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Left hemisphere lateralization for lexical and acoustic pitch processing in Cantonese speakers as revealed by mismatch negativity

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ABSTRACT

For nontonal language speakers, speech processing is lateralized to the left hemisphere and musical processing is lateralized to the right hemisphere (i.e., function-dependent brain asymmetry). On the other hand, acoustic temporal processing is lateralized to the left hemisphere and spectral/pitch processing is lateralized to the right hemisphere (i.e., acoustic-dependent brain asymmetry). In this study, we examine whether the hemispheric lateralization of lexical pitch and acoustic pitch processing in tonal language speakers is consistent with the patterns of function- and acoustic-dependent brain asymmetry in nontonal language speakers. Pitch contrast in both speech stimuli (syllable /ji/ in Experiment 1) and nonspeech stimuli (harmonic tone in Experiment 1; pure tone in Experiment 2) was presented to native Cantonese speakers in passive oddball paradigms. We found that the mismatch negativity (MMN) elicited by lexical pitch contrast was lateralized to the left hemisphere, which is consistent with the pattern of function-dependent brain asymmetry (i.e., left hemisphere lateralization for speech processing) in nontonal language speakers. However, the MMN elicited by acoustic pitch contrast was also left hemisphere lateralized (harmonic tone in Experiment 1) or showed a tendency for left hemisphere lateralization (pure tone in Experiment 2), which is inconsistent with the pattern of acoustic-dependent brain asymmetry (i.e., right hemisphere lateralization for acoustic pitch processing) in nontonal language speakers. The consistent pattern of function-dependent brain asymmetry and the inconsistent pattern of acoustic-dependent brain asymmetry between tonal and nontonal language speakers can be explained by the hypothesis that the acoustic-dependent brain asymmetry is the consequence of a carryover effect from function-dependent brain asymmetry. Potential evolutionary implication of this hypothesis is discussed.

Introduction

Function-dependent brain asymmetry has been found since the 19th century in nontonal language speakers. Speech processing is lateralized to the left hemisphere (LH) in an overwhelming majority of right-handed individuals (Binder et al., 1996; Broca, 1861; Wernicke, 1874; Zatorre et al., 1992), whereas musical processing is lateralized to the right hemisphere (RH) (Peretz, 1990; Tramo, 2001; Zatorre et al., 2002; Zatorre et al., 1994). In the past few decades, acoustic-dependent brain asymmetry has been found in nontonal language speakers as well. Temporal processing is lateralized to the LH, whereas spectral/pitch processing is lateralized to the RH (Jamison et al., 2006; Okamoto et al., 2009; Schonwiesner et al., 2005; Zatorre and Belin, 2001). Because speech perception mainly depends on temporal information (Shannon et al., 1995; Tallal et al., 1993) and music perception mainly depends on pitch information (Sauter et al., 2010; Shofner, 2005) for nontonal language speakers, previous studies speculated that acoustic-dependent brain asymmetry is the low-level acoustic processing basis and evolutionary precursor of function-dependent brain asymmetry (Belin et al., 1998; Devlin et al., 2003; Jamison et al., 2006; Okamoto et al., 2009; Schonwiesner et al., 2005; Zaehle et al., 2009; Zaehle et al., 2004; Zatorre and Belin, 2001).

Interestingly, for tonal language speakers, the two aforementioned brain asymmetry observations (i.e., function-dependent brain

Abbreviations: MMN, mismatch negativity; LH, left hemisphere; RH, right hemisphere; L2 MCE, L2 minimum-norm current estimates; f0, fundamental frequency.

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asymmetry and acoustic-dependent brain asymmetry) should diverge in their predictions of hemispheric lateralization for lexical tone processing. Function-dependent brain asymmetry predicts LH lateralization because lexical tones are used systematically to determine lexical meanings (Pike, 1948), whereas acoustic-dependent brain asymmetry predicts RH lateralization because pitch information provides the primary cue for lexical tone perception (Abramson, 1978; Gandour, 1978). Previous brain imaging studies have found LH lateralization for lexical pitch processing, which is consistent with the pattern of function-dependent brain asymmetry (e.g., Gandour et al., 2000; Hsieh et al., 2001; for a review, see Zatorre and Gandour, 2008). However, the hemispheric lateralization of acoustic pitch processing in tonal language speakers has been less well studied.

In this study, two experiments were carried out to examine the hemispheric lateralization for lexical pitch (i.e., lexical tones) and acoustic pitch (i.e., harmonic tone/pure tone without linguistic information) processing in native Cantonese speakers. Pitch contrast in both speech stimuli (i.e., Cantonese syllable /ji/ in Experiment 1) and nonspeech stimuli (i.e., harmonic tone in Experiment 1 and pure tone in Experiment 2) was presented in passive oddball paradigms. The mismatch negativity (MMN) response, which has been widely used to study function- and acoustic-dependent brain asymmetry (Rinne et al., 1999; Shestakova et al., 2002; Shtyrov et al., 2000; Shtyrov et al., 2005; Zaehle et al., 2009), was analyzed.

We found that the MMN elicited by lexical pitch contrast was LH lateralized. This is consistent with the pattern of function-dependent brain asymmetry in nontonal language speakers which suggests LH lateralization for speech processing. Strikingly, acoustic pitch contrast, in the absence of linguistic information, also elicited LH lateralized MMN (harmonic tone in Experiment 1). This, however, is inconsistent with the pattern of acoustic-dependent brain asymmetry in nontonal language speakers which suggests RH lateralization for acoustic pitch processing. Taking into account the different functions of pitch information in tonal and nontonal languages, the consistent pattern of function-dependent brain asymmetry and the inconsistent pattern of acoustic-dependent brain asymmetry can be accommodated by the "lateralization-carryover hypothesis", which suggests that the acoustic-dependent brain asymmetry is the consequence of a carryover effect from function-dependent brain asymmetry in both tonal and nontonal language speakers.

Materials and methods

Experiment 1

Subjects

Sixteen native Cantonese speakers (8 male; mean age = 19.5 years, SD = 2.1 years; right-handed; normal hearing; musically untrained) participated in this study. All subjects were students at the Northwest University for Nationalities. They all started learning Mandarin Chinese at around age 5, and started learning English at around age 11. No subjects had experience learning any other language. The experimental procedures were approved by the Ethics Committee of the Institute of Medicine, Northwest University for Nationalities. All subjects provided informed written consent.

Stimuli

Speech stimuli used in this study were syllable /ji/ which carries three Cantonese level tones, i.e., /ji55/ (high level tone, 醫 "doctor"), /ji33/ (mid level tone, 意 "spaghetti"), and /ji22/ (low level tone, 二 "two"). Note that the tones were transcribed with Chao's 5-scale tone letters (Fig. 1A), with 1 and 5 referring to the lowest and highest pitch of a talker's normal voice range respectively (Chao, 1947; Yip, 2002). These three stimuli were synthesized using SenSyn (Sensimetrics Corporation, Malden, Massachusetts, U.S.A.), a Klatt-style cascade/parallel formant synthesizer (Klatt and Klatt, 1990). The fundamental frequency (f0), formant frequencies, syllable duration, and amplitude envelope of the synthetic syllables were modeled after naturally produced speech sounds. The f0s of /ji55/, /ji33/, and /ji22/ were 140.0 Hz, 117.5 Hz, and 100.0 Hz respectively. The duration (300 ms), formant frequencies and amplitude envelope were kept identical across the three stimuli (Fig. 1B). These three speech stimuli have been previously used in a behavioral study of categorical perception, and each stimulus has been confirmed to be recognized by Cantonese speakers with high accuracy rates when presented in isolation (accuracy rate > 70%) and when presented in a speech context (accuracy rate > 90%) (Francis et al., 2003).

Nonspeech stimuli used in this study were three harmonic tone stimuli which matched the three speech stimuli in terms of the duration, amplitude envelope, and f0 (Fig. 1B). Previous study shows that the 2–10th harmonics in the harmonic tone stimulus dominate the pitch perception for human being (Yost, 2009). In this study the harmonics below the 10th were preserved in order to ensure salient pitch perception. The harmonics of each harmonic tone stimulus were limited to 0–1500 Hz so that the sound timbre was matched across these three stimuli. The sound waveforms, spectrograms, and f0 of the speech and nonspeech stimuli are shown in Fig. 1B.

Procedure

Speech and nonspeech stimuli were presented in two separate sessions. For the speech session, each of the three stimuli was paired with the other two stimuli, giving rise to six pairs in total (/ji55/-/ji33/, /ji55/-/ji22/, /ji33/-/ji55/, /ji33/-/ji22/, /ji22/-/ji55/, and /ji22/-/ji33/). Each pair of stimuli was presented in an oddball paradigm, with the first stimulus serving as the standard and the second stimulus serving

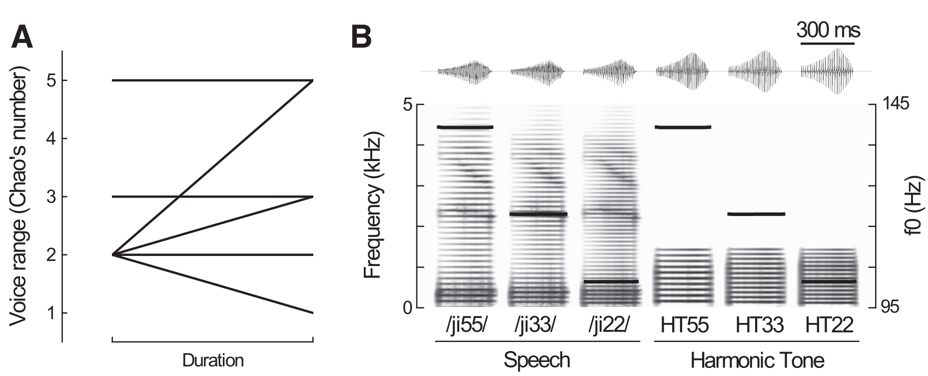

Fig. 1. The Cantonese tonal system and the stimuli used in Experiment 1. (A) A schematic for Cantonese tonal system. Tones were transcribed with Chao's 5-scale tone letters, with 1 and 5 referring to the lowest and highest pitch of a talker's normal voice range. There are six tones in Cantonese, i.e., high-level tone (55), high-rising tone (25), mid-level tone (33), low-rising tone (23), low-level tone (33), and low-falling tone (21). (B) Acoustic waveforms, spectrograms, and fundamental frequency (f0) contours of the three speech stimuli (syllables) and three nonspeech stimuli (harmonic tones) used in Experiment 1.