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Cortical basis for dichotic pitch perception in developmental dyslexia

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ABSTRACT

The current study examined auditory processing deficits in dyslexia using a dichotic pitch stimulus and functional MRI. Cortical activation by the dichotic pitch task occurred in bilateral Heschl's gyri, right planum temporale, and right superior temporal sulcus. Adolescents with dyslexia, relative to age-matched controls, illustrated greater activity in left Heschl's gyrus for random noise, less activity in right Heschl's gyrus for all auditory conditions, and less activity in right superior temporal sulcus for a dichotic melody. Subsequent analyses showed that these group differences were attributable to dyslexic readers who performed poorly on the psychophysical task. Furthermore, behavioral performance on phonological reading was correlated to activity from dichotic conditions in right Heschl's gyrus and right superior temporal sulcus. It is postulated that these differences between reader groups is primarily due to a noise exclusion deficit shown previously in dyslexia.

1. Introduction

Developmental dyslexia is defined as difficulty learning to read, despite average intelligence, lack of sensory impairments, and adequate access to educational resources (Lyon, Shaywitz, & Shaywitz, 2003). This learning disability affects 5–12% of the population (Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001), and while the etiology is unknown, it appears to have genetic and neurobiological bases (Fisher & DeFries, 2002; Habib, 2000). It is well established that most persons with dyslexia experience difficulty with phonological encoding and decoding (Snowling, 1981; Stanovich & Siegel, 1994). Some children may also have problems with orthographic processing, which includes awareness of irregular words that do not have phonological representations, such as "yacht" (Castles & Coltheart, 1993; Edwards & Hogben, 1999). The existence of a phonological deficit in dyslexia is not disputed; however, it may be one aspect of a "multifactorial" disorder (Caylak, 2011).

Another component to reading may be rapid auditory processing (reviewed in Caylak, 2011; Farmer & Klein, 1995; Hämäläinen, Salminen, & Leppänen, 2012). Tallal (1980) originally hypothesized that young children who have difficulty processing rapidly presented information, such as speech sounds, have subsequent difficulties with phonemic awareness and reading. Auditory processing deficits in dyslexia have been shown in many studies measuring temporal ordering of tones (e.g., Tallal, 1980), auditory gap detection (e.g., Boets, Wouters, van Wieringen, & Ghesquière, 2007), frequency-modulated tone discrimination and detection (e.g., Edwards et al., 2004; Talcott et al., 2003), and binaural pitch perception (e.g., Dougherty, Cynader, Bjornson, Edgell, & Giaschi, 1998; Edwards et al., 2004; McAnally & Stein, 1996). However, the relationship between reading and auditory temporal processing continues to be an area of debate (Landerl & Willburger, 2010; Ramus, 2003; Rosen & Manganari, 2001).

In adults with normal hearing, rapid auditory processing occurs primarily in the left temporal cortex, including Heschl's gyrus and superior temporal gyrus, whereas spectral or melody perception occurs in the right temporal cortex (Warrier et al., 2009; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002). Furthermore, larger left Heschl's gyri were correlated with greater activation in this region when adults listened to rapidly presented noise stimuli (Warrier et al., 2009), and thicker gray matter in left Heschl's gyrus was correlated with better performance on a frequency-modulated tone detection task in children (Sutherland et al., 2012). In contrast, right Heschl's gyrus showed a positive relationship between volume and spectral-related activity (Warrier et al., 2009). These anatomical and functioning neuroimaging studies show that although both hemispheres are involved in auditory processing, the left hemisphere is predominantly implicated for rapid auditory perception and the right hemisphere for melody perception.

Only a few functional neuroimaging studies have examined auditory temporal processing deficits in dyslexia. Temple et al. (2000) showed that rapidly changing acoustic stimuli activated

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the left superior and middle frontal gyri for average reading adults, but not for adults with dyslexia. Similar results were shown for children with dyslexia; after completing a reading remediation program, children showed increased activity in several regions used for rapid auditory processing, including the frontal and parietal lobes as well as the thalamus (Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007). Two recent studies with German speakers have examined auditory processing in adults with and without dyslexia. Steinbrink, Ackermann, Lachmann, and Riecker (2009) presented click stimuli or syllables at rates between 1 and 9 Hz. In average readers, with increased rate presentation, increased activation was shown in left insular cortex, right cerebellum, and thalamus and decreased activation was shown in right insular cortex. In contrast, the dyslexic group did not show this pattern of results in bilateral insula when syllables were presented. The authors concluded that dyslexic readers have speech-specific auditory temporal processing deficits; however, since their click and syllable stimuli differed in signal complexity, they did not rule out that stimulus characteristics also contributed to their results. In another study, Steinbrink, Groth, Lachmann, and Riecker (2012) used long and short German vowels to measure auditory temporal processing and phonological processing. In average readers, activation from the temporal task was shown in bilateral superior temporal gyri, bilateral anterior insula, and left inferior frontal gyrus. Although the dyslexic readers had lower discrimination accuracy than controls on their temporal task, there were no significant differences between groups in cortical activity. Subsequent analyses showed that low performers on the discrimination task (<60% accuracy; all dyslexic readers) had decreased activity in bilateral insular cortex and left inferior frontal gyrus in comparison to high performers (>90% accuracy; five average readers, one dyslexic reader). Given that low performers were all dyslexic readers, this suggests that some adults with dyslexia have impairments in insular cortex and left inferior frontal gyrus in response to rapid auditory stimuli. In summary, the functional neuroimaging studies have shown that dyslexic readers have impaired activation in response to rapid auditory processing tasks and these deficits are distributed throughout the brain, including frontal (Gaab et al., 2007; Steinbrink et al., 2012; Temple et al., 2000), parietal (Gaab et al., 2007), and insular (Steinbrink et al., 2009, 2012) cortices, as well as the thalamus (Gaab et al., 2007).

Further evidence, however, is needed to determine the neurobiological basis of auditory processing deficits in dyslexia, particularly in children and adolescents. We have previously shown that children with dyslexia have difficulty with dichotic pitch perception (Dougherty et al., 1998; Edwards et al., 2004). Dichotic pitch is an auditory stimulus created using two white noise sources that are presented to both ears. The fusing of binaural cues is needed to perceive pitch, whereas monaural cues on their own cannot be used. Our stimulus uses an ongoing interaural time difference (ITD) of 0.6 ms and thus, it requires sensitivity to the rapid temporal structure of the acoustic signals. It also probes the auditory system's ability to extract signals from noise and to compute sound location. Therefore, the dichotic pitch task is similar to previous dyslexia research as it examines rapid auditory processing (i.e., the ongoing ITD) and binaural pitch perception (e.g., McAnally & Stein, 1996). Neuroimaging results with adults illustrate that dichotic pitch stimuli activate bilateral Heschl's gyri, planum temporale, and planum polare (Garcia, Hall, & Plack, 2010; Puschmann, Uppenkamp, Kollmeier, & Thiel, 2010), as well as right superior temporal sulcus (Giaschi, Bjornson, Dougherty, & Au Young, 2000).

In the current study, we measured dichotic pitch processing in adolescents with dyslexia and adolescents with average reading ability using functional magnetic resonance imaging (fMRI) to assist in elucidating the neural basis of dyslexia. Our first goal was to establish that a similar dichotic pitch perception system is involved in adolescents because previous studies on auditory development reported more regions of activity in adults than in children (e.g., Koelsch, Fritz, Schulze, Alsop, & Schlaug, 2005). Our second goal was to examine deficits in dyslexia and we hypothesized that adolescents with dyslexia would have altered activity in regions such as Heschl's gyrus, planum temporale, planum polare, and superior temporal sulcus, relative to adolescents with average reading ability (Garcia et al., 2010; Giaschi et al., 2000; Puschmann et al., 2010).

2. Methods

2.1. Participants

Participants included 10 adolescents with average reading ability (6 male, 4 female) and 9 adolescents with dyslexia (6 male, 3 female) between 12 and 16 years old. All adolescents were right-handed and had a mean IQ score greater than or equal to 1 *SD* below the standardized norm on the Wechsler Intelligence Scale for Children-IV (WISC-IV) ($M = 10$, $SD = 3$; i.e., all adolescents had scaled scores greater than 7; Wechsler, 2003). The mean IQ score was derived from the Block Design and Vocabulary subtests, which measured perceptual reasoning and verbal comprehension, respectively. Adolescents were grouped into average or dyslexic reading groups based on their performance on the Gray Oral Reading Test, 4th edition (GORT-4) (Wiederholt & Bryant, 2001). Reading fluency was established by the rate and accuracy of reading aloud short paragraphs. Average readers were characterized by a fluency score greater than or equal to 1 *SD* below the standardized norm ($M = 10$, $SD = 3$; i.e., scaled score of 7 or greater) and dyslexic readers were characterized by a fluency score less than or equal to 1.5 *SD* below the standardized norm (i.e., scaled score of 5 or less). Groups were similar on age and IQ measures, while there were significant differences between groups on the GORT-4 reading measures (see Table 1). Additionally, all participants had normal hearing with a threshold of 25 dB HL or less in both ears at 500 and 1000 Hz, which was assessed using a Maico MA-39 audiometer.

2.2. Behavioral tasks

2.2.1. Reading measures

A modified version of the Coltheart and Leahy (1996) reading lists was used to assess phonological and orthographic reading ability. Participants were asked to read aloud single words and non-words, which were printed on cards and placed in random order in a book. There were 30 words in each of three lists: regular words (e.g., plant), pronounceable non-words (e.g., norf) to measure phonological reading ability, and irregular words (e.g., yacht) to measure orthographic reading ability. Each participant read the words in the same order at their own pace and the number of errors was recorded.

2.2.2. Dichotic pitch

Auditory temporal processing was assessed with a dichotic pitch task (Dougherty et al., 1998), which has been shown to differentiate between average and dyslexic readers (Dougherty et al., 1998; Edwards et al., 2004). Dichotic pitch stimuli were generated by filtering two independent flat-amplitude noise sources. One source was band-pass filtered to create the signal tones, while the other source was notch filtered to create the background noise. The signal tones had an ongoing ITD of ±0.6 ms and the background noise had an ITD of 0 ms, which created the perception of tones that appeared to come from the left or right and noise from the middle of the head. The complementary signal and noise filters were modified to adjust the signal-to-noise ratio (SNR) from 0