International Journal of Psychophysiology 94 (2014) 298–310

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Enhancement of brain event-related potentials to speech sounds is associated with compensated reading skills in dyslexic children with familial risk for dyslexia

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ARTICLE INFO

Article history:
Received 2 August 2014
Received in revised form 26 September 2014
Accepted 2 October 2014
Available online 12 October 2014

Keywords:
Dyslexia
Speech perception
ERP
EEG
Phonemic length discrimination
Compensation

ABSTRACT

Specific reading disability, dyslexia, is a prevalent and heritable disorder impairing reading acquisition characterized by a phonological deficit. However, the underlying mechanism of how the impaired phonological processing mediates resulting dyslexia or reading disabilities remains still unclear. Using ERPs we studied speech sound processing of 30 dyslexic children with familial risk for dyslexia, 51 typically reading children with familial risk for dyslexia, and 58 typically reading control children. We found enhanced brain responses to shortening of a phonemic length in pseudo-words (/at:a/ vs. /ata/) in dyslexic children with familial risk as compared to other groups. The enhanced brain responses were associated with better performance in behavioral phonemic length discrimination task, as well as with better reading and writing accuracy. Source analyses revealed that the brain responses of sub-group of dyslexic children with largest responses originated from a more posterior area of the right temporal cortex as compared to the responses of the other participants. This is the first electrophysiological evidence for a possible compensatory speech perception mechanism in dyslexia. The best readers within the dyslexic group have probably developed alternative strategies which employ compensatory mechanisms substituting their possible earlier deficit in phonological processing and might therefore be able to perform better in phonemic length discrimination and reading and writing accuracy tasks. However, we speculate that for reading fluency compensatory mechanisms are not that easily built and dyslexic children remain slow readers during their adult life.

1. Introduction

1.1. Background

Specific reading disability, dyslexia, is a problem in learning to read and write despite adequate cognitive level, training, motivation, and other extraneous factors (Lyon et al., 2003; Vellutino et al., 2004). Heritability and familial clustering of dyslexia has been well established pointing to genetic factors behind dyslexia (Galaburda, 2005; Lyon et al., 2003; Lyytinen et al., 2004; Vellutino et al., 2004). Phonological skills, i.e., ability to recognize and manipulate speech sound elements, is one of the key components for acquiring the ability to read, and deficit in phonological processing is one of the most relevant factors linked to dyslexia (Goswami, 2002; Ramus, 2003; Snowling, 2000; Stanovich, 1988; Torgesen et al., 1997; Vellutino et al., 2004; Wagner and Torgesen, 1987). However, the underlying mechanism of how the impaired phonological processing mediates resulting dyslexia or reading disabilities remains still unclear. Here, we studied the brain event-related potential (ERPs) responses in dyslexic and typically reading children with and without familial risk for dyslexia to pseudo-words. Pseudo-words varied in consonant duration, i.e., phonemic length, which is a semantically distinguishing feature in the Finnish language. Also association of brain responses with outcomes in phonemic length discrimination, reading, and writing tasks were investigated.

1.1.1. Phonological processing deficit

Deficit in phonological processing is often suggested to derive from auditory or speech processing problems via inaccurate or otherwise inadequate phonological representations (Elbro et al., 1998; Griffiths and Snowling, 2002; McBride-Chang, 1995; Mody et al., 1997; Snowling, 2000). The brain's ability to discriminate between acoustic features in speech, crucial for formation of speech sound representations, may be insufficient in dyslexic readers. Defective representations in turn may lead to disability in reading and spelling by hindering the learning of fluent and automatic decoding of phoneme-grapheme correspondences

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http://dx.doi.org/10.1016/j.ijpsycho.2014.10.002
0167-8760/

(Elbro et al., 1998; Share, 1995; Snowling, 2000). Several theories have been formulated for the association between auditory and speech processing deficits and reading problems. The rapid auditory temporal processing (RATP) theory suggests that dyslexics have difficulties in perceiving brief auditory stimuli when they are presented in rapid succession (Tallal and Piercy, 1973; Tallal, 1980, 2004). It has been proposed that perception of slow modulations in speech, reflected in rise time discrimination, would be impaired in dyslexics (Goswami et al., 2002; Goswami, 2011). Furthermore, studies using functional magnetic resonance imaging (fMRI) to investigate speech processing have found deficits in access to phonetic representations without deficits at the cortical processing of speech sounds (Boets et al., 2013). However, there is no consensus yet on the mechanism how the deficit in phonological awareness is associated with the reading deficit or dyslexia. Nevertheless, there is strong evidence for neurobiological risk factors for dyslexia (for reviews see Habib, 2000; Démonet et al., 2004; Richlan et al., 2011, 2013). These neurobiological risk factors specifically related to speech include, for example, reduced gray matter volume at posterior Sylvian areas (Richlan et al., 2013), structural brain anomalies, such as neuronal ectopias around the Sylvian fissure (Galaburda et al., 1985), and abnormal activation and connectivity in posterior and perisylvian systems (Démonet et al., 2004).

1.1.2. Structural brain differences

Anomalies in dyslexic brain have been seen in autopsy and brain imaging studies (for reviews see Eckert, 2004; Habib, 2000). Reduction in gray matter volume has been found in areas relevant in speech and language processing, such as the superior temporal gyrus and the inferior frontal gyrus (Frye et al., 2010; Steinbrink et al., 2008). Gray matter volume in the left anterior fusiform gyrus/hippocampus, left precuneus, right hippocampus, and right anterior cerebellum have been found to increase during reading intervention in dyslexic children (Krafnick et al., 2011). Furthermore, in typical readers, gray matter thickening in the left inferior frontal cortex has been found to be associated with improving phonological skills (Lu et al., 2007). Compared to typical readers, many areas in dyslexics have been found to contain more ectopias, displacements of neurons developed during neuronal migration, near and around Sylvian fissure, particularly in the left hemisphere (Galaburda et al., 1985; Galaburda, 2005; Ramus, 2004). Also, dyslexic brains are often characterized by reduced asymmetry particularly at the posterior superior temporal gyrus, i.e., symmetrical plana temporale in the posterior Sylvian fissure (Galaburda et al., 1978, 1985; Illingworth and Bishop, 2009; Leonard and Eckert, 2008; Sun et al., 2010). The brain symmetry in dyslexics suggest anatomical differences in areas activated heavily by speech and language and possibly differences in the distribution of activity in the left and right perisylvian cortex (Binder et al., 1996; Galaburda et al., 1985). However, also different hemispheric symmetry patterns of posterior perisylvian areas, including planum temporale, have been observed in dyslexic individuals (Chiarello et al., 2006; Leonard et al., 1993).

1.1.3. Speech perception related brain responses

Deficits linked to the abovementioned anatomical differences include speech processing problems, which could be a cause for phonological deficits (e.g., Blomert, 2011; Price, 2012). In dyslexics, poor speech perception manifests itself as difficulties to discriminate and categorize speech sound contrasts like syllables, consonants and vowels (e.g., Bradley and Bryant, 1978; Godfrey, Syrdal-Lasky, Millay, and Knox, 1981; Manis et al., 1997; Mody et al., 1997; Pennala et al., 2010; Reed, 1989). Nevertheless, there are studies that fail to find differences between dyslexics and controls for some speech contrasts (Blomert et al., 2004; Groth et al., 2011). For example, Groth et al. (2011) found that dyslexics were poorer in discriminating longer vowels from shorter ones if they were made shorter by manipulation (only durational cues available), but they found no group effect for naturally shorter versus longer vowels (both spectral and durational cues available). Further, using functional magnetic resonance imaging (fMRI), Steinbrink et al. (2012) observed decreased activation of left inferior frontal gyrus and insular cortices in dyslexics during processing of the same temporal stimuli, but only in the subgroup of low performing dyslexics (Steinbrink et al., 2012). Also, it should be kept in mind that in certain conditions dyslexics can be even more sensitive to speech sound contrasts, i.e., dyslexics have been reported to be poorer in discriminating between phoneme categories, but more sensitive in discriminating within category contrasts (Serniclaes et al., 2001, 2004).

Speech sound discrimination is often studied using event-related potentials (ERPs), especially the discriminative components, which are thought to be a pre-attentive index of cortical accuracy of sound processing. They capture low level processing, and therefore work as an objective measure that is not determined by level of motivation, attention or arousal (for reviews, see Bishop, 2007; Näätänen et al., 2005; Schulte-Körne and Bruder, 2010). Using ERPs to study speech sound discrimination, abnormal responses have been found in dyslexics. In most studies responses have been smaller (e.g., Bishop, 2007; Kujala et al., 2006; Maurer et al., 2003; Schulte-Körne et al., 1998), although in some studies larger responses have been reported (e.g., Helenius et al., 2002; Hämäläinen et al., 2013). In dyslexic children, the development of ERP components has been reported to be delayed, being similar to younger typically developing children (Blomert, 2011; McArthur and Bishop, 2004), but the brain responses of children who have a history of reading difficulty but are currently reading age appropriately, i.e., compensated readers, have been found to follow those of same aged controls (Sharma et al., 2006). Sharma et al. (2006) studied three groups of school-aged children: children with current reading difficulty, compensated readers, and age appropriately reading controls. They found that compensated readers were similar in their brain responses and in behavioral auditory tasks as was the control group, whereas children with reading difficulty differed from other groups in their performance in both brain and behavioral measures.

1.1.4. Atypical quantity perception

In the 'Quantity languages' like Finnish, Japanese, and Swedish, phonemic length is a semantically distinguishing feature (Lidestam, 2009; Tervaniemi et al., 2006). Two qualities exist: a phoneme can be perceived either as short or long in relation to other phonemes in the word, although physically both phoneme durations vary and may even overlap in duration (Suomi et al., 2008; Vainio, 2001). Differences between children at risk for dyslexia and non-risk control children have been seen in ERP responses to syllables with vowel or consonant duration changes already at birth and early childhood (Leppänen et al., 1999; Leppänen et al., 2002; Pihko et al., 1999). More recently, corresponding results have been found in children and adults with dyslexia (e.g., Hämäläinen et al., 2013; Kujala et al., 2006; Lovio et al., 2010; Sharma et al., 2006). Impaired perception of phonemic length has also been found using behavioral tasks (e.g., Hämäläinen et al., 2009; Pennala et al., 2010; 2013; Richardson et al., 2003, 2004).

Although corresponding group differences between dyslexic and control children have been found, speech perception abilities change during development. In early childhood, native language environment starts to shape the perception of speech sounds (Kuhl et al., 1992; Kuhl et al., 2006; Ortiz-Mantilla et al., 2013), and improvements in speech perception accuracy are still seen during the first three grades (Pennala et al., 2010; 2013). Further, longitudinal studies have found that the differences in speech perception ability between children with and without dyslexia vary depending on age (Pennala et al., 2010), and suggestions have been made of different developmental trajectory of the perceptual abilities of children with language related difficulties (McArthur and Bishop, 2004; Wright and Zecker, 2004). Similar changes in perceptual abilities during development have been found using non-linguistic stimuli as well (Stefanics et al., 2011).