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TONE-LANGUAGE SPEAKERS SHOW HEMISPHERIC SPECIALIZATION AND DIFFERENTIAL CORTICAL PROCESSING OF CONTOUR AND INTERVAL CUES FOR PITCH

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Abstract—Electrophysiological studies demonstrate that the neural coding of pitch is modulated by language experience and the linguistic relevance of the auditory input; both rightward and leftward asymmetries have been observed in the hemispheric specialization for pitch. In music, pitch is encoded using two primary features: contour (patterns of rises and falls) and interval (frequency separation between tones) cues. Recent evoked potential studies demonstrate that these ''global'' (contour) and ''local'' (interval) aspects of pitch are processed automatically (but bilaterally) in trained musicians. Here, we examined whether alternate forms of pitch expertise, namely, tone-language experience (i.e., Chinese), influence the early detection of contour and intervallic deviations within ongoing pitch sequences. Neuroelectric mismatch negativity (MMN) potentials were recorded in Chinese speakers and English-speaking nonmusicians in response to continuous pitch sequences with occasional global or local deviations in the ongoing melodic stream. This paradigm allowed us to explore potential cross-language differences in the hemispheric weighting for contour and interval processing of pitch. Chinese speakers showed differential pitch encoding between hemispheres not observed in English listeners; Chinese MMNs revealed a rightward bias for contour processing but a leftward hemispheric laterality for interval processing. In contrast, no asymmetries were observed in the English group. Collectively, our findings suggest tone-language experience sensitizes auditory brain mechanisms for the detection of subtle global/local pitch changes in the ongoing auditory stream and exaggerates functional asymmetries in pitch processing between cerebral hemispheres. **© 2015 IBRO. Published by Elsevier Ltd. All rights reserved.**

Key words: auditory event-related potentials (ERPs), hemispheric laterality, mismatch negativity (MMN), melody perception, Mandarin Chinese.

INTRODUCTION

Following sequences of tones within the auditory stream is a basic aspect of music listening. From a perceptual perspective, tonal melodies are said to contain two types of pitch structure: *contour* and *interval* cues. Pitch contour signals directions i.e., the patterns of tonal rises and falls, whereas interval information emphasizes the precise pitch distance between two adjacent tones (Dowling, 1982). Contour and interval cues are often mapped onto ''global'' and ''local'' structures of the auditory stream, respectively (Dowling, 1982). While both of these pitch features are important in identifying and memorizing tonal sequences (Dowling, 1982), previous studies have shown that musically naïve listeners are better at detecting global (contour) compared to local (interval) changes in melodies (Fujioka et al., 2004). This suggests that contour processing is a more basic mechanism or perhaps a more dominant cue than interval processing.

In recent years, the mismatch negativity (MMN) has been used to examine if contour and interval information is automatically extracted by the auditory system at pre-attentive levels of pitch processing (e.g., Fujioka et al., 2004). The MMN is a scalp-recorded, event-related brain potential that indexes early cortical stages of auditory processing (Naatanen, 2001). To understand whether pitch contour and interval are encoded automatically, Trainor et al. (2002) examined nonmusicians' MMNs, evoked by a passive presentation of continuous pitch sequences that contained occasional contour or interval deviations in the ongoing melodic stream. Both pitch contour and interval cues generated a ''pre-attentive'' MMN, suggesting that the brain automatically encodes salient features of melodic streams (i.e., contour and interval) even in listeners who lack formal musical training (Trainor et al., 2002).

Extending these findings, Fujioka et al. (2004) showed that MMNs to contour deviations were larger in trained musicians compared to nonmusicians. Interestingly, musicians also showed a bias in pitch processing not observed in nonmusicians where interval responses were larger than contour responses. These results suggest pitch interval and contour features are automatically extracted by early auditory cortex and moreover, that

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Abbreviations: ANOVA, analysis of variance; ERPs, event-related potentials; LH, left hemisphere; L2, second language; MMN, mismatch negativity; PCA, principal component analysis; RH, right hemisphere.

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processing of these cues is differentially heightened in listeners with extensive auditory (pitch) experience. Pitch contour cues are crucial not only to musical melodies but also speech prosody (Patel et al., 1998). In addition to the normal suprasegmental use of pitch (e.g., signaling stress patterns), tone languages further exploit variation in pitch at the syllable level to signal word meaning (Gandour, 1983). Given their extensive use of pitch at both local (syllable) and global (phrase) levels of processing, we hypothesized that tone language (i.e., linguistic pitch) experience might similarly influence the early cortical processing of interval (cf. local; word-level) and contour (cf. global; phrase-level) information of ongoing pitch sequences.

Additionally, we aimed to delineate possible functional asymmetries in pitch processing between the cerebral hemispheres. Evidence from brain lesioned patients and comparisons among musically trained versus untrained listeners suggests a hemispheric specialization for contour and interval processing. For instance, musicians show a right ear advantage for melodies behaviorally, whereas nonmusicians show a left ear advantage (Bever and Chiarello, 1974). Identification of melodic sequences sharing common pitch contours is also better in the left compared to the right ear (Peretz and Babaï, 1992). Lesion-deficit studies further indicate a functional distinction between contour and interval processing between the cerebral hemispheres. Indeed, right brain-damaged patients are more impaired in using contour cues for melodic processing than are left brain-damaged patients and neurologically normal individuals (Peretz, 1990). Complementary findings were reported by Liégeois-Chauvel et al. (1998), who found that left temporal lobe lesions produce deficiencies in interval-related processing. Collectively, these findings suggest that the left hemisphere (LH) is specialized for analytic pitch processing and the right hemisphere (RH) is more adapted for holistic pitch processing (e.g., Zatorre et al., 2002). That is, the LH is sensitive to intervallic changes whereas the RH is specialized for analyzing contour changes in pitch.

Although hemispheric specialization has been reported in the aforementioned behavioral and lesion studies, electrophysiological reports have been unable to demonstrate hemispheric laterality for pitch contour and interval processing using scalp-recorded event-related potentials (ERPs). This inconsistency presumably results from the fact that laterality effects are either too subtle to detect via ERPs or that they occur in processing stages after the automatic generation of the MMN (Trainor et al., 2002; Fujioka et al., 2004). However, previous studies have demonstrated that both cortical (Gandour et al., 2000; Chandrasekaran et al., 2007; Giuliano et al., 2011) and subcortical (Bidelman et al., 2011a,b) neural activity is modulated by long-term experience with a tone language (e.g., Mandarin Chinese). While all languages use pitch for suprasegmental linguistic distinctions (e.g., stress, intonation), tone languages are unique in that pitch is used to make lexical distinctions at the word level. In this regard, tonal languages provide an ideal window into the hemispheric specialization of pitch given the strong link between this auditory cue and speech-language processing.

Indeed, native listeners of Mandarin Chinese show enhanced MMNs in response to changes in linguistic pitch patterns (Chandrasekaran et al., 2007, 2009a) with stronger responses over the right compared to left hemisphere (Luo et al., 2006; Ren et al., 2009). These studies demonstrate that early cortical pitch processing for isolated tones, as indexed by the MMN, is heightened by linguistic pitch experience (i.e., languages which use pitch to signal word meaning). As such, tone language speakers provide a unique opportunity to further investigate potential hemispheric biases in pitch processing given their long-term exposure and use of the complex pitch patterns of the Mandarin tonal space. Yet to our knowledge, it remains an open question whether or not tone language experience enhances functional asymmetries between hemispheres with regard to contour and interval processing *in continuous auditory sequences.*

The aim of the current study was to determine the effects of tone language experience on cortical processing of pitch contour and interval within ongoing tonal sequences. To this end, we recorded neuroelectric MMN responses in native Chinese- and English-speaking listeners in response to continuous tonal patterns that featured occasional deviants in ‘‘global'' (contour) or ‘‘local'' (interval) aspects of the ongoing, continuous auditory stream (Fig. 1). The presence of a mismatch response in this stimulus paradigm would provide further evidence that the MMN is sensitive to the *relations* among tones that comprise pitch patterns (i.e., Gestalt properties) rather than only physical properties of individual stimuli, per se (e.g., ‘‘auditory pattern MMN''; Alain et al., 1998, 1999). Comparisons between language groups allowed us to assess whether tone language speakers show a hemispheric specialization for contour and interval processing. Consistent with previous neurophysiological studies (Gandour et al., 2000; Chandrasekaran et al., 2007; Giuliano et al., 2011; Bidelman and Lee, 2015), we expected to observe enhanced pitch MMNs in Chinese listeners across the board. Additionally, based on previous behavioral and lesion data (Peretz, 1990; Liégeois-Chauvel et al., 1998), we expected to find that the cortical encoding of pitch contour and interval in Chinese listeners is dominated by neural mechanisms of the right and left hemisphere, respectively. This would support the notion that the hemispheric weighting of these two pitch cues is modulated in an experience-dependent manner according to language experience.

EXPERIMENTAL PROCEDURES

Participants

Twelve adult native speakers of Mandarin Chinese (3 males) and twelve adult native speakers of American English (3 males) participated in the experiment. Musical training is known to enhance the auditory-evoked potentials for pitch stimuli (e.g., Chandrasekaran et al., 2009a; Bidelman et al., 2011a; Bidelman and Alain, 2015). Thus, all subjects were required to have min-

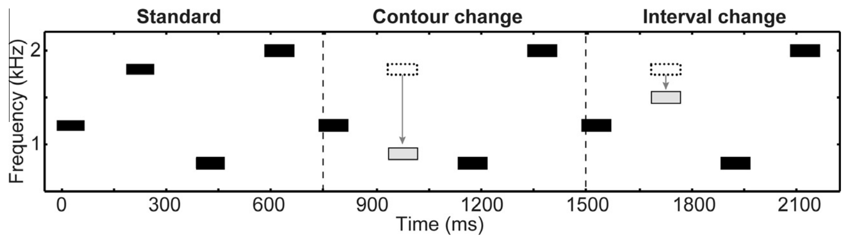

Fig. 1. Schematic spectrogram of pitch contour and interval stimuli. Stimuli are shown for a standard four-tone sequence and deviant conditions which altered the "global" contour or "local" interval structure of the repeating pitch pattern by altering the sequence's second tone (dotted and open boxes). Pitch sequences were presented continuously (without pause) to establish the expectancy of the entire auditory pattern as a whole (Alain et al., 1998). Deviants occurred with 15% probability for each type of pitch deviant.

imal (less than 3 years) formal music instruction. Participants were closely matched in age (Chinese: $M = 30.09$, $SD = 4.37$ years; English: $M = 27.81$, $SD = 3.60$ years), years of formal education (Chinese: $M = 19.04$, $SD = 2.23$ years; English: $M = 18.5$ years, $SD = 2.53$), and were right handed ($\geqslant$78%) as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). An independent *t*-test revealed that there was no significant difference in handedness between Chinese and English speakers [$t(11.13) = 1.91$, $p = 0.083$]. Participants reported no history of hearing, speech, language, neuropsychiatric disorders. Each participant also completed a language history questionnaire (Li et al., 2006). Following our previous studies (Bidelman et al., 2011a; Bidelman and Lee, 2015), Chinese participants were characterized as late bilinguals whose first language was Mandarin. They were born and raised in China or Taiwan, and their onset age of L2 English learning was ~11 years ($M = 11.33$, $SD = 1.37$ years). English-speaking participants had no experience of learning a tone language of any kind. The majority of participants were students enrolled at the University of Memphis at the time of their participation. All gave written informed consent in compliance with a protocol approved by the University of Memphis Institutional Review Board.

Stimuli

Four-tone pitch patterns were synthesized using MATLAB 2013b (The Mathworks, Inc., Natick MA, USA) based on previous studies of auditory pattern MMN (Alain et al., 1998) modified to accommodate the contour/interval manipulations of Ziegler et al. (2012). Both contour and the interval conditions consisted of a standard pattern of four tones (1200, 1800, 800, 2000 Hz, see Fig. 1). Each tone was 50 ms in duration including a 5-ms rise/fall time. The interstimulus interval (ISI) between consecutive tones was 150 ms. Tonal patterns were presented continuously (i.e., sequences repeated back-to-back) and periodically contained one of two types of deviants within the four-tone pattern: (1) a *contour change*, in which the standard second tone was 1800 Hz, but the deviant tone was 900 Hz; and (2) *interval change* condition, in which the standard second tone was 1800 Hz, but the deviant was 1500 Hz. Contour deviants altered the "global" pattern of pitch rises and falls whereas interval deviants preserved the contour of the pitch sequence but altered the "local" pitch distance between tones. The two conditions were presented in separate blocks with one pitch type occurring per block. Deviants occurred with a probability of 15%. In total, listeners heard 7200 standard and 1080 deviant pitch sequences (i.e., 3600 standard and 540 deviants per condition).

Data acquisition and preprocessing

Electrophysiological recording procedures followed typical procedures used in our laboratory (Bidelman, 2015; Bidelman and Lee, 2015). Participants reclined comfortably in an electro-acoustically shielded booth to facilitate recording of neurophysiologic responses. They were instructed to relax and refrain from extraneous body movement (to minimize myogenic artifacts), ignore the sounds they hear (to divert attention away from the auditory stimuli), and were allowed to watch a muted subtitled movie to maintain a calm yet wakeful state. In other words, MMNs for pitch contour and interval stimuli were recorded under a passive listening paradigm. Stimulus presentation was controlled by a MATLAB routed to a TDT RP2 interface (Tucker-Davis Technologies, Alachua, FL, USA) and delivered binaurally at an intensity of 82-dB SPL through insert earphones (ER-2A; Etymotic Research, Elk Grove Village, IL, USA).

Neuroelectric activity was recorded from 64 electrodes at standard 10–10 locations around the scalp (Oostenveld and Praamstra, 2001). EEGs were digitized using a sampling rate of 500 Hz (SynAmps RT amplifiers; Compumedics Neuroscan, Charlotte, NC, USA) using an online passband of DC-200 Hz. Responses were then stored to disk for offline analysis. Electrodes placed on the outer canthi of the eyes and the superior and inferior orbit were used to monitor ocular activity. During online acquisition, all electrodes were referenced to an additional sensor placed ~1 cm posterior to Cz. However, data were re-referenced off-line to a common average reference. Contact impedances were maintained $< 10\ k\Omega$ throughout the duration of the experiment.

Subsequent preprocessing was performed in Curry 7 (Compumedics Neuroscan) and custom routines coded in MATLAB. Data visualization and scalp topographies were computed using EEG/ERPLAB (Delorme and Makeig, 2004; Lopez-Calderon and Luck, 2014). Prior to artifact correction, excessively noisy channels were interpolated and paroxysmal segments (i.e., $> 500\ \mu V$) were automatically discarded. Ocular artifacts (saccades and blink artifacts) were then corrected in the continuous EEG using a principal component analysis (PCA) (Wallstrom et al., 2004). The PCA decomposition provided a set of independent components which best explained the topography of the blink/saccadic artifacts. The scalp projection of the first two PCA loadings was subtracted from the continuous EEG traces to nullify ocular contamination in the final ERPs. Cleaned EEGs were then digitally filtered (1–20 Hz; zero-phase filters), epoched (−50–725 ms), baseline-corrected to the pre-stimulus period, and subsequently averaged in the time domain to obtain ERPs for each pitch condition per participant.

ERP response analysis

MMNs for both contour and interval conditions were computed as the difference between the ERPs recorded for deviant contour/interval stimuli and those recorded for standard stimuli (i.e., deviant-standard). For the purpose of data reduction and to explicitly test hemispheric laterality effects, we collapsed the sensor data into two electrode clusters covering left and right temporal regions on the scalp. This a priori selection of left and right clusters was used to minimize potential bias in electrode selection and was informed by regions of interest reported in previous work (cf. Marie and Trainor, 2012). The mean response of four adjacent electrodes within each cluster defined the two "super electrodes" in each of the left and right hemispheres (LH cluster: FC5, FC3, C5, C3; RH cluster: FC4, FC6, C4, C6) (see Fig. 2).

Auditory pattern MMNs tend to emerge after ~250 ms following the initiation of change in the running sequence (Alain et al., 1998), later than typical MMNs to isolated pitch deviants (Chandrasekaran et al., 2009a; Hutka et al., 2015). To objectively select an analysis window to quantify MMNs, we first examined the magnitude of difference potentials between pitch conditions (i.e., $|MMN_{cont} - MMN_{int}|$) (see Fig. 3). For each time sample of the MMN, we then conducted single-sample *t*-tests (null hypothesis = 0 voltage across listeners) to identify where within the epoch window, contour and interval deviants were reliably distinguished ($p < 0.05$) in each hemisphere. We required that running significant periods persist for >20 ms to be considered reliable and help control false positives (e.g., Guthrie and Buchwald, 1991). This preliminary analysis identified a temporal extent between ~500 and 600 ms that showed prominent differential responses between pitch conditions (see Fig. 3). Consequently, MMN amplitudes were quantified for each participant per group, condition, and hemisphere as the peak negativity within this 500–600-ms time window.

Statistical analysis

MMM amplitudes were analyzed using a 3-way mixed model Analysis of variance (ANOVA) with hemisphere (2 levels: LH, RH) and pitch type (2 levels: contour, interval) as fixed, within-subject factors and group as a between-subject factor (2 levels: Chinese, English). Subjects served as a random factor. Following this omnibus analysis, separate 2-way ANOVAs by group (hemi x pitch type) allowed us to tease apart differences in stimulus and laterality effects between groups. Post hoc multiple comparisons were adjusted using Tukey corrections to control Type I error inflation. An a priori alpha level was set at $\alpha = 0.05$.

RESULTS

Fig. 2 shows the MMN time waveforms and scalp-topographies in response to contour and interval

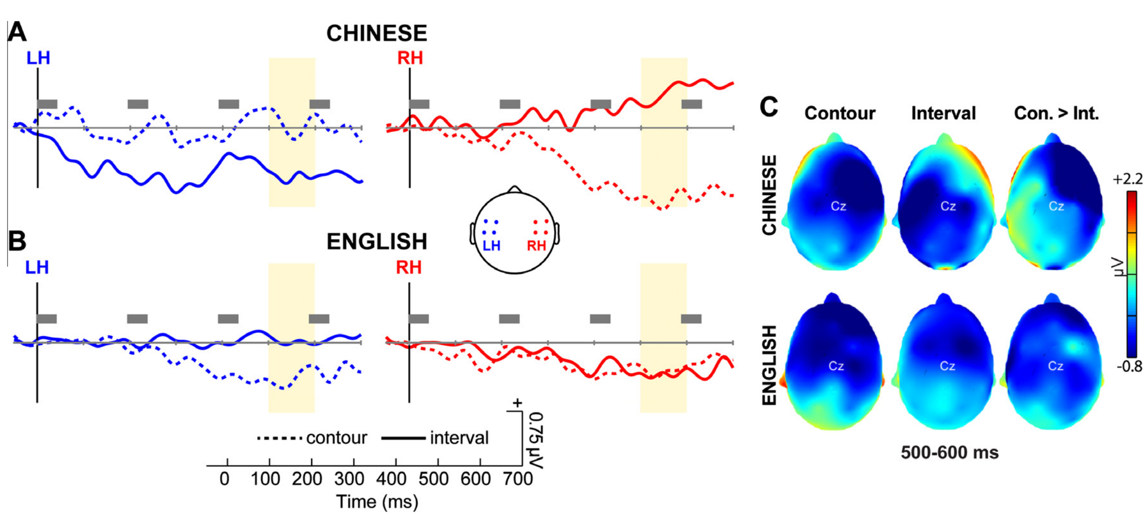

Fig. 2. Tone-language listeners show a differential pattern of cortical processing for interval vs. contour pitch cues. MMN time waveforms for the Chinese (A) and English (B) group extracted from the left and right hemisphere regions of interest (inset head). MMNs were quantified in the 500–600-ms time window (highlighted region). Chinese listeners show stronger sensitivity to pitch interval changes in the LH and contour changes in the RH. No laterality is observed in English listeners who demonstrated more bilaterally-symmetric MMNs. (C) Scalp topographies of the MMN to pitch interval and contour stimuli per language group (500–600-ms window). Difference maps illustrate a rightward shift in hemispheric laterality for the Chinese group when processing "global" (contour) compared to "local" (interval) features within a continuous stream of pitch.

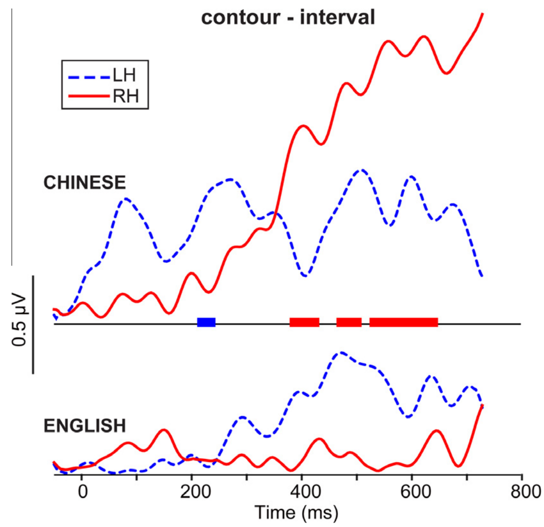

Fig. 3. Differential MMN responses ($|MMN_{contour} - MMN_{int}|$) contrasting cortical deviance detection between contour and interval conditions. Colored segments along the time axes demarcate temporal periods (> 20 ms) which showed significant differences between pitch types based on a running *t*-test (i.e., Guthrie and Buchwald, 1991). Right/left hemisphere (RH/LH): red and blue, respectively. Contour responses are dominant in the RH ~500–600 ms after the onset of the stimulus (i.e., 300–400 ms after onset of the deviant pattern). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sequences for Chinese and English listeners. Chinese demonstrated larger MMNs for deviant pitch intervals in the LH and for deviant pitch contours in the RH. In contrast, no asymmetry was found in the English group. Scalp topographies further illustrate the relative dominance of pitch interval and contour encoding between language groups (Fig. 2C). In both groups, MMNs appeared maximal at frontal areas of the scalp. However, compared to English listeners, Chinese showed a distinct shift in the hemispheric laterality of cortical activity between interval and contour stimuli. Whereas interval cues tended to elicit stronger neural activity in the LH, variations in pitch contour evoked stronger activity in the RH. This asymmetry was less pronounced in English listeners, who showed more bilaterally distributed mismatch responses over the scalp.

Difference potentials contrasting responses to each condition (i.e., $|MMN_{cont} - MMN_{int}|$) were used to objectively identify where in time contour and interval processing differed in each hemisphere (Fig. 3). A running *t*-test at each time sample allowed us to identify temporal extents (> 20 ms) that showed reliable differences between conditions (Guthrie and Buchwald, 1991). Whereas no reliable contour > interval differential was observed in English speakers, prominent differences between pitch types were observed in Chinese listeners MMNs ~500–600 ms after stimulus onset (i.e., 300–400 ms after deviance in the auditory pattern, Fig. 1). Consequently, we quantified MMN amplitudes per group, hemisphere, and participant in this 500–600-ms search window.

An omnibus ANOVA on MMN amplitudes showed a strong three-way group x pitch type x hemisphere interaction [$F(1, 66) = 7.53$, $p = 0.0078$]. By group, separate two-way ANOVAs revealed a pitch type x hemisphere interaction only in Chinese listeners [$F(1, 33) = 6.10$, $p = 0.0189$] (Fig. 4A). Follow up contrasts revealed that for interval deviants, in Chinese the LH responded more strongly (i.e., more negative MMN) than RH ($p = 0.0302$). By hemisphere, we found that the RH distinguished contour and interval deviants ($p = 0.0035$). In contrast, no main effects of pitch type, hemisphere, nor a pitch type x hemisphere interaction were observed in English listeners [pitch type x hemisphere: $F(1, 33) = 1.92$, $p = 0.1751$] (Fig. 4B). That is, English listeners' MMNs were invariant to contour and interval manipulations in both hemispheres.

Between-group comparisons revealed a significant group x pitch type interaction in the RH [$F(1, 22) = 8.12$, $p = 0.0093$] but not LH [$F(1, 22) = 2.55$, $p = 0.1245$]. Follow-up contrasts revealed this RH interaction was attributable to Chinese listeners having stronger responses to contour compared to interval deviants. Collectively, these results suggest a differential pattern of cortical pitch processing between language groups whereby the cerebral hemispheres (particularly RH) differentiate pitch contour and interval cues in tone-language speakers; this hemispheric lateralization is not present in English-speaking individuals.

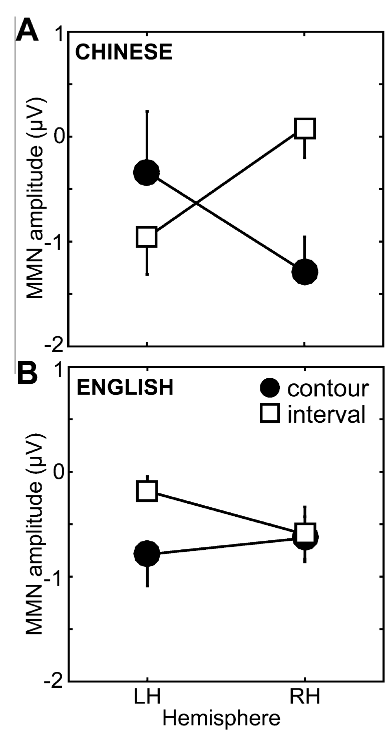

Fig. 4. MMN magnitude as a function of pitch deviation and language experience. (A) Chinese listeners show a hemisphere x pitch type interaction, indicating a differential pattern in the cortical pitch processing of contour and interval cues between hemispheres. (B) English listeners show relatively bilateral MMNs in response to both forms of pitch deviation and no hemispheric specialization is observed as in the Chinese group. Errorbars denote ± 1 s.e.m.

DISCUSSION

Previous studies have investigated language-dependent changes in the hemispheric laterality of tone processing in isolated pitch stimuli (e.g., Gandour et al., 2004; Luo et al., 2006). Our results extend these previous studies by demonstrating a hemispheric asymmetry in the cortical processing of contour and interval features *within ongoing, continuous pitch patterns*. We found that in Chinese speakers, RH controls detection of changes in contour (“global” attribute) and LH controls detection of changes in interval structure (“local” attribute). Moreover, comparisons between language groups suggest that the hemispheric weighting of these two pitch cues is modulated in an experience-dependent manner. Tone language (Chinese) listeners who have extensive experience with the linguistic use of pitch in their native language showed stronger, more asymmetric processing of contour and interval cues than non-tone language listeners (English) who lack extensive pitch expertise. That is, pitch is less important for English prosodic perception relative to amplitude and duration cues (Choi et al., 2005; Kochanski et al., 2005). Previous studies have shown enhanced cortical responses to *isolated* linguistic pitch patterns (Gandour et al., 2000; Chandrasekaran et al., 2009a,b; Bidelman and Lee, 2015). Yet, in addition to attending to pitch at the syllable level to distinguish word identity, Mandarin speakers must also track ongoing, *global* (i.e., phrase-level) changes in pitch patterns to integrate lexical pitch items over time. It is conceivable that the higher cortical sensitivity to global aspects of pitch patterns observed in Chinese speakers results from a need to concurrently process pitch at both local and global levels of analysis. While the mechanistic connection between lexical tone experience and global pitch processing is not immediately apparent, our data are nevertheless broadly consistent with the finding that contour analysis is important for language-related skills. Indeed, English word reading abilities are associated with successful analysis of global acoustic structure because English stress perception is dependent on pitch contour processing (e.g., Foxton et al., 2003).

In the present study, deviations in contour and interval structure established by a continuous stream of a repeating pitch pattern elicited reliable MMNs. Moreover, these mismatch responses were observed under a passive listening paradigm. These findings support the notion that contour and interval features are extracted by early auditory cortical structures in pre-attentive manner (Trainor et al., 2002). Compared with previous studies (Trainor et al., 2002; Fujioka et al., 2004), deviant four-tone patterns in the current study differed from standard ones in the second tone rather than the final tone. In other words, listeners needed to process the entirety of the sequence and detect oddball tones embedded *within* rather than simply at the end of the tonal patterns as in previous work. The presence of a mismatch response in this embedded stimulus paradigm provides further evidence that MMN generation depends on an analysis of the integrated, abstract representation of multiple tonal events (comparison of larger auditory patterns) rather than only sensory features of constituent tones (Saarinen et al., 1992; Alain et al., 1994, 1998, 1999; Paavilainen et al., 1998; Trainor et al., 2002).

In Chinese listeners, MMNs elicited by contour deviations were also larger than those elicited by interval stimuli in the RH, whereas the reverse (but weaker pattern) was found in the LH. This double-dissociation (in Chinese speakers) points to a functional asymmetry between the two hemispheres when processing different perceptual attributes of pitch. Our findings here support the hypothesis in previous behavioral studies that contour processing is dominant in the RH and interval processing in the LH (Peretz, 1990; Peretz and Babaï, 1992; Liégeois-Chauvel et al., 1998). In Chinese, however, we found that MMN amplitudes elicited by contour deviants were much larger than those elicited by interval deviants in the RH. This further supports the notion that RH plays a critical role in processing fine spectral information necessary for pitch perception (Zatorre et al., 2002) and the idea that pitch contour is analyzed primarily by right auditory brain mechanisms.

In contrast, we found that English-speaking listeners’ MMNs were much weaker to both contour and interval deviations and did not show prominent laterality effects as in the tone language group. This corroborates previous findings that have been unable to establish hemispheric specialization for contour and interval processing in non-tone language speakers (Trainor et al., 2002; Fujioka et al., 2004). However, the equivocality of findings from previous neuroimaging studies indicates the subtlety of this laterality effect; functional asymmetries for contour and interval processing seem to be only detectable in tone-language listeners, i.e., those highly adept at perceiving pitch subtleties as a result of their extensive *linguistic pitch* experience. That tone language experience affects hemispheric specialization adds to the growing body of evidence that indicates a differential processing of pitch information between left and right perisylvian brain areas. They also agree with the notion that asymmetries reflect a complex interaction between (tone-)language experience and the degree to which the acoustic stimuli engage linguistic vs. domain-general auditory brain mechanisms (Zatorre and Gandour, 2008).

Interestingly we found more robust responses for contour relative to interval processing in Chinese listeners (i.e., contour > interval), particularly in the RH. This finding contrasts with studies examining other forms of auditory experience and the opposite pattern in musicians (i.e., interval > contour) (Fujioka et al., 2004). Taken together, our findings support the proposition that the influence of one domain on another might be differentially weighted depending the functional relevance of the auditory signal in question and the degree to which it matches with the listener’s specific expertise (Bidelman et al., 2011a,b, 2013). Indeed, specific training or long-term exposure in one domain (i.e., music or language) entrains a listener to utilize pitch cues associated with that domain (Bidelman et al., 2011a). Neurophysiological evidence from cortical brain potentials suggest that musicians exploit interval-based pitch cues (Fujioka et al., 2004; Bidelman et al., 2011a) while tone language speakers exploit contour-based cues (Chandrasekaran et al., 2007; Bidelman et al., 2011a). Such "cue weighting" is consistent with each group's unique listening experience and the relative importance of these dimensions to music (Burns and Ward, 1978) and lexical tone perception (Gandour, 1983), respectively. This argument partially assumes that lexical pitch and musical pitch involve similar mechanisms and developmental time courses—or at least alter the neural processing of pitch in a semi-parallel fashion. Under this premise, lexical pitch and musical pitch abilities should be correlated. Indeed, we have recently shown that in native speakers of Cantonese, more experience with lexical pitch in listeners' native tone language is associated with improved discrimination of musical melodies (Bidelman et al., 2013). The exact nature of hemispheric weighting in linguistic and musical pitch experts is undoubtedly more nuanced. Nevertheless, the preferential responses to contour pitch attributes in tone language speakers (present study) and interval attributes in musically trained listeners (Fujioka et al., 2004) might reflect a byproduct of the relative importance of these cues within the language and music domains, respectively.

In addition to explanations based on language experience and "cue weighting", differences in the magnitude of acoustic change may have also contributed to the observed data. In the present study, contour changes were associated with larger pitch differences (1800 vs. 900 Hz) than were intervals (1800 vs. 1500 Hz). Consequently, laterality effects might emerge due to a differential responsiveness between hemispheres to small vs. large pitch deviations. However, if this were the case, we would have expected similar laterality effects between language groups. Moreover, previous studies also indicate that the RH is more sensitive to smaller spectral deviations than the LH (Zatorre and Belin, 2001). On the contrary, we found that contour manipulations (with larger pitch changes) were actually lateralized rightward. While our data cannot fully rule out interplays between language experience, acoustic factors, and hemispheric specialization (e.g., Zatorre and Gandour, 2008), our results are corroborated by several lesion studies, which demonstrate the importance of LH for interval (Liégeois-Chauvel et al., 1998) and RH for contour (Peretz, 1990) processing.

Future studies might expand the work on the hemispheric specialization of feature-based pitch processing from a number of perspectives. As noted earlier, the fact that we only found hemispheric specialization for pitch processing in Chinese listeners might be due to tone language experience. Assuming tone language experience does indeed influence functional asymmetries between cerebral hemispheres, specialization of pitch processing would be predicted in young tone language speakers, and possibly second language (L2) learners as they acquire knowledge of the lexical tonal space. Based on this premise, we would predict that the strength of functional asymmetries in pitch processing would emerge according to the length of L2 experience with the tonal language. Moreover, certain tone languages (e.g., Cantonese) involve more level tones than Mandarin, which makes use of primarily contour tones. This implies there might be a differential sensitivity to contour/intervals cues even among tonal language speakers. Indeed, our recent studies suggest Mandarin speakers are less sensitive to interval-based pitch cues than their Cantonese peers (cf. Bidelman et al., 2011b, 2013). An interesting extension of the current study would be to examine how our findings of hemispheric dominance for contour and interval cues generalize to speakers of other tone languages.

Second, it remains unclear why music experience does not produce the same dissociation in contour and interval pitch processing as we find here with tone language experience. Previous studies directly comparing linguistic and musical pitch experience have generally shown stark similarities in the neuroplastic enhancements for pitch; experience in one of these domains often benefits pitch processing in the other (Pfordresher and Brown, 2009; Bidelman et al., 2011a, b, 2013; Hutka et al., 2015). It should be noted that most studies examining interval/contour lateralization have only examined *amateur* musicians with ~10–23 years of training (Fujioka et al., 2004). It remains possible that more advanced, professional musicians might show similar asymmetries as observed in our tone-language cohort as pitch experience would be more closely matched between groups. Chinese listeners had ~30 years of tone language experience in our sample. Alternatively, the hemispheric weighting for specific features of pitch might be more exaggerated with tone language experience given the parallel processing and natural tradeoffs between left and right brain regions when processing linguistically-relevant compared to nonspeech signals (Tervaniemi and Hugdahl, 2003; Zatorre and Gandour, 2008). Future studies are needed to test these alternate interpretations.

Lastly, based on scalp-recordings, our data cannot necessarily adjudicate between changes in the strength of MMN sources between hemisphere and other generator factors (e.g., polarity or orientation). Indeed, hemispheric effects might partially be explained by differences in dipole orientation between conditions. Nevertheless, the observed group difference in our data suggest that the neural generators underlying contour and interval pitch processing do differ on *some dimension* of the underlying sources (e.g., intensity and/or orientation) (Urbach and Kutas, 2006) and in a language-dependent manner. Future studies could address this issue by examining cross-language differences in our stimulus paradigm with neuroimaging techniques more amenable to source localization (e.g., MEG or fMRI).

In summary, results of the current study indicate stimulus- and language-dependent influences on the hemispheric laterality of pitch processing. Namely, we find that interval and contour information in continuous pitch patterns is processed differentially between left and right auditory cortices, respectively (RH: contour > interval; LH: interval > contour). Tone language experience enhances neural representations for pitch and the early auditory discrimination of contour and interval deviations. Moreover, linguistic pitch expertise exaggerates functional hemispheric asymmetries of contour and interval processing as non-tone language listeners show more symmetric, bilateral activation for these two pitch cues.

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