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FMRI of phonemic perception and its relationship to reading development in elementary- to middle-school-age children

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Neuroimaging studies suggest that categorical perception of speech phonemes in adults is primarily subserved by a pathway from bilateral primary auditory areas to association areas in the left middle superior temporal cortex, but the neural substrates underlying categorical speech perception in children are not yet known. Here, fMRI was used to examine the neural substrates associated with phoneme perception in 7- to 12-year-old children as well as the relationships among level of expertise in phoneme perception, the associated activation, and the development of reading and phonological processing abilities. While multiple regions in left frontal, temporal, and parietal cortex were found to be more responsive to phonemic than nonphonemic sounds, the extent of left lateralization in posterior temporal and parietal regions during phonemic relative to nonphonemic discrimination differed depending on the degree of categorical phoneme perception. In addition, an unexpected finding was that proficiency in categorical perception was strongly related to activation in the left ventral occipitotemporal cortex, an area frequently associated with orthographic processing. Furthermore, in children who showed lower proficiency in categorical perception, the level of categorical perception was positively correlated with reading ability and reading and reading-related abilities were inversely correlated with right mid-temporal activation in the phonemic relative to nonphonemic perception contrast. These results suggest that greater specialization of left hemisphere temporal and parietal regions for the categorical perception of phonemes, as well as activation of the region termed the visual word form area, may be important for the optimal developmental refinement of both phoneme perception and reading ability.

Introduction

Repeated expressions of the same speech utterance inevitably vary acoustically, both between and within speakers. Speech perception entails disregarding phonemically irrelevant acoustic variability and recognizing a wide variety of physically different sounds as exemplars of the same phoneme. As a result, the adult human brain is more sensitive to acoustic variations that cue phonemic categories than to acoustic variations of a similar extent within a phonemic category, a phenomenon known as categorical perception (CP) of speech (Liberman et al., 1957). While CP is not limited to speech (Pastore et al., 1990; Pisoni, 1977), nor to humans (Kuhl and Miller, 1975), it is an essential marker of phonemic perception.

Young infants can discriminate not only contrasts that are phonemic in their native language but also those that are phonemic in languages to which they have had no exposure. However, sensitivity to non-native phoneme contrasts begins to decline in the latter part of the first year of life (Cheour et al., 1998; Eimas, 1975; Werker and Tees, 1984). CP of native phonemes continues to develop between the ages of 6 and 12 years, with performance still not reaching adult levels at the upper end of this age range (Bogliotti, 2003; Elliott et al., 1981; Hazan and Barrett, 2000). This immaturity in speech perception manifests as less precise phoneme boundaries and significantly greater inter-individual variability in phonemic categorization than seen in adults (Hazan and Barrett, 2000).

Several lines of evidence suggest a relationship between reading development and development of CP of speech. Bogliotti (2003) reported an increase in CP in children between age 6, before reading acquisition, and age 7, after initial reading acquisition. At age 7, those who were poor readers showed lower discrimination at the category boundary but stronger discrimination of a phonemically irrelevant contrast relative to those who were good readers. Less developed CP has also been linked with developmental dyslexia in both children and adults (Chiappe et al., 2001; Godfrey et al., 1981; Lieberman et al., 1985; Maassen and Groenen, 2001; Serniclaes, 2001). In addition, studies have found CP performance to be associated not only with reading ability (Godfrey et al., 1981), but also with phonological processing abilities thought to be areas of core deficits in dyslexia, specifically, rapid naming

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of visual stimuli (McBride-Chang, 1996) and phonological awareness (Chiappe et al., 2001; McBride-Chang, 1996), with the latter referring to an appreciation of the segmental nature of spoken language and the ability to manipulate its constituent parts.

The mechanisms underlying these relationships are still unclear. The increase in explicit phonological awareness and letter-name learning that accompanies reading development may sharpen the perception of phoneme categories. Alternatively, maturation of CP may facilitate development of phonological awareness and rapid naming abilities, or a common factor might jointly influence all of these processes. In this regard, anomalies in speech perception and associated event-related potentials (ERPs) can be seen well before the emergence of phonological awareness and rapid naming abilities in infants at familial risk for dyslexia, and these early differences in speech processing have been found to be predictive of future phonological processing performance (for review, see Leppänen et al., 2011; Lyytinen et al., 2004). Specifically, across multiple studies conducted as part of the Jyväskylä Longitudinal Study of Dyslexia, not only was a behavioral difference in categorical perception seen between infants at familial risk for dyslexia relative to control infants (Richardson et al., 2003), but ERP differences were seen suggesting diminished left hemisphere (Leppänen et al., 2002) and enhanced right hemisphere processing during speech perception in the at-risk group (Guttorm et al., 2001; Leppänen et al., 1999). Furthermore, infant speech perception ERPs were associated with later phonological awareness, rapid serial naming, letter knowledge (Guttorm et al., 2010), and second-grade reading and writing skills (Leppänen et al., 2011). Finally, further support for a more direct, or potentially causal, role of speech perception in the development of phonological awareness can be found in two studies showing improvements on measures of phonological awareness following phonemic discrimination training in mainstream children (Moore et al., 2005) and children with reading disabilities (Hurford, 1990). These studies suggest that not only development of CP but also specific left lateralization of CP neural processing may be important for optimal development of reading and phonological processing abilities.

FMRI studies in adults suggest that analysis of acoustic information, such as spectral content, harmonic structure, and pitch, involves the dorsal aspect of the superior temporal gyrus bilaterally, whereas later stages of speech processing involve specific subsystems that are relatively left lateralized (Binder et al., 2000; Davis and Johnsrude, 2003; Scott et al., 2000). In adults, primarily the middle portion of the left ventral superior temporal gyrus and sulcus (STG/STS) is engaged during discrimination of phonemic relative to acoustically matched nonphonemic stimuli, implicating this area in phonemic perception (DeWitt and Rauschecker, 2012; Liebenthal et al., 2005, 2010; Obleser et al., 2007). These results are consistent with a hierarchical speech sound processing system in the superior temporal cortex, extending from dorsal areas in the STG bilaterally, associated with analysis of the physical features of complex sounds, to areas in the left STS, associated with mapping complex auditory patterns in speech to learned phonemic representations.

Developmental changes in activation patterns at the stage of phonemic recoding have not yet been studied using fMRI. FMRI studies examining activation patterns associated with higher-level speech and language processing in children have suggested that, consistent with the ERP infant studies, children as young as two to three months of age show left hemisphere dominance for speech processing (Dehaene-Lambertz et al., 2002); however, the degree of lateralization may continue to increase with age (Gaillard et al., 2000; Szaflarski et al., 2006). In addition, some studies have reported a greater spatial extent of activation or less functional specialization in children ranging in age from 8 to 13 years compared to adults and older adolescents (Gaillard et al., 2000; Lidzba et al., 2011; Tatsuno and Sakai, 2005). These findings, however, are not universal, with some studies finding no differences in degree of lateralization or extent of activation (Gaillard et al., 2003).

In this study, we compared brain responses to phonemic stimuli (the syllables/ba/and/da/) and acoustically-matched nonphonemic sounds in 32 children, aged 7.9 to 12.9 years, during performance of a discrimination task. Our goal was to investigate the neural substrates associated with phonemic perception in children as well as the relationships among level of expertise in phoneme perception, the associated activation, and the development of reading and phonological processing abilities. We hypothesized that children would show patterns of brain activation associated with CP that are generally similar to those previously seen in adults, including the preferential engagement of the left temporal lobe; however, we expected greater variability in activation patterns among the children, and an association between this variability and both CP performance and reading-related abilities. To examine the latter hypothesis, we examined different subgroups of children defined by their behavioral performance on a categorical perception task as well as by the relationship between proficiency on this task and their level of reading ability.

Material and methods

Participants

Participants were 39 monolingual, right-handed children, 7 to 12 years of age, who had no history of significant neurological illness or injury, hearing impairment, developmental speech, language or learning disorder, chronic medical illness, or psychiatric disorder. Participants as well as at least one of their parents were native speakers of American English. The latter was necessary to ensure that the children were exposed to American English phonemes from birth. Children were excluded if they had fewer than 40 trials remaining in the phonemic (P) or the nonphonemic (N) scanner conditions after removal of trials in which no response was given or excessive movement occurred. Application of this criterion resulted in the exclusion of 6 children. One additional child was excluded due to poor image quality, leaving a final sample of 32 children (see Table 1 for sample characteristics). The study protocol was approved by the Children's Hospital of Wisconsin Institutional Review Board. Parents of all participants gave written informed consent, and children provided written assent.

Table 1
Means and standard deviations (in parentheses) for the demographic and behavioral measures for the full sample and the Low and High Categorical Perception Index (CPI) groups.

	All ($n = 32$)	Low CPI ($n = 9$)	High CPI ($n = 23$)
Age	10.30 (1.54)	10.52 (1.82)	10.22 (1.46)
Sex (% F)	37.5	33.3	39.1
Socioeconomic status	50.1 (12.4)	49.8 (10.9)	50.2 (13.2)
WASI estimated IQ	115.13 (11.11)	111.56 (10.04)	116.52 (11.41)
WRAT-3 Reading	111.72 (7.68)	109.67 (8.63)	112.52 (7.33)
CTOPP Elision	11.66 (2.27)	11.64 (2.24)	11.67 (2.35)
CTOPP RLN	10.72 (2.56)	10.89 (2.37)	11.96 (2.20)
CPI	68.77 (22.37)	37.44 (11.69)	81.02 (9.85)
P response time	1133.48 (267.32)	1113.56 (401.73)	1141.28 (204.41)
N response time	1088.23 (251.51)	1034.83 (363.25)	1109.13 (198.83)
P identification slope	1.39 (1.09)	1.13 (1.19)	1.45 (1.02)
N identification slope	0.51 (0.49)	0.39 (0.50)	0.58 (0.47)
% P motion trials removed	10.59 (7.23)	13.52 (8.09)	9.44 (7.60)
% N motion trials removed	11.39 (10.09)	14.32 (5.74)	10.24 (11.24)
% missed in P	4.34 (3.81)	4.51 (4.49)	4.28 (3.62)
% missed in N	4.88 (5.57)	4.69 (5.15)	4.95 (5.84)

WASI = Wechsler Abbreviated Scale of Intelligence; WRAT-3 = Wide Range Achievement Test-3; CTOPP = Comprehensive Test of Phonological Processing; RLN = Rapid Letter Naming; P = Phonemic; N = Nonphonemic.