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EARLY CORTICAL PROCESSING OF LINGUISTIC PITCH PATTERNS AS REVEALED BY THE MISMATCH NEGATIVITY

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Abstract—Previous brain imaging studies have shown the left hemispheric dominance for processing of lexical tone in native speakers. However, the low temporal resolution related to neuroimaging techniques might not explicitly detect the brain activities that occur at a relatively small or a determined time frame. We used the mismatch negativity (MMN) and a source estimation technique (low-resolution electromagnetic tomography [LORETA]) to probe the brain activities underlying the early pre-attentive processing of Mandarin lexical tone and intonation. A passive oddball paradigm was applied to present tone and intonation contrast in a speech and nonspeech context. The results showed that no difference of the MMN amplitudes existed between speech and nonspeech conditions, although a larger MMN was found for tone than intonation condition. Source localization of the MMNs for all of the conditions showed the right hemispheric dominance, regardless of their linguistic functions (tone vs. intonation) or speech context (speech vs. nonspeech). Interestingly, the MMN generator for normal tone and hummed tone originated from the same cortical area (right parietal lobe, BA 19). These findings suggest that the pre-attentive cortical processing can be modulated not only by speech stimuli, but also by their nonspeech hums. Our data are compatible with the acoustic hypothesis of speech processing.

Key words: auditory, pitch, mandarin Chinese, lexical tone, intonation, mismatch negativity.

Linguistic pitch patterns are used to signal different aspects of spoken language such as emphatic stress and word meaning. An important issue that is particularly relevant to the processing of linguistic pitch patterns concerns language lateralization in the human brain. Two competing hypotheses were proposed to state the neural mechanisms underlying human pitch perception. The functional hypothesis (task-dependent hypothesis) claims that the hemispheric dominance of pitch patterns perception is determined by their psychological functions (Van Lancker, 1980). Those pitch patterns that carry a greater linguistic load (e.g. lexical tone) are preferentially processed in the left hemisphere, while those that carry a less linguistic load (e.g. intonation) are preferentially processed in the right hemisphere (Van Lancker, 1980; Wong, 2002). Alternatively, the acoustic hypothesis (cue-dependent hypothesis) claims that, regardless of psychological functions, all pitch patterns are lateralized to the same hemisphere, the right hemisphere in particular (Klouda et al., 1988; Zatorre and Belin, 2001; Zatorre et al., 2002). Empiric evidence exists either for the functional hypothesis (Hsieh et al., 2001; Gandour et al., 2000, 2002; Wong et al., 2004) or for the acoustic hypothesis (Zatorre and Belin, 2001; Luo et al., 2006; Warrier and Zatorre, 2004). Up to the present, the nature of these neural mechanisms underlying hemispheric lateralization for the perception of linguistic pitch patterns still remains a matter of debate.

The evidence for the functional hypothesis usually came from dichotic listening (Wang et al., 2001) or imaging studies (Hsieh et al., 2001; Klein et al., 2001; Gandour et al., 2000, 2002; Wong et al., 2004). These studies revealed the left hemispheric superiority in lexical tone perception for native speakers of tone languages, and suggested that hemispheric lateralization seems more sensitive to language-specific factors irrespective of the low-level acoustic processing. For example, when Thai and Chinese subjects were required to perform discrimination judgments of Thai tone, only Thai subjects displayed an increased activation in the left inferior prefrontal cortex (Gandour et al., 2002). Similar lateralization was obtained in Chinese speakers when Chinese and English speakers were required to discriminate the pitch patterns in Chinese words (Klein et al., 2001). In an functional magnetic resonance imaging (fMRI) study, Gandour et al. (2003) demonstrated that pitch contours associated with Mandarin lexical tones are processed in the left hemisphere, whereas pitch contours associated with intonation are processed mainly in the right hemisphere by Chinese speakers. These findings were against the view that hemispheric lateralization is sensitive to low-level auditory processing in the perception of linguistic pitch patterns.

However, because of the low temporal resolution of dichotic or imaging measures, the results mentioned above may reflect temporally aggregated neural events. In a passive oddball paradigm, Luo et al. (2006) demonstrated the right hemispheric lateralization for early auditory processing of lexical tones. The early pre-attentive cortical processing was found to be sensitive not only to speech sound, but also to nonspeech sound which is of phonological relevance in a particular language (Tervaniemi et al., 2006). In fact, these dichotomous views need not be mutually exclusive (Zatorre and Gandour, 2008). Both linguistic and acoustic factors are all necessary for developing a neural model of speech perception, and this

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Abbreviations: ANOVA, analysis of variance; ERP, event-related potential; fMRI, functional magnetic resonance imaging; F0, fundamental frequency; LORETA, low-resolution electromagnetic tomography; MMN, mismatch negativity.

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model relies on dynamic interactions between the two hemispheres (Gandour et al., 2004). Moreover, subsequent stages of linguistic processing might have developed from these early low-level acoustic processing (Zatorre et al., 2002; Luo et al., 2006).

This study focused on the early auditory processing of the two types of linguistic pitch patterns, Mandarin lexical tone and intonation. Mandarin lexical tone and intonation can be taken as stimuli for a robust test of these two hypotheses. In tonal languages such as Chinese, lexical tone is signaled by pitch variations and associated with spectral processing. Moreover, lexical tone is lexically contrastive and can distinguish lexical meaning, just as phonemes are. Mandarin Chinese has four lexical tones and tones 1–4 can be described phonetically as high level, high rising, low rising, and high falling pitch patterns respectively. For example, the syllable/ma/in Mandarin Chinese pronounced in a high level pitch means "mother," but the same syllable means "horse" when pronounced in a low rising pitch. Intonation, which is also signaled by pitch variation, does not distinguish lexical meanings. Intonation may convey several types of meanings such as attitudinal meanings, discursive meanings, or grammatical meanings which suggest that there are typical intonations associated with syntactic structures like declaratives, interrogatives, and imperatives (Cruttenden, 1997). Mandarin tone and intonation thus have equal acoustic features and different linguistic functions. The functional hypothesis predicts that the perception of lexical tone would be lateralized to the left hemisphere and the perception of intonation to the right hemisphere. On the contrary, the acoustic hypothesis predicts that both the processing of lexical tone and intonation would be lateralized to the right hemisphere regardless of their linguistic functions.

In the present study, we used event-related potentials and a source estimation technique low-resolution electromagnetic tomography (LORETA) to test which hypothesis prevails at an early pre-attentive cortical stage of linguistic pitch patterns processing. The event-related potential (ERP) component of interest is the mismatch negativity (MMN), which is an event-related response elicited by infrequent auditory stimulus (deviant) occurring among frequently repeated sounds (standard). The MMN has been proved to be an excellent tool for investigating the automatic detection of auditory changes (Näätänen and Escera, 2000; Näätänen, 2001; Näätänen et al., 2001, 2007; Pulvermüller and Shtyrov, 2006). Furthermore, LORETA was used to estimate the sources of the MMN. The LORETA approach has recently been successfully used in the studies on auditory processing (Meyer et al., 2006; Gottselig et al., 2004; Laufer and Pratt, 2005; Marco-Pallarés et al., 2005), and proved to be valuable in assessing the neural mechanisms underlying auditory processing.

A passive MMN paradigm was applied to present normal lexical tone contrast, normal intonation contrast, and their corresponding hummed versions. The aim of using hummed versions was to eliminate consonant and vowel information while preserving suprasegmental information of the normal speech stimuli. That is, compared to the normal versions, the hummed versions only preserved the purely acoustic pattern of speech melody. Our focus here was to compare the brain responses to lexical tone contrast and intonation contrast in speech and nonspeech context. By comparing the normal version and their hummed counterparts, we are able to determine whether the acoustic features of linguistic pitch patterns play an important role, and whether the modulation of ERPs to linguistic pitch patterns is speech-specific or not in the early pre-attentive processing of speech. If the functional hypothesis prevails, we would observe the left hemisphere lateralization for the lexical tone perception in speech context, and the right hemisphere lateralization for the lexical tone perception in nonspeech context and the intonation perception in both speech and nonspeech contexts. Otherwise, if the acoustic hypothesis prevails, the right hemisphere dominance for the perception of all the stimuli would be obtained.

EXPERIMENTAL PROCEDURES

Participants

Twelve graduate students (age range 21–25; six male, six female) participated in this study as paid volunteers. All the participants were native Mandarin Chinese speakers and right-handed, with no history of neurological or psychiatric impairment. Informed consent was obtained from all the participants.

Stimuli

Four experimental conditions were defined by linguistic function and context. Stimuli were presented in four oddball conditions (see Fig. 1). *The normal tone condition* consisted of two Mandarin syllables that have the same vowel and consonant /gai/ but different lexical tone (tone 3 and tone 4). Both were pronounced in a declarative intonation, syllable /gai3/ was frequently presented as the standard stimulus and syllable /gai4/ was infrequently presented as the deviant stimulus. The *hummed tone condition* was the hummed version of normal tone condition. The *normal intonation condition* consisted of the syllable /gai4/ pronounced in a declarative intonation and an interrogative intonation respectively. The declarative one was presented as the standard stimulus and the interrogative one was presented as the deviant stimulus. The *hummed intonation condition* was the hummed version of normal intonation condition.

Table 1 presents the acoustic characteristics of the experimental stimuli. The syllables used in speech conditions were pronounced by a well-trained male speaker and digitized at a sampling rate of 22,050 Hz. The hummed stimuli were created by resynthesizing the speech stimuli with Praat software (Boersma and Weenink, 2004, from http://www.praat.org) to eliminate the segmental information (vowel and consonant). The hums only conveyed the pitch changes and the suprasegmental information such as the fundamental frequency (F0), duration, and intensity of the normal speech stimuli. All the stimuli were normalized to 70 dB in intensity and 450 ms in duration, including 5 ms rising and falling times.

Concerning the acoustic manifestation of declarative and interrogative intonation in non-tonal languages, F0 contours of interrogative intonations are typically associated with final rises compared to declarative intonations. However, in tonal languages such as Chinese, the interrogative intonation involves not only local F0 variations but also more global patterns (Xu, 2005). For example, in the case of the Mandarin falling tone (as showed in Fig. 1), F0 drops even in a question but the overall height of the F0 is rising. The reasons are likely that in a tone language the local pitch targets are not easily changed, for they encode lexical information (Liu and Xu, 2005).