | 0.322 | 0.830 | -2.210 | 0.027 | 0.863 |
| Fp2 | -1.481 | 0.139 | 0.830 | -0.742 | 0.458 | 0.863 |
| AF7 | -0.917 | 0.359 | 0.830 | 0.568 | 0.570 | 0.863 |
| AF3 | -0.294 | 0.768 | 0.946 | 0.552 | 0.581 | 0.863 |
| AFz | -1.464 | 0.143 | 0.830 | 0.394 | 0.694 | 0.863 |
| F1 | -1.414 | 0.157 | 0.830 | 1.033 | 0.302 | 0.863 |
| F5 | -1.066 | 0.286 | 0.830 | 1.074 | 0.283 | 0.863 |
| FT7 | 0.460 | 0.645 | 0.870 | 0.278 | 0.781 | 0.863 |
| FC3 | -1.116 | 0.265 | 0.830 | 0.950 | 0.342 | 0.863 |
| C1 | 0.858 | 0.391 | 0.830 | 0.286 | 0.775 | 0.863 |
| C5 | 0.477 | 0.633 | 0.870 | -0.643 | 0.520 | 0.863 |
| TP7 | 0.129 | 0.898 | 0.956 | -0.037 | 0.970 | 0.990 |
| CP3 | 1.016 | 0.310 | 0.830 | 0.079 | 0.937 | 0.990 |
| P1 | 0.684 | 0.494 | 0.850 | 0.402 | 0.687 | 0.863 |
| P5 | -0.228 | 0.820 | 0.946 | 0.494 | 0.622 | 0.863 |
| PO7 | 0.294 | 0.768 | 0.946 | 0.435 | 0.663 | 0.863 |
| PO3 | 0.087 | 0.931 | 0.959 | 0.369 | 0.712 | 0.863 |
| POz | 1.257 | 0.209 | 0.830 | 0.494 | 0.622 | 0.863 |
| PO4 | 0.751 | 0.453 | 0.850 | 0.460 | 0.645 | 0.863 |
| PO8 | 1.074 | 0.283 | 0.830 | 0.344 | 0.731 | 0.863 |
| P6 | 0.850 | 0.395 | 0.830 | 1.016 | 0.310 | 0.863 |
| P2 | 1.157 | 0.247 | 0.830 | 0.917 | 0.359 | 0.863 |
| CPz | 2.003 | 0.045 | 0.830 | 0.485 | 0.628 | 0.863 |
| CP4 | 0.941 | 0.346 | 0.830 | 0.734 | 0.463 | 0.863 |
| TP8 | 0.112 | 0.911 | 0.956 | 0.693 | 0.489 | 0.863 |
| C6 | 0.170 | 0.865 | 0.956 | -1.729 | 0.084 | 0.863 |
| C2 | 1.091 | 0.275 | 0.830 | -0.386 | 0.700 | 0.863 |
| FC4 | 0.759 | 0.448 | 0.850 | -0.825 | 0.409 | 0.863 |
| FT8 | 0.535 | 0.593 | 0.870 | -0.925 | 0.355 | 0.863 |
| F6 | -0.593 | 0.553 | 0.870 | -0.336 | 0.737 | 0.863 |
| AF8 | -0.021 | 0.983 | 0.983 | -1.481 | 0.139 | 0.863 |
| AF4 | -1.099 | 0.272 | 0.830 | -0.452 | 0.651 | 0.863 |
| F2 | -1.472 | 0.141 | 0.830 | -0.568 | 0.570 | 0.863 |

## Appendix of Chapter 4

**A. List of words (left column) and pseudowords (right column) of the reading test within the artificial orthography. Note that the two lists were presently in separate paper sheets.**

## B. Translation of words and pseudowords

| Words | | Pseudowords |
|---|---|---|
| **Dutch** | **Translation** | |
| of | or | ot |
| fout | wrong | foun |
| zon | sun | zof |
| zei | said | teif |
| tot | until | fot |
| zout | salt | zoun |
| tent | tent | nent |
| zijn | are | zijf |
| ton | tons | fon |
| fijn | nice | nijf |
| net | not | fet |
| zou | would | oun |
| en | and | et |
| zet | move | tef |

## C. Supplementary analyses

As in section **4.4.3.** we saw a significant relationship between non-verbal selective sustained attention and artificial symbol-speech sound learning task accuracy and (pseudo)word reading, we also examined the correlation between these measures and neural correlates of non-verbal selective attention (ITPC difference between active and passive conditions at 3 Hz or at 6 Hz) with channel-wise Spearman correlation (see **Chapter 3** for a complete rationale of the channel-wise method). False Discovery Rate (FDR; Benjamini & Hochberg, 1995) correction was used to adjust for multiple comparisons.

In summary, we found a significant correlation between (pseudo)word reading within the artificial orthography and ITPC difference between active and passive conditions at 3 Hz in fronto-central channels (**Figure A4.1; Table A4.1**) but not at 6 Hz (**Table A4.1**). No significant correlations were found between the artificial symbol-speech sound learning task accuracy and the neural correlates of non-verbal selective attention (**Table A4.2**).

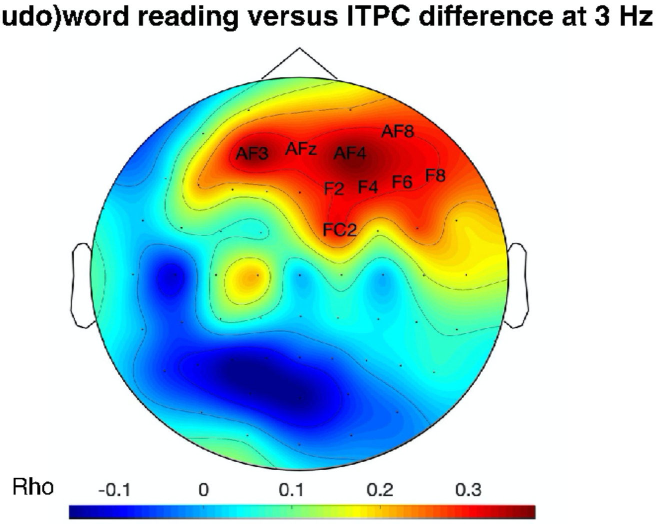

**Figure A4.1. Topographic plot displaying the rho values of the Spearman correlations between the sum of the number of words and pseudowords read correctly within the time limit and the ITPC difference between active and passive conditions at 3 Hz. The labelled channels are the ones remaining significant after FDR-correction was applied.**

**Table A4.1. Channel-wise correlations between ITPC (active-passive) at 3 and 6 Hz and (pseudo)word reading within the artificial orthography.**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **rho** | **p** | **FDR-corrected p** | **rho** | **p** | **FDR-corrected p** |
| Fp1 | 0.157 | 0.148 | 0.443 | 0.038 | 0.728 | 0.849 |
| Fz | 0.260 | 0.016 | 0.090 | -0.016 | 0.885 | 0.944 |
| F3 | 0.185 | 0.089 | 0.310 | 0.058 | 0.598 | 0.792 |
| F7 | 0.042 | 0.699 | 0.892 | -0.056 | 0.609 | 0.792 |
| FT9 | 0.041 | 0.708 | 0.892 | -0.055 | 0.616 | 0.792 |
| FC5 | 0.085 | 0.436 | 0.858 | 0.109 | 0.316 | 0.630 |
| FC1 | 0.058 | 0.596 | 0.892 | -0.040 | 0.711 | 0.845 |
| C3 | 0.104 | 0.342 | 0.735 | 0.216 | 0.046 | 0.414 |
| T7 | 0.015 | 0.892 | 0.962 | -0.106 | 0.330 | 0.630 |
| TP9 | 0.049 | 0.651 | 0.892 | -0.052 | 0.635 | 0.792 |
| CP5 | -0.053 | 0.627 | 0.892 | -0.023 | 0.832 | 0.936 |
| CP1 | 0.063 | 0.564 | 0.892 | -0.179 | 0.099 | 0.414 |
| Pz | -0.062 | 0.570 | 0.892 | -0.227 | 0.036 | 0.414 |
| P3 | -0.139 | 0.203 | 0.534 | -0.156 | 0.152 | 0.460 |
| P7 | -0.068 | 0.533 | 0.892 | -0.190 | 0.080 | 0.414 |
| O1 | 0.043 | 0.693 | 0.892 | -0.163 | 0.133 | 0.460 |
| Oz | -0.028 | 0.800 | 0.916 | -0.242 | 0.025 | 0.414 |
| O2 | -0.037 | 0.737 | 0.909 | -0.144 | 0.186 | 0.510 |
| P4 | 0.012 | 0.915 | 0.962 | -0.179 | 0.099 | 0.414 |
| P8 | 0.058 | 0.597 | 0.892 | -0.091 | 0.403 | 0.680 |
| TP10 | 0.050 | 0.646 | 0.892 | -0.158 | 0.147 | 0.460 |
| CP6 | 0.057 | 0.605 | 0.892 | -0.134 | 0.220 | 0.559 |
| CP2 | 0.056 | 0.609 | 0.892 | -0.084 | 0.443 | 0.698 |
| Cz | 0.007 | 0.947 | 0.975 | -0.088 | 0.421 | 0.680 |
| C4 | 0.006 | 0.959 | 0.975 | 0.080 | 0.466 | 0.700 |
| T8 | 0.173 | 0.112 | 0.371 | -0.089 | 0.415 | 0.680 |
| FT10 | 0.223 | 0.039 | 0.176 | -0.133 | 0.222 | 0.559 |
| FC6 | 0.275 | 0.010 | 0.066 | 0.021 | 0.848 | 0.937 |
| **FC2** | **0.301** | **0.005** | **0.036** | 0.191 | 0.078 | 0.414 |
| **F4** | **0.325** | **0.002** | **0.036** | 0.107 | 0.328 | 0.630 |
| **F8** | **0.299** | **0.005** | **0.036** | -0.088 | 0.418 | 0.680 |
| Fp2 | 0.229 | 0.034 | 0.176 | 0.059 | 0.592 | 0.792 |
| AF7 | 0.102 | 0.350 | 0.735 | -0.016 | 0.884 | 0.944 |
| **AF3** | **0.369** | **0.000** | **0.015** | -0.004 | 0.974 | 0.974 |
| **AFz** | **0.306** | **0.004** | **0.036** | 0.014 | 0.899 | 0.944 |
| F1 | 0.189 | 0.081 | 0.301 | -0.042 | 0.704 | 0.845 |
| F5 | 0.224 | 0.038 | 0.176 | -0.051 | 0.641 | 0.792 |
| FT7 | 0.018 | 0.872 | 0.962 | -0.080 | 0.462 | 0.700 |
| FC3 | 0.068 | 0.535 | 0.892 | 0.008 | 0.943 | 0.974 |
| C1 | 0.206 | 0.057 | 0.238 | 0.123 | 0.257 | 0.567 |
| C5 | -0.112 | 0.305 | 0.709 | 0.122 | 0.261 | 0.567 |
| TP7 | 0.003 | 0.982 | 0.982 | -0.125 | 0.250 | 0.567 |
| CP3 | 0.077 | 0.481 | 0.892 | -0.006 | 0.959 | 0.974 |
| P1 | -0.121 | 0.268 | 0.649 | -0.219 | 0.043 | 0.414 |
| P5 | -0.099 | 0.366 | 0.744 | -0.155 | 0.153 | 0.460 |
| PO7 | -0.011 | 0.917 | 0.962 | -0.189 | 0.082 | 0.414 |
| PO3 | -0.135 | 0.216 | 0.544 | -0.182 | 0.094 | 0.414 |
| POz | -0.152 | 0.162 | 0.464 | -0.226 | 0.037 | 0.414 |
| PO4 | -0.070 | 0.521 | 0.892 | -0.200 | 0.065 | 0.414 |
| PO8 | -0.032 | 0.769 | 0.909 | -0.106 | 0.330 | 0.630 |
| P6 | 0.031 | 0.779 | 0.909 | -0.144 | 0.185 | 0.510 |
| P2 | -0.043 | 0.695 | 0.892 | -0.200 | 0.065 | 0.414 |
| CPz | 0.020 | 0.853 | 0.960 | -0.161 | 0.139 | 0.460 |
| CP4 | 0.033 | 0.760 | 0.909 | -0.104 | 0.341 | 0.632 |
| TP8 | 0.075 | 0.493 | 0.892 | -0.129 | 0.236 | 0.567 |
| C6 | 0.142 | 0.193 | 0.528 | 0.034 | 0.756 | 0.865 |
| C2 | 0.110 | 0.315 | 0.709 | 0.053 | 0.630 | 0.792 |
| FC4 | 0.161 | 0.139 | 0.437 | 0.164 | 0.132 | 0.460 |
| FT8 | 0.193 | 0.074 | 0.293 | -0.067 | 0.541 | 0.792 |
| **F6** | **0.306** | **0.004** | **0.036** | 0.201 | 0.063 | 0.414 |
| **AF8** | **0.305** | **0.004** | **0.036** | -0.061 | 0.579 | 0.792 |
| **AF4** | **0.375** | **0.000** | **0.015** | 0.181 | 0.095 | 0.414 |
| **F2** | **0.302** | **0.005** | **0.036** | 0.094 | 0.390 | 0.680 |

**Table A4.2. Channel-wise correlations between ITPC (active-passive) at 3 and 6 Hz and symbol-speech sound accuracy score.**

| | 3 Hz | | | 6 Hz | | |
|---|---|---|---|---|---|---|
| **Channel** | **rho** | **p** | **FDR-corrected p** | **rho** | **p** | **FDR-corrected p** |
| Fp1 | 0.079 | 0.463 | 0.806 | 0.141 | 0.188 | 0.489 |
| Fz | 0.147 | 0.170 | 0.591 | 0.017 | 0.875 | 0.919 |
| F3 | 0.152 | 0.156 | 0.591 | -0.026 | 0.806 | 0.908 |
| F7 | 0.072 | 0.503 | 0.812 | 0.165 | 0.123 | 0.419 |
| FT9 | 0.138 | 0.197 | 0.591 | 0.153 | 0.152 | 0.459 |
| FC5 | -0.079 | 0.459 | 0.806 | 0.119 | 0.266 | 0.490 |
| FC1 | 0.117 | 0.273 | 0.716 | 0.042 | 0.694 | 0.858 |
| C3 | 0.041 | 0.706 | 0.856 | 0.134 | 0.209 | 0.489 |
| T7 | 0.017 | 0.871 | 0.927 | 0.094 | 0.381 | 0.593 |
| TP9 | 0.053 | 0.623 | 0.835 | 0.005 | 0.966 | 0.966 |
| CP5 | -0.107 | 0.318 | 0.716 | 0.027 | 0.798 | 0.908 |
| CP1 | 0.056 | 0.599 | 0.835 | -0.021 | 0.841 | 0.919 |
| Pz | -0.014 | 0.896 | 0.927 | -0.201 | 0.059 | 0.370 |
| P3 | -0.131 | 0.219 | 0.627 | -0.082 | 0.445 | 0.663 |
| P7 | -0.031 | 0.774 | 0.903 | -0.108 | 0.313 | 0.547 |
| O1 | 0.023 | 0.830 | 0.927 | -0.163 | 0.126 | 0.419 |
| Oz | -0.016 | 0.882 | 0.927 | -0.268 | 0.011 | 0.248 |
| O2 | 0.054 | 0.613 | 0.835 | -0.177 | 0.098 | 0.411 |
| P4 | 0.098 | 0.361 | 0.784 | -0.177 | 0.096 | 0.411 |
| P8 | 0.144 | 0.178 | 0.591 | -0.080 | 0.453 | 0.663 |
| TP10 | 0.087 | 0.419 | 0.806 | -0.131 | 0.221 | 0.489 |
| CP6 | 0.014 | 0.898 | 0.927 | -0.095 | 0.373 | 0.593 |
| CP2 | 0.080 | 0.454 | 0.806 | -0.005 | 0.964 | 0.966 |
| Cz | 0.053 | 0.621 | 0.835 | 0.051 | 0.632 | 0.829 |
| C4 | 0.041 | 0.704 | 0.856 | 0.122 | 0.253 | 0.489 |
| T8 | 0.151 | 0.158 | 0.591 | -0.126 | 0.240 | 0.489 |
| FT10 | 0.201 | 0.059 | 0.410 | -0.205 | 0.054 | 0.370 |
| FC6 | 0.254 | 0.017 | 0.255 | 0.027 | 0.801 | 0.908 |
| FC2 | 0.293 | 0.006 | 0.159 | 0.189 | 0.076 | 0.371 |
| F4 | 0.239 | 0.024 | 0.255 | 0.230 | 0.030 | 0.370 |
| F8 | 0.244 | 0.022 | 0.255 | -0.106 | 0.323 | 0.549 |
| Fp2 | 0.141 | 0.187 | 0.591 | 0.072 | 0.502 | 0.718 |
| AF7 | 0.160 | 0.135 | 0.591 | 0.190 | 0.075 | 0.371 |
| AF3 | 0.215 | 0.043 | 0.346 | 0.153 | 0.153 | 0.459 |
| AFz | 0.108 | 0.313 | 0.716 | 0.209 | 0.049 | 0.370 |
| F1 | 0.019 | 0.857 | 0.927 | -0.049 | 0.645 | 0.829 |
| F5 | 0.140 | 0.189 | 0.591 | 0.042 | 0.692 | 0.858 |
| FT7 | 0.028 | 0.791 | 0.906 | 0.134 | 0.210 | 0.489 |
| FC3 | -0.058 | 0.585 | 0.835 | 0.051 | 0.631 | 0.829 |
| C1 | 0.110 | 0.302 | 0.716 | 0.118 | 0.272 | 0.490 |
| C5 | -0.148 | 0.165 | 0.591 | 0.068 | 0.525 | 0.735 |
| TP7 | -0.040 | 0.706 | 0.856 | -0.018 | 0.867 | 0.919 |
| CP3 | 0.005 | 0.963 | 0.963 | -0.018 | 0.864 | 0.919 |
| P1 | -0.078 | 0.469 | 0.806 | -0.129 | 0.228 | 0.489 |
| P5 | -0.061 | 0.571 | 0.835 | -0.121 | 0.256 | 0.489 |
| PO7 | -0.034 | 0.754 | 0.897 | -0.138 | 0.196 | 0.489 |
| PO3 | -0.119 | 0.266 | 0.716 | -0.139 | 0.195 | 0.489 |
| POz | -0.077 | 0.474 | 0.806 | -0.201 | 0.058 | 0.370 |
| PO4 | 0.008 | 0.942 | 0.957 | -0.189 | 0.076 | 0.371 |
| PO8 | 0.075 | 0.486 | 0.806 | -0.093 | 0.386 | 0.593 |
| P6 | 0.060 | 0.573 | 0.835 | -0.202 | 0.057 | 0.370 |
| P2 | 0.044 | 0.679 | 0.856 | -0.166 | 0.120 | 0.419 |
| CPz | 0.090 | 0.399 | 0.806 | -0.065 | 0.545 | 0.746 |
| CP4 | 0.046 | 0.671 | 0.856 | -0.026 | 0.807 | 0.908 |
| TP8 | 0.078 | 0.466 | 0.806 | -0.122 | 0.256 | 0.489 |
| C6 | 0.107 | 0.315 | 0.716 | 0.013 | 0.901 | 0.931 |
| C2 | 0.060 | 0.574 | 0.835 | 0.133 | 0.213 | 0.489 |
| FC4 | 0.182 | 0.088 | 0.555 | 0.170 | 0.111 | 0.419 |
| FT8 | 0.156 | 0.144 | 0.591 | -0.103 | 0.335 | 0.556 |
| F6 | 0.282 | 0.008 | 0.159 | 0.332 | 0.002 | 0.098 |
| AF8 | 0.283 | 0.007 | 0.159 | -0.027 | 0.804 | 0.908 |
| AF4 | 0.214 | 0.044 | 0.346 | 0.266 | 0.012 | 0.248 |
| F2 | 0.153 | 0.153 | 0.591 | 0.228 | 0.032 | 0.370 |