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Neural systems for auditory perception of lexical tones

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ABSTRACT

Previous neuroimaging research on cognitive processing of speech tone has generated dramatically different patterns of findings. Even at the basic perception level, brain mapping studies of lexical tones have yielded inconsistent results. Apart from the data inconsistency problem, experimental materials in past studies of tone perception carried little or minimal lexical semantics, an important dimension that should not be dispensed with because speech tones serve to distinguish lexical meanings. The present study sought to examine the neural correlates of the perception of speech tone using lexically meaningful experimental stimuli. A simple lexical tone perception task was devised in which native Mandarin speakers were asked to judge whether or not the two syllables of an auditorily presented Chinese bisyllabic word had the same tone. We selected bisyllabic words as experimental stimuli because Chinese monosyllables often convey little or very vague meanings due to rampant homophony. We found that the left inferior frontal gyrus, the right middle temporal gyrus and bilateral superior temporal gyri are responsible for basic perception of linguistic pitches. Our interpretation of the data sees the left superior temporal gyrus as engaged in primary acoustic analysis of the auditory stimuli, while the right middle superior temporal gyrus and the left inferior frontal region are involved in both tonal and semantic processing of the language stimuli.

In a tonal language, lexical tone is used to distinguish lexical or grammatical meanings. Since tonal languages account for around 50% of the world's languages (Maddieson, 2013), understanding the neural substrates underlying speech tone perception in native speakers has been a central question in electrophysiological and neuroimaging research on spoken language (Luo et al., 2006; Nan, Friederici, Shu, & Luo, 2009; Ren, Yang, & Li, 2009; Ren, Tang, Li, & Sui, 2013; Tsang, Jia, Huang, & Chen, 2011; Xi, Zhang, Shu, Zhang, & Li, 2010; Yang, Gates, Molenaar, & Li, 2015; Zhang, Shu, Zhou, Wang, & Li, 2010, 2011). While existing research has yielded important findings on how lexical tone is neuroanatomically represented, the experimental tasks employed in brain mapping studies tap dramatically different cognitive processes, including perception and working memory (Gandour et al., 2002, 2003; Hsieh, Gandour, Wong, & Hutchins, 2001; Klein, Zatorre, Milner, & Zhao, 2001;

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Li et al., 2003, 2010; Nan & Friederici, 2013; Wang, Sereno, Jongman, & Hirsch, 2003; Xu et al., 2006; Zhang et al., 2010, 2011), and the neural correlates of perception of speech tone in native listeners have not been precisely pinpointed.

Klein et al. (2001) used PET to identify the brain systems subserving auditory lexical tone perception in native Mandarin speakers. In their tone discrimination task, pairs of monosyllabic Chinese words were presented auditorily. Within each pair, the syllables were identical; half of them carried the same tone (e.g./tou2/and/tou2/) and the other half had different tones (e.g./fei2/and/fei4/). Subjects were required to make same-different lexical tone judgments of the syllable pairs. Peak activation was found in bilateral superior temporal gyri (STG), bilateral parietal areas and bilateral cerebellum in native Mandarin speakers. Similarly, Gandour et al. (2002) used fMRI to examine how the brain processes linguistically relevant pitch patterns (spectral vs. temporal cues) in tonal language speakers. The tone discrimination task they used is the same as in Klein et al.'s study, where subjects were required to make same–different judgments on the syllable pairs they heard. The authors of this study used the same stimuli for the spectral (i.e. lexical tone) and temporal (i.e. vowel length) conditions, and the syllable pairs were monosyllabic Thai pseudowords which either (1) had the same tone with different vowel duration (e.g., $p^{h}in^{R}$ and $p^{h}iin^{R}$), (2) had different tones with the same vowel duration (e.g., $haaj^{M}$ and $haaj^{H}$), or (3) had same tone and same vowel duration. They found that native Thai speakers showed greater activation in left inferior prefrontal gyrus in discriminating Thai tone relative to nonspeech pitch. Wong, Parsons, Martinez, and Diehl (2004) used PET to compare the neural correlates underlying lexical tone perception between Mandarin natives and native English speakers. Their task is a tone judgment on Chinese syllable pairs (e.g./fei2/and/wei2/). Relative to passive listening of Mandarin syllables, lexical tone judgment in native Mandarin speakers induced stronger activation in the left insular cortex, putamen, thalamus, fusiform gyrus, and medial frontal gyrus. Activation in the right hemisphere was also observed in middle frontal gyrus and post-central gyrus. In an fMRI study, Xu et al. (2006) found that when native Mandarin speakers performed tone discrimination tasks on two different Chinese syllables (e.g.,/bai2/and/yao2/) or stimuli resynthesized by superimposing Thai tones onto Chinese syllables, stronger activity in the left planum temporale (PT) was seen in response to native compared with non-native tones.

The tasks used by Klein et al., Gandour et al., Wong et al., and Xu et al. are highly similar and are all perception-based, but their findings are inconsistent. This inconsistency may be related to the different languages used in the studies. Indeed, in Gandour et al.'s study (2002), native Chinese exhibited stronger activation in the left anterior superior temporal cortex in identifying Chinese speech tones relative to the nonspeech baseline.

Gandour and associates conducted several functional imaging studies to elucidate the neural mechanisms dedicated to Mandarin lexical tone processing. In their experiments, participants were presented a list of three to five monosyllables consecutively (Gandour et al., 2003; Hsieh et al., 2001; Li et al., 2003, 2010); they were asked to make tone judgments of the two syllables located first and last in the sequence on each trial (Gandour et al., 2003; Hsieh et al., 2001), to match the last item in the sequence with the probe (Li et al., 2003), or to match the probe with the target syllable within the sequence in random positions (Li et al., 2010). Tonal processing yielded greater brain activations in bilateral frontal-parietal networks, including the inferior prefrontal cortex, posterior inferior frontal gyrus (IFG), middle frontal gyrus (MFG) and the inferior parietal lobule. Nan and Friederici (2013) compared pitch processing of tonal language and music in native Mandarin speakers. Experimental stimuli involved sequences of Chinese four-syllable phrases and four-note musical phrases. Half of the Chinese phrases were semantically meaningful, and the other half were similar except that the pitch contours of the last syllables of the phrases were manipulated, making these phrases semantically and syntactically incongruent. Subjects were asked to judge whether the four-syllable phrases presented sounded congruous. Nan and Friederici found that processing of Mandarin pitch congruities involved greater cortical activations in bilateral STG and left IFG. In the tasks of Gandour et al. and Nan and Friederici, working memory is required to hold linguistic items in mind during the task, and therefore, lexical tone processing may occur at a late short-term memory stage, instead of at the perceptual phase.

In summary, previous research on speech tone processing has generated markedly different patterns of findings, partly because the tasks employed in those studies measured different levels of cognitive processing. As a matter of fact, even in neuroimaging experiments on basic perception of lexical tones in native Mandarin speakers, the findings are highly inconsistent too. Thus, it is worthwhile to further address the neuroanatomical representation issue of speech tone.

Apart from the data inconsistency problem, we have also noted that experimental stimuli in past studies of tone perception carried little or minimal lexical semantics, an important facet that should not be ignored because speech tones serve, after all, to distinguish lexical meanings. For example, when the syllables/fei2/and/fei4/are used in a tone decision task, the two syllables have little or very vague meanings because of the rampant homophony in Mandarin Chinese. In this case, the neural basis for tone processing may be related to general tone analysis (e.g., pure tone) but is hardly associated with natural, meaning-related lexical tone. Perception of lexical tones includes both acoustic processing and semantic processing of the pitch signal. Yet, it seems that most of the past studies have emphasized on the processing of acoustic/phonological information carried by lexical tones, and little focus is put on the neural substrates associated with the semantic processing aspect. Nan and Friederici (2013) used Chinese word phrases as experimental materials, in which word meaning of each lexical item was very precise. They observed that the left inferior language region (BA45) was activated in Mandarin speakers while performing the Mandarin tone task. Previous studies have also found that the inferior frontal gyrus (BA 44, 45, 47) was responsible for semantic processing of Chinese characters (Chee et al., 2000; Chou, Chen, Wu, & Booth, 2009; Ding et al., 2003; Price et al., 2012; Tan et al., 2001). Since lexical tones are closely linked to the processing of lexical semantics, the left inferior frontal and surrounding language regions might also play a role in processing linguistic information of lexical tones.