Subgroup differences in the lexical tone mismatch negativity (MMN) among Mandarin speakers with congenital amusia

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A B S T R A C T

The association/dissociation of pitch processing between music and language is a long lasting debate. We examined this music-language relationship by investigating to what extent pitch deficits in these two domains were dissociable. We focused on a special neurodevelopmental pitch disorder — congenital amusia, which primarily affects musical pitch processing. Recent research has also revealed lexical tone deficits in speech among amusics. Approximately one-third of Mandarin amusics exhibits behavioural difficulties in lexical tone perception, which is known as tone agnosia. Using mismatch negativities (MMNs), our current work probed lexical tone encoding at the pre-attentive level among the Mandarin amusics with (tone agnosics) and without (pure amusics) behavioural lexical tone deficits compared with age- and IQ-matched controls. Relative to the controls and the pure amusics, the tone agnosics exhibited reduced MMNs specifically in response to lexical tone changes. Their tone-consonant MMNs were intact and similar to those of the other two groups. Moreover, the tone MMN reduction over the left hemisphere was tightly linked to behavioural insensitivity to lexical tone changes. The current study thus provides the first psychophysiological evidence of subgroup differences in lexical tone processing among Mandarin amusics and links amusics’ behavioural tone deficits to impaired pre-attentive tone processing. Despite the overall music pitch deficits, the subgroup differences in lexical tone processing in Mandarin-speaking amusics suggest dissociation of pitch deficits between music and speech.

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1. Introduction

As the percept of the repetition rate of sound waveforms (frequency), pitch is an important characteristic of sound, playing essential roles in both music and language. A great deal of prior research has examined the relationship between music and language by investigating the transferability of pitch expertise across domains. Although ample research suggests a common neural architecture encoding pitch processing across domains (Besson, Chobert, & Marie, 2011; Bidelmann, Gandour, & Krishnan, 2011; Bidelmann, Hutka, & Moreno, 2013; Wong, Skoe, Russo, Dees, & Kraus, 2007), recent evidence indicates a music-language dissociation in pitch processing (Hutka, Bidelman, & Moreno, 2013; Nan & Friederici, 2013). We tackled this debate from another perspective, investigating this music-language relationship by examining to what extent pitch deficits in these two domains were dissociable.

In the music domain, the widely recognized pitch deficit affects a small portion (approximately 4%) of the general population, which is known as congenital amusia (hereafter amusics) (Peretz, 2001). The amusics individuals exhibit a characteristic musical pitch deficit (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Hyde & Peretz, 2004) that is neither of clear neurological origin nor due to a lack of musical exposure. Research suggests that congenital amusics may also have difficulties with pitch memory (Tillmann, Schulze, & Foxton, 2009; Albouy, Schulze, Caclin, & Tillmann, 2013; Gosselin, Jolicouer, & Peretz, 2009; Williamson & Stewart, 2010; Williamson, McDonald, Deutsch, Griffiths, & Stewart, 2010), timbre processing (Marin, Gingras, & Stewart, 2012), and emotional prosody perception (Thompson, Marin, & Stewart, 2012).

Nonetheless, amusics’ core deficit is related to musical pitch processing (Foxton et al., 2004; Hyde & Peretz, 2004). ERP studies from different research groups have demonstrated that amusics’ auditory musical pitch processing might be intact, whereas their explicit judgment or awareness of pitch perception might be compromised (Peretz, Brattico, Jarvenpaa, & Tervaniemi, 2009; Mignault,
Moreau, Robitaille, & Peretz, 2012; Moreau, Jolicoeur, & Peretz, 2013; Omigie, Pearce, Williamson, & Stewart, 2013). This interpretation is in line with brain-imaging results that have revealed structural abnormalities in the bilateral superior temporal and inferior frontal regions of amusics' brains (Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006; Hyde et al., 2007; Mandell, Schulze, & Schlaug, 2007). The associated abnormalities may reside not only in the auditory cortices (Albouy et al., 2013) but also in the temporoparietal frontal pathway that connects the auditory cortex to the inferior frontal region (Hyde, Zatorre, & Peretz, 2011; Loui, Alsop, & Schlaug, 2009; Albouy et al., 2013).

However, in the language domain, pitch deficits have rarely been reported alone in normal populations. Very often, they coexist with the condition of amusia. Accumulating evidence suggests that amusics are also impaired in linguistic tone processing at both the word (i.e., lexical tone, Liu et al., 2012; Nan, Sun, & Peretz, 2010; Tillmann et al., 2011) and sentence levels (i.e., intonation, Jiang, Hamm, Lim, Kirk, & Yang 2010; Jiang et al., 2012a; Liu, Patel, Fourcin, & Stewart, 2010; Patel, Foxton, & Griffiths, 2005).

The coexistence of pitch deficits in music and language may first appear to imply a close music-language association. However, the neural mechanisms that could account for the speech tone deficits have not been assessed as deeply as those underlying the music pitch deficits, i.e., amusia. So far, the neurophysiological nature of amusics' behavioural linguistic tone deficits remains largely unknown. To the best of our knowledge, there is only one study that has addressed possible abnormal event-related brain potentials in Mandarin-speaking amusics during speech intonation comprehension (Jiang et al., 2012a). In their study, inappropriate relative to appropriate intonation elicited a larger P600 and a smaller N100 in controls but not in amusics, which was taken as neurobiological evidence for intonation deficits in Mandarin-speaking amusics (Jiang et al., 2012a). Investigations of the neural mechanisms underpinning the linguistic tone deficits of amusics will expand our knowledge of the nature of amusia and consequently inform us about the possible optimal intervention options for helping to ameliorate the condition. Moreover, a deep understanding of the speech tone deficits in amusics will ultimately shed light on the intricate relationship between music and speech pitch processing.

Using mismatch negativities (MMNs), the current study probed pre-attentive lexical tone processing among native Mandarin-speaking amusics compared with age- and IQ-matched controls. It is well known that the auditory discrimination accuracy of speech sounds can be investigated with MMN, which is an automatic change-detection neural response in event-related brain potentials (ERPs) (Naätänen, Paavilainen, Rinne, & Alho, 2007). It indexes not only the behavioural discrimination accuracy but also the sensory memory traces of the preceding stimulation, forming the bases for change detection (Naätänen et al., 2007). More importantly, the MMN is localized in bilateral auditory and right frontal regions in the brain (Alain, Woods, & Knight, 1998), which converges with the affected auditory-frontal cortical network of pitch processing in amusics (Albouy et al., 2013; Hyde et al., 2011; Loui et al., 2009).

Hence, the MMN seems well suited to examine the neurophysiological basis underlying amusics' lexical tone deficits. In our earlier studies (Nan et al., 2010; Yang, Feng, Huang, Zhang, & Nan, 2013), behavioural lexical tone deficits were found to be most prominent in a subgroup of amusics (hereafter ‘tone agnosics’), whereas behavioural tone processing seemed to be unaffected in other amusics (hereafter ‘pure amusics’). These two subgroups of amusics (i.e., pure amusics and tone agnosics) were both included in the current study.

We examined the MMN responses to tonal (/da2/ meaning ‘to answer’, 2 = rising tone) and tone-consonant (/ba2/, ‘to pull out’, 2 = rising tone) changes in a stream of standard stimuli (/da1/, ‘to put up’, 1 = level tone) of Mandarin-speaking pure amusics (amusics without lexical tone deficits) and tone agnosics (amusics with lexical tone deficits) compared to age- and IQ-matched controls. The tone-consonant deviant was different from the standard stimulus not only in terms of tone but also in terms of the consonant. Because amusics' speech difficulties are largely limited to linguistic tones (but see Wang & Peng, 2014; Jones, Lucker, Zalewski, Brewer, & Drayna, 2009; Jones, Zalewski, Brewer, Lucker, & Drayna, 2009 for possible phonological deficits in amusics), tone change detection was more likely to be physiologically affected than tone-consonant change detection.

As mentioned above, amusics’ musical pitch deficits are primarily related to impaired pitch awareness, while pre-attentive encoding is intact (Moreau et al., 2013; Peretz et al., 2009). For example, Peretz and her colleagues reported that although amusics are behaviourally insensitive to semitone changes in a melody, amusics’ brains can track quarter-tone mistuning, as reflected by their N200 responses (Peretz et al., 2009). These authors thus suggested that the amusics’ neural processing of fine-grained pitch changes is intact and that they are only behaviourally unaware (Peretz et al., 2009). Moreau et al. (2013) followed up this line of research and re-examined amusics’ brain responses to 25 cents (an eighth of a tone) or 200 cents (one whole tone) changes in an acoustical context. These authors observed normal MMN responses to both the 25 and 200 cents tone changes in amusics.

Similarly, in the current study, it is possible that despite their behavioural lexical tone difficulties, tone agnosics could exhibit MMN responses to lexical tone changes that are similar to those of the controls and pure amusics, which would suggest normal pre-attentive processing with possibly compromised behavioural awareness of the lexical tones among tone agnosics and resemble the findings regarding amusics’ affected pitch awareness (Moreau et al., 2013; Peretz et al., 2009). Alternatively, tone agnosics might exhibit reduced MMNs in response to tone changes relative to the controls and pure amusics. This would indicate impaired pre-attentive lexical tone processing in the tone agnosics. Moreover, for pure amusics, despite the music pitch deficits, their behavioural lexical tone processing seems intact. It would be interesting to examine whether a similar integrity in lexical tone processing existed at the neurophysiological level as reflected by tone MMNs.

2. Material and methods

2.1. Participants

Twelve neurologically healthy controls (five females), twelve pure amusics (five females), and eight tone agnosics (three females) participated in the current study. All participants were native speakers of Mandarin Chinese who were recruited through internet advertising from universities in Beijing. None of the participants had any formal music training. All of the participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). All of the participants’ audiometric thresholds were equal to or below 20 dB HL for octaves ranging from 250 to 8000 Hz. The participants were assessed with the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz, Champod, & Hyde, 2003), which includes three pitch-based tests (scale, contour and interval), two time-based tests (rhythm and meter), and one memory test. Each participant in the pure amusic and tone agnosic groups scored below the cut-off score of 71.7%, which corresponded to two SDs below the mean of the controls as obtained in our previous study (Nan et al., 2010). Additionally, eight tone agnosics were identified as a special group of participants who not only had musical pitch deficits, as measured by the MBEA, but also had lexical tone difficulties, as measured with the lexical tone perception
Table 1
The demographic characteristics of the controls, pure amusics, and tone agnosics. IQ indicates the intelligence quotient. MBEA refers to the Montreal Battery of Evaluation of Amusia, and the scores on the subtests are listed as per cent correct responses. The performance of the lexical tone perception tests is also reported as per cent correct responses. SD indicates the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Controls (n = 10)</th>
<th>Pure amusics (n = 12)</th>
<th>Tone agnosics (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (range)</td>
<td>22.3 (18–25)</td>
<td>22.2 (18–26)</td>
<td>21.4 (19–25)</td>
</tr>
<tr>
<td>Male/female</td>
<td>6/4</td>
<td>7/5</td>
<td>5/3</td>
</tr>
<tr>
<td>Performance IQ/SD</td>
<td>12.1 (1.9)</td>
<td>118.8 (7.0)</td>
<td>112.3 (10.9)</td>
</tr>
<tr>
<td>Verbal IQ/SD</td>
<td>130.2 (6.5)</td>
<td>127.8 (5.2)</td>
<td>124.1 (10.0)</td>
</tr>
<tr>
<td>MBEA mean (SD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale</td>
<td>84.9 (9.3)</td>
<td>62.5 (11.8)</td>
<td>60.0 (7.4)</td>
</tr>
<tr>
<td>Contour</td>
<td>86.5 (7.5)</td>
<td>68.4 (4.2)</td>
<td>57.3 (10.9)</td>
</tr>
<tr>
<td>Interval</td>
<td>84.2 (9.4)</td>
<td>58.8 (11.5)</td>
<td>56.4 (10.4)</td>
</tr>
<tr>
<td>Rhythm</td>
<td>83.5 (10.5)</td>
<td>73.8 (12.8)</td>
<td>63.4 (9.4)</td>
</tr>
<tr>
<td>Meter</td>
<td>73.1 (14.4)</td>
<td>60.9 (13.6)</td>
<td>60.1 (11.7)</td>
</tr>
<tr>
<td>Memory</td>
<td>94.3 (5.3)</td>
<td>72.0 (10.9)</td>
<td>69.4 (16.2)</td>
</tr>
<tr>
<td>Global</td>
<td>84.1 (6.2)</td>
<td>66.1 (3.1)</td>
<td>61.1 (6.9)</td>
</tr>
<tr>
<td>Lexical tone mean (SD)</td>
<td>96.2 (3.5)</td>
<td>96.1 (3.9)</td>
<td>64.9 (10.8)</td>
</tr>
</tbody>
</table>

tests (Nan et al., 2010). The lexical tone perception tests comprise tone discrimination and identification tasks (Nan et al., 2010). These eight tone agnosics scored less than 80% for the lexical tone perception tests, which corresponded to three SDs below the means of the controls, as observed in our earlier study (Nan et al., 2010). Regarding the behavioural and ERP results, two participants in the control group were excluded from the final analysis due to excessive artefacts in the recordings. The remaining 10 participants were matched to the other two groups in terms of age and IQ. Table 1 displays the demographic characteristics and the mean scores on all of the behavioural tests for the participants in all three groups. The experiment was approved by the Institutional Review Board at Beijing Normal University, and informed written consent was obtained from each participant.

In summary, in the MBEA tests, the control group significantly outperformed both the pure amusic and tone agnosic groups (both ps < .001), whereas the latter two groups did not differ statistically (p = .166). However, regarding the lexical tone tests, the tone agnosics lagged significantly behind both the controls and the pure amusics (both ps < .001), whereas the latter two groups performed similarly (p = .821). All three groups were matched for age (p = .662), handedness, and performance IQ (p = .158) and verbal IQ (p = .423) based on the Wechsler Adult Intelligence Scale-Revised by China (WAIS-RC; Gong, 1992).

2.2. Stimuli

Three Chinese monosyllabic words were constructed for this experiment: /da1/, /da2/, and /ba2/ (1 = level tone and 2 = rising tone; Fig. 1). The original stimuli were recorded from a female native Mandarin speaker in a soundproof booth using a Sony 60EC digital recorder at a sampling rate of 44.1 kHz. The monosyllables were digitally standardized using Praat (Boersma, 2001), and each had a duration of 300 ms and a sound pressure level of 70 dB. The /da1/ was used as the standard stimulus, and the /da2/ and /ba2/ were employed as the tone deviant and tone-consonant deviant, respectively. As mentioned above, in Mandarin Chinese, these three words have different meanings: /da1/ means to put up, /da2/ means to answer, and /ba2/ means to pull out. These three words are all commonly used in modern Mandarin and have frequencies of usage below 4000 (the Contemporary Chinese Corpus Research Group, 2008).

2.3. Procedure

2.3.1. EEG session

An oddball block was presented to each participant during the electroencephalogram (EEG) session. The tone deviant /da2/ and the tone-consonant deviant /ba2/ varied in tone or in both tone and consonant relative to the standard stimuli /da1/. The stimulus sequence contained a total of 640 stimuli with alternating standards and deviants (80 tone deviants /da2/ and 80 tone-consonant deviants /ba2/; deviant probability p = .125). The deviants occurred pseudo-randomly among the standards, and two adjacent deviants were separated by at least two standards. The inter-stimulus interval varied randomly between 600 and 800 ms at a step of 1 ms.

The participants were seated comfortably in an electrically shielded room and were instructed to ignore the presented sounds while watching a silent movie. To avoid unnecessary electromagnetic interference, the movie was played with a projector placed outside the room. The projection screen was 2 m in front of each participant. The sound stimuli were presented through two loudspeakers that were placed one meter in front of the participant at 45° to the left or right, approximately one meter apart, and covered with silver paper. The participants were instructed to minimize head motion and eye blinking during the EEG recording. The EEG session lasted approximately 40 mins including preparation and data acquisition.

2.3.2. EEG recording

The EEGs were recorded using a SynAmps EEG amplifier and the Scan 4.5 package (NeuroScan, Inc.) with a 1000-Hz sampling rate through a bandpass filter of 0.05–200 Hz. Each participant wore a Quick-Cap with 32 tin scalp channels placed according to the international 10–20 system. The ground electrode was placed at the midpoint between FP1 and FP2. Vertical and horizontal electrooculograms (EOGs) were recorded above and below the left eye and next to the outer canthi of both eyes. The reference electrode was placed on the tip of the nose. The impedance of each channel was kept below 5 kΩ.
2.3.3. Behavioural session
Following the EEG session, the participants were asked to listen to another sequence of 150 stimuli that were identical to those presented in the EEG session with the exception of a different distribution, that was, 90 standards /da1/, 30 tone deviants /da2/, and 30 tone-consonant deviants /ba2/. In this session, the participants first learned the three stimuli, that is, the standard (/da1/), tone deviant (/da2/), and tone-consonant deviant (/ba2/), before testing. Next, the participants were required to respond to the standard and the two deviant stimuli by pressing two corresponding buttons (standard or deviant) without feedback. The behavioural session lasted approximately five minutes. The stimuli in the EEG and behavioural sessions were presented with the E-prime software (Psychological Software Tools, Pittsburgh, PA, USA).

2.4. Data analysis
For the off-line signal processing, the trials with saccades were discarded upon visual inspection. Eye blinks were corrected using the linear regression function provided by the NeuroScan software (Semlitsch, Anderer, Schuster, & Presslich, 1986). The data were digitally filtered (low-pass filter of 30 Hz; zero-phase, and 24 dB/octave) and segmented into 1000 ms epochs that included a 100 ms pre-stimulus baseline and 900 ms after the onset of the stimuli. After baseline correction, epochs containing voltage changes that exceeded ± 80 µV at any electrode were excluded from the analysis, which resulted in the exclusion of approximately 7% of the epochs from the average. The remaining epochs were separately averaged for each stimulus. The average trial numbers for each group across conditions were all above 70. The controls had 71.8 ± 8.9 (mean ± SD) trials for the tone deviant and 72.4 ± 9.3 trials for the tone consonant deviant, the pure amusics group had 78.1 ± 2.9 trials for tone deviant and 77.8 ± 2.9 trials for tone consonant deviants, and the tone agnosics had 77.6 ± 3.3 trials for the tone deviant and 77.8 ± 1.9 trials for the tone consonant deviant.

The obligatory P1 and N1 were determined from the grand average standard waveform. The peak latencies of the P1 and N1 were determined as the most positive or negative peaks in the time window of 80–140 ms. The P1 and N1 amplitudes were calculated from a 30-ms window centred on the peaks (P1 95 ms and N1 125 ms). The P1 and N1 peak latencies at nine centro-frontal electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) were compared between the controls, the pure amusics, and the tone agnosics with one-way analyses of variance (ANOVA). The amplitudes and amplitude scalp distributions of the P1 and N1 were assessed with repeated-measures two-way ANOVAs that included group (controls, pure amusics, and tone agnosics) as the between-subjects factor and hemisphere (the left hemisphere included F3, FC3, and C3, the midline area included Fz, FCz, and Cz, and the right hemisphere included F4, FC4, and C4) as the within-subjects factor.

Based on the MMN topographies that have been reported in previous studies (see Näätänen et al., 2007 for review) and visual inspection of the current grand-average waveforms, nine centro-frontal electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) were selected for statistical analysis. For each participant, the amplitude of the stimulus-triggered response was calculated as the mean value of the 40-ms window centred on the grand-mean average peak latency, that was, 180 ms post-stimulus.

A difference waveform for each individual participant was obtained by subtracting the standard waveform from the respective deviant waveform. Accordingly, the MMN amplitude was obtained by subtracting the mean amplitude of the standard from the deviant amplitude for each individual participant and reflected the difference between the deviant and standard responses. The MMN peak latency was measured as the time point of the peak amplitude that was detected within a time window of 160–200 ms. Three-way repeated-measures ANOVAs with area (frontal, centro-frontal, and central areas) and hemisphere (the left: F3, FC3, C3; the midline: Fz, FCz, Cz; the right: F4, FC4, C4) as the within-subjects factors and group (the controls, pure amusics, and tone agnosics) as the between-subjects factor were performed for each deviant condition to examine the effects of the MMN amplitudes and peak latencies.

Additionally, the behavioural performance d-prime was calculated based on both the hit rates and the false alarms: hits were the correct answers to the deviants; false alarms were the wrong answers to the standards. The demographic measures and the behavioural results were analysed using one-way ANOVAs with group as the between-subjects factor (controls, pure amusics, and tone agnosics). Greenhouse-Geisser corrections were performed when necessary. The Bonferroni correction was used for post hoc multiple comparisons.

3. Results
3.1. Behavioural results
Significant group effects were obtained with d-primes for both the tone deviants and tone-consonant deviants (both ps < .01). The reaction times revealed no group differences for either deviant condition (both ps > .8). Bonferroni-corrected pairwise comparisons revealed that for both deviants, the tone agnosics exhibited significantly worse discrimination sensitivities (as reflected by the d-prime measures) than both the controls and the pure amusics (all ps < .01), whereas the latter two groups were similarly sensitive in these discrimination tasks (all ps = 1; Table 2).

| Table 2 | The behavioural results. The d-prime and reaction time (RT, in ms) results for the controls, pure amusics, and tone agnosics in the behavioural lexical tone and tone-consonant deviant discriminations. SD indicates the standard deviation. |
|---|---|---|---|
| | Controls (n = 10) | Pure amusics (n = 12) | Tone agnosics (n = 8) |
| Lexical tone d-prime (SD) | 2.1 (0.5) | 2.1 (0.5) | 1.2 (0.7) |
| Tone-consonant d-prime (SD) | 2.7 (0.4) | 2.6 (0.4) | 2.0 (0.6) |
| Lexical tone RT (SD) | 608.4 (65.7) | 596.4 (67.6) | 596.3 (89.9) |
| Tone-consonant RT (SD) | 532.9 (57.1) | 520.0 (45.6) | 539.5 (79.6) |

Fig. 2. The grand average waveforms elicited by standard stimuli at the Cz electrode. There were no significant differences in the P1 or N1 amplitudes or latencies between the controls (solid line), pure amusics (dotted line), and tone agnosics (dashed line).
Fig. 3. Difference waveforms between the standard and deviant responses (deviant - standard subtraction) for the two deviant types (tone and tone-consonant) at Fz for the three groups. The time windows of analyses (160–200 ms) for the MMNs are marked by the open rectangles. In the tone deviant condition, the tone agnostic group (dashed line) exhibited significantly reduced MMN amplitude compared with both the controls (solid line) and the pure amusics (dotted line; both ps < .05). However, in the tone-consonant condition, the three groups exhibited statistically similar MMNs (p = .536).

Fig. 4. The grand average waveforms elicited by standard (solid line) and deviant (dotted line) stimuli at the Fz electrode for the three groups. The time windows of analyses (160–200 ms) for the MMNs are marked by the open rectangles.
compared frontal similar deviant FCz, plot indicate Fig. 64 three-way that electrode of p

Electrodes controls, pure amusics, and tone agnosics. The nine electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) that were chosen for the statistical analysis are marked in each topographic plot across the three groups for each deviant type. Time window was 160–200 ms. The bright areas indicate negativity, that is, brighter areas indicate greater negativity and dimmer areas indicate greater positivity. In the tone deviant condition, the tone agnostic group exhibited a significantly reduced MMN compared with the controls and the pure amusics (both ps < .05, the topographical plot for the tone agnostics is much dimmer than those of the other two groups). However, in the tone-consonant condition, the three groups exhibited statistically similar MMNs (p = .536). Across the three groups and both deviant types, the central electrodes generated greatly reduced MMNs (much dimmer) compared to the frontal and fronto-central electrodes (all ps < .05), and there were no significant MMN amplitude differences between the frontal and fronto-central areas (all ps > .2).

3.2. ERP results

The grand-average ERP waveforms that were elicited by the standard stimuli at Cz are presented in Fig. 2, and the difference waveforms between the standard and deviant responses at the electrode Fz for both the tone and tone-consonant conditions are shown in Fig. 3. Fig. 4 shows the grand-average ERP waveforms that were elicited by the standard and deviant stimuli in tone and tone-consonant conditions among the three groups at the electrode Fz. Fig. 5 illustrates the scalp distributions of the difference waveforms in each condition. The obligatory P1 and N1 responses (Fig. 2) were not significantly different across the three groups in terms of amplitude, amplitude scalp distribution, or latency. Similarly, the MMN latency measures did not differ between the groups for either deviant type. Thus, the analyses related to these results were not reported here.

For the tone deviants, a three-way repeated-measures ANOVA of the MMN amplitudes with area (frontal, centro-frontal, and central areas) and hemisphere (left: F3, FC3, C3; midline: Fz, FC2, Cz; right: F4, FC4, C4) as the within-subjects factors and group (controls, pure amusics, and tone agnosics) as the between-subjects factor revealed significant main effects of group (F(2, 27) = 3.508, p = .045, η² = .212, medium effect size) and area (F(2, 54) = 8.259, p = .001, η² = .156, medium effect size) and no other main effects or interactions. Bonferroni-corrected pairwise comparisons revealed that the tone agnostic group exhibited significantly reduced MMN amplitudes compared with both the controls and the pure amusics (both ps < .05), whereas the MMNs of the latter two groups did not differ significantly (p = .764). Across all three groups, the frontal and fronto-central electrodes exhibited significantly larger MMNs than the central electrodes (both ps < .05), whereas the frontal and fronto-central electrodes exhibited MMNs of similar amplitudes (p = 1). However, for the tone-consonant deviants, three-way ANOVA revealed only a significant main effect of area (F(2, 54) = 5.759, p = .005, η² = .126, small effect size) and no signifi-

![Fig. 5. MMN amplitude scalp distributions for tone and tone-consonant conditions in the controls, pure amusics, and tone agnosics. The nine electrodes (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4) that were chosen for the statistical analysis are marked in each topographic plot across the three groups for each deviant type. Time window was 160–200 ms. The bright areas indicate negativity, that is, brighter areas indicate greater negativity and dimmer areas indicate greater positivity. In the tone deviant condition, the tone agnostic group exhibited a significantly reduced MMN compared with the controls and the pure amusics (both ps < .05, the topographical plot for the tone agnostics is much dimmer than those of the other two groups). However, in the tone-consonant condition, the three groups exhibited statistically similar MMNs (p = .536). Across the three groups and both deviant types, the central electrodes generated greatly reduced MMNs (much dimmer) compared to the frontal and fronto-central electrodes (all ps < .05), and there were no significant MMN amplitude differences between the frontal and fronto-central areas (all ps > .2).](image1)

![Fig. 6. A significant negative correlation between the lexical tone MMN amplitude at F3 and the tone d-prime across the three groups (r(30) = −.519, p = .003). Similar negative correlations were also found for FC3 and C3 in the left hemisphere.](image2)

...cant group or other effects. The area effect resembled that observed in the tone deviant condition, with larger MMNs in the frontal and fronto-central areas than in the central area (both ps < .05) and no MMN amplitude differences between the frontal and fronto-central areas (p = .238).

There were significant negative correlations between the tone MMN amplitudes at the electrodes in the left hemisphere (F3, FC3, and C3) and the behavioural tone d-primes across the three groups (F3, r(30) = −.519, p = .003; FC3, r(30) = −.471, p = .009; C3, r(30) = −.371, p = .047) but not within any individual group. Fig. 6 demonstrates the significant correlation between the tone MMN amplitude and the tone d-prime at F3 as an example. No similar correlations were found for the other electrodes in the tone deviant condition. There were no correlations between the behavioural performance and the MMN amplitude in the tone-consonant deviant condition across the three groups.

4. Discussion

Congenital amusia is a neurodevelopmental disorder that may affect the processing of both musical pitch and linguistic tone. It thus represents an ideal window into the debate of association/dissociation of pitch processing in music and language. The present study aimed at investigating the neurophysiologic correlates underlying Mandarin-speaking amusics’ behavioural lexical tone difficulties, as reflected by the MMN responses. We observed specific MMN reductions in response to lexical tone changes only in the subgroup of Mandarin-speaking amusics who had behavioural lexical tone deficits, that was, the tone agnosics. Moreover, the tone agnosics’ MMN reduction was only apparent for lexical tone changes but not for tone-consonant changes. In the latter condition, the tone agnosics exhibited intact MMN responses that were not statistically different from those of the controls and pure amusics who had no behavioural lexical tone deficits.

Across the three groups, the tone MMN amplitudes at the electrodes in the left hemisphere (F3, FC3, and C3) were significantly correlated with the behavioural tone d-prime measures. These data indicate that the MMN sensitivity to lexical tone changes corresponds well with the d-prime behavioural lexical tone discrimination measure, which is consistent with earlier findings that the MMN is indeed an objective index of the discrimination accuracies for different acoustic features (Kujala & Näättänen, 2010). Moreover, the left-lateralized correlation between the behavioural and neurophysiological indexes implies that the MMN sensitiv-
ity in the left hemisphere is more closely related to behavioural tone deviant change detection. This is congruent with an earlier MMN study investigating categorical perception of lexical tones (Xi, Zhang, Shu, Zhang, & Li, 2010). The categorical effect was only observable at a left-frontal electrode F3, where the across-category deviants elicited much larger MMNs than the within-category deviants (Xi et al., 2010). Similar results were also obtained in children. In an MMN study with categorical tone perception in dyslexic children, same pattern of left-lateralized categorical tone MMN was observed in age-matched control children, but not in dyslexic children (Zhang et al., 2012). However, no consensus has been reached regarding the laterality effect of lexical tone MMN. For instance, when compared to consonant changes, lexical tone changes elicited a right-lateralized MMN (Luo et al., 2006). Indeed, previous reports suggest that lexical tone processing might involve both the left and right hemispheres (Liang & van Heuven, 2004; Liu et al., 2006; Luo et al., 2006; Klein, Zatorre, Milner, & Zhao, 2001; Gandour et al., 2000; Gandour, Wong, & Hutchins, 1998), but the left hemisphere normally dominates when the lexical tone processing is of a more linguistic nature (e.g., Nan & Friederici, 2013; Xi et al., 2010).

The MMN represents feature-specific coding of stimulus changes at the pre-attentive level, and it typically provides an objective index of the auditory discrimination accuracies for specific acoustic features (Kujala & Näätänen, 2010). Consequently, MMN reductions in specific participant groups and clinical populations typically indicate perceptual deficits that are normally linked to behavioural defects in discrimination tasks (Ludlow et al., 2014; Murphy et al., 2013; Shaikh et al., 2012). Tone agnosics’ abnormally reduced lexical tone MMN responses, therefore, suggest that their behavioural lexical tone deficits may be related to impairments in basic auditory discrimination that involve the auditory cortex, similar to the MMN results of children with autism spectrum disorders and individuals who are clinically at risk for psychosis that have been reported in earlier studies (Ludlow et al., 2014; Murphy et al., 2013; Shaikh et al., 2012). Notably, the basic encoding of sound features in these tone agnosics seems to be intact as suggested by the normal P1 and N1 responses.

The tone MMNs might represent the acoustic and/or phonetic processing of the lexical tones (Näätänen et al., 2007). Our recent studies found that tone agnosics demonstrated significantly larger just-noticeable differences of tone pitch contour change (Huang, Nan, Dong, & Liu, 2015), and their categorical perception of lexical tones were also greatly impaired compared with the controls and pure amusics (Huang, Liu, Dong, & Nan, 2015). These results converge with the abnormal tone MMNs observed in the present tone agnostic group. Moreover, it is also likely that the reduced tone MMNs in tone agnosics might be associated with a much weaker memory trace for encoded tones (Näätänen et al., 2007), which in turn was insufficient to support successful tone discrimination. This corroborates the observed tight link between tone MMN amplitudes and behavioural tone discrimination performances across the three groups.

This study thus adds important neurophysiological evidence to the previously observed behavioural subgroup differences in lexical tone processing among Mandarin speakers with congenital amusia (Huang, Liu et al., 2015; Huang, Nan et al., 2015; Nan et al., 2010; Yang et al., 2013) showing that music pitch deficit does not necessarily compromise lexical tone processing; those who are impaired in lexical tone processing only constitute a small subgroup of amusics. This line of research suggests that it is important to take into account the possible subgroup difference in behavioural lexical tone deficits when investigating the linguistic tone processing in Mandarin-speaking amusics. An overall association between music pitch deficits and linguistic tone impairments may be attributed to lack of subgroup distinction within the amusics (Huang, Liu et al., 2015; Huang, Nan et al., 2015). As shown in our recent study (Huang, Liu et al., 2015), only amusics with tone agnosia were impaired in categorical tone perception. However, if the subgroup differences were overlooked, impairments in categorical tone perception would have been wrongly attributed to the whole amusic group (Huang, Liu et al., 2015). The lack of categorical tone perception in amusics was indeed reported in a previous study where the possible subgroup differences within the amusic group were not considered (Jiang, Hamm et al., 2012b). The observed dissociation between music pitch and lexical tone deficits in the current study converge with the notion that although some overlap exists in music and speech, there might be two different pitch processing systems across domains (Zatorre & Baum, 2012).

Congenital amusia is a genetic developmental disorder (Peretz, Cummings, & Dube, 2007) and a result of the interplay between genes and the environment (Peretz, 2014). Mandarin-speaking amusics are born and raised in a tonal language environment and are thus different from other amusics from non-tonal language backgrounds. Daily communication makes language learning and, inevitably, tone learning a compulsory task for everyone involved. The question of nature or nurture naturally arises: are the observed subgroup differences in lexical tone processing (both behavioural and physiological) among Mandarin amusics congenital (born with) or a result of long-term tone language learning? Longitudinal and cross-cultural studies, preferably beginning with child populations, might be able to answer these questions.

In summary, the current study provides the first physiological evidence of the subgroup differences in lexical tone MMN responses among Mandarin amusics. Our results revealed that the subgroup of Mandarin amusics who have behavioural lexical tone difficulties exhibited reduced lexical tone MMNs relative to the controls and the other amusics without behavioural lexical tone deficits. This MMN reduction was specific to lexical tone changes and tightly linked to behavioural insensitivity in lexical tone change detection. These results imply that amusics’ lexical tone deficits might compromise pre-attentive tone processing. Moreover, the current study also extends previous findings of dissociation between music pitch and lexical tone deficits. The subgroup of Mandarin amusics without behavioural lexical tone deficits seems also intact in lexical tone processing at the neurophysiological level as reflected by tone MMNs. The fact that the pitch deficits in speech and music can dissociate suggests the existence of different neural architectures subserving pitch processing in these two domains.

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