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Differential recognition of pitch patterns in discrete and gliding stimuli in congenital amusia: Evidence from Mandarin speakers

Fang Liu [a,*], Yi Xu [b], Aniruddh D. Patel [c], Tom Francart [d,e], Cunmei Jiang [f,*]

[a] Center for the Study of Language and Information, Stanford University, Stanford, USA
[b] Department of Speech, Hearing and Phonetic Sciences, University College London, London, UK
[c] The Neurosciences Institute, San Diego, CA, USA
[d] ExpORL, Department of Neurosciences, Katholieke Universiteit Leuven, Belgium
[e] The Bionics Institute, Melbourne, Australia
[f] Music College, Shanghai Normal University, Shanghai, China

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ABSTRACT

This study examined whether “melodic contour deafness” (insensitivity to the direction of pitch movement) in congenital amusia is associated with specific types of pitch patterns (discrete versus gliding pitches) or stimulus types (speech syllables versus complex tones). Thresholds for identification of pitch direction were obtained using discrete or gliding pitches in the syllable /ma/ or its complex tone analog, from nineteen amusics and nineteen controls, all healthy university students with Mandarin Chinese as their native language. Amusics, unlike controls, had more difficulty recognizing pitch direction in discrete than in gliding pitches, for both speech and non-speech stimuli. Also, amusic thresholds were not significantly affected by stimulus types (speech versus non-speech), whereas controls showed lower thresholds for tones than for speech. These findings help explain why amusics have greater difficulty with discrete musical pitch perception than with speech perception, in which continuously changing pitch movements are prevalent.

1. Introduction

Congenital amusia (amusia hereafter) is a neuro-genetic disorder of musical processing that impacts upon speech processing in subtle ways (Ayotte, Peretz, & Hyde, 2002; Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001; Hutchins, Gosselin, & Peretz, 2010; Jiang, Hamm, Lim, Kirk, & Yang, 2010; Liu, Patel, Fourcin, & Stewart, 2010; Nan, Sun, & Peretz, 2010; Patel, Wong, Foxton, Lochy, & Peretz, 2008; Peretz, Cummings, & Dubé, 2007). It affects about 4% of the general population for speakers of both tone and non-tonal languages (Henry & McAuley, 2010; Kalmus & Fry, 1980; Nan et al., 2010). Individuals with amusia (amusics hereafter) have difficulty detecting fine-grained pitch changes and anomalous pitches in melodies (Ayotte et al., 2002; Hyde & Peretz, 2004; Jiang, Hamm, Lim, Kirk, & Yang, 2011; Jones, Zalewski, Brewer, Lucker, & Drayna, 2009; Peretz et al., 2002). They also show deficits in processing contours of pitch sequences (Dalla Bella, Giguère, & Peretz, 2009; Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Jiang et al., 2010), and judging/discriminating pitch direction (up versus down) in both psychophysical tasks and tasks involving speech intonation contours (Foxton et al., 2004; Liu et al., 2010; Loui, Guenther, Mathys, & Schlaug, 2008; Patel et al., 2008).

The pitch perception problems in amusia may be linked to an inability to process pitch information consciously, or a lack of “pitch awareness” (Loui, Kroog, Zuk, Winner, & Schlaug, 2011), since neuroimaging studies have revealed unconscious processing of pitch changes (as small as 0.25 st) and melodic incongruities (at the quarter-tone level) in amusia (Hyde, Zatorre, & Peretz, 2011; Moreau, Jolicoeur, & Peretz, 2009; Peretz, Brattico, Järvenpää, & Tervaniemi, 2009). Furthermore, compared with their impaired performance on conscious identification of pitch direction (Loui et al., 2008), lexical tone (Nan et al., 2010), and speech intonation (Liu et al., 2010), amusics demonstrated near-normal performance on production or imitation of the same pitch events, where conscious processing of pitch information was not required.

In fact, the ability to consciously identify the direction of pitch changes even varies among non-amusic individuals (Foxton, Weisz, Bauchet-Lecaignard, Delpuech, & Bertrand, 2009; Mathias, Bailey, Semal, & Demany, 2011; Mathias, Micheyl, & Bailey, 2010; Neuhoff, Knight, & Wayand, 2002; Semal & Demany, 2006). Compared with simple sensory pitch discrimination, judgment of pitch

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* Corresponding authors. Addresses: Center for the Study of Language and Information, Stanford University, Ventura Hall, 220 Panama Street, Stanford, CA 94305-4101, USA. Fax: +1 650 721 9405 (F. Liu), Music College, Shanghai Normal University, 100 E. Guilin Road, Shanghai 200234, China. Fax: +86 21 64322935 (C. Jiang).

E-mail addresses: liufang@uchicago.edu (F. Liu), cunmeijiang@126.com (C. Jiang).

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direction requires higher-order cognitive processing in the right auditory cortex (Johnsrude, Penhune, & Zatorre, 2000). The amusic brain has reduced functional connectivity in the right frontotemporal pathway and right arcuate fasciculus (Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006; Hyde et al., 2007; Hyde et al., 2011; Loui, Alsop, & Schlaug, 2009), which may underlie amusics' impaired higher-level pitch processing abilities.

The finding that the core deficit of amusia may lie "at a higher processing level than simple pitch-change detection" was first reported in Patel, Foxton, and Griffiths (2005:312), which tested the hypothesis that amusia is a disorder of low-level fine-grained pitch discrimination (Peretz & Hyde, 2003). Patel et al. (2005) examined British amusics' discrimination of focus-shift utterance pairs (such as "I like BULE ties on gentlemen" versus "I like blue TIES on gentlemen", with the focus on "BLUE" and "TIES", respectively) and their gliding-pitch and discrete-pitch analogs. Each utterance pair had sentences with identical syllabic timing patterns, with focus being signaled primarily by pitch excursions in the intonation contour. The nonlinguistic pitch analog of each sentence mirrored the timing of the spoken syllables and used clarinet-like complex tones. The gliding-pitch analogs used tones that reproduced the gliding pitches of the spoken syllables, while the discrete-pitch analogs used tones with fixed pitches (each tone was set to the median F_0, the fundamental frequency, of the associated syllable). The amusics discriminated the spoken sentences well, but had difficulty discriminating both the gliding-pitch and discrete-pitch analogs. Since the gliding-pitch analogs shared the same pitch patterns as the speech stimuli, the dissociation between amusics' speech and music processing abilities (intact performance for speech; impaired for tone analogs) cannot be explained by the idea that speech intonation employs coarse pitch contrasts that exceed amusics' pitch-change detection thresholds. Rather, amusia may be due to insensitivity to the direction of pitch movement, or "melodic contour deafness" (Patel, 2008: 233).

However, although "melodic contour deafness" (Patel, 2008) or impaired "pitch awareness" (Loui et al., 2011) may help explain pitch-processing deficits in amusia, it is unclear whether, and to what extent, this "deafness/unawareness" depends on the different pitch patterns (e.g., discrete versus gliding pitches) and stimulus types (e.g., complex tones versus speech syllables) employed in music and speech (Ayotte et al., 2002; Jiang et al., 2010; Liu et al., 2010; Patel et al., 2005; Patel et al., 2008). One previous study using pure tones showed that amusics achieved smaller (better) pitch thresholds for gliding versus discrete tones (Foxton et al., 2004). However, it is not known if this same advantage would be seen in spoken syllables and in complex tones, which are more representative of natural speech and music.

Using adaptive tracking procedures in APEX 3 (Francart, van Wieringen, & Wouters, 2008), the current investigation examined the thresholds at which amusics start to be able to identify discrete (high–low versus low–high) and gliding (rising–falling versus falling–rising) pitch patterns in speech syllables and in complex tones. In order to directly compare music with speech, we tested Mandarin-speaking amusics (Mandarin amusics hereafter) and controls, using pitch patterns that coincide with the four Mandarin tones (Tone 1: High; Tone 2: Rising; Tone 3: Low; Tone 4: Falling) that are used to distinguish words at the syllable level in the language (Chao, 1968). It was predicted that amusics would have comparable pitch thresholds for speech syllables and complex tones, given prior results regarding their performance on identification/discrimination of speech intonation and tone analogs (Ayotte et al., 2002; Jiang et al., 2010; Liu et al., 2010; Patel et al., 2005, 2008). On the other hand, given that British amusics showed better (lower) pitch-change detection thresholds for gliding than discrete pure tones (Foxton et al., 2004) and French amusics achieved better discrimination of contour tones than level tones in Thai (Tillmann et al., 2011), we hypothesized that Mandarin amusics would have lower pitch-direction identification thresholds for gliding than discrete pitches in both speech syllables and complex tones.

2. Method

2.1. Participants

Nineteen amusics and nineteen matched controls were recruited through advertisements in the bulletin board system of universities in Shanghai, China. All were undergraduate or postgraduate students with Mandarin Chinese as their native language. The Montreal Battery of Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003) was used to measure the musical abilities of these participants (scale, contour, interval, rhythm, meter, and memory processing of melodies; scored using number of correct responses out of the total thirty trials in each subtest). A detailed questionnaire was also collected to gather further information about the participants. None reported any learning or memory problems with their university studies, or any history of neurological/psychiatric disorders or speech/hearing difficulties. Among all participants, only one amusic received 6 months' extracurricular musical training during childhood. All but one control were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Ethical approval was granted by Shanghai Normal University in China, and written informed consents were obtained from all participants before testing. Table 1 lists the characteristics of the participants (see Appendix A for further details). The amusic and control groups were matched in sex, handedness, age, and years of education, but amusics performed significantly worse than controls on all MBEA subtests.

2.2. Stimuli

The stimuli were of two different types: the Mandarin syllable /ma/ and its complex tone analog. Fig. 1 shows waveforms and spectrograms of /ma/ and complex tone at the fundamental frequency (F_0) of 120 Hz. The Mandarin syllable /ma/ has different meanings depending on different tones: "mother" (High, or Tone 1), "hemp" (Rising, or Tone 2), "horse" (Low, or Tone 3), and to "scold" (Falling, or Tone 4). The complex tone analog of /ma/ comprises F_0 and its seven odd harmonics, of the same amplitude and with sine phase, which leads to a clarinet sound quality (Liu et al., 2010; Patel, Peretz, Tramo, & Labrecque, 1998; Patel et al., 2005, 2008). A 15-ms linear amplitude ramp was applied to the onset and offset of complex tones to adjust for rise/decay time.

Using custom-written scripts for the Praat program (Boersma, 2001), the syllable /ma/ (original stimulus produced by author YX) and its complex tone analog were manipulated to carry a range of discrete/gliding pitches, at a sampling rate of 44.1 kHz. Given that the role of intensity in tone perception is negligible when pitch is present (Lin, 1988) and in keeping with previous studies on speech processing in amusia (Ayotte et al., 2002; Jiang et al., 2010; Liu et al., 2010; Patel et al., 2005; Patel et al., 2008), we intentionally did not manipulate the amplitude of the stimuli in order to preserve the natural quality of these sounds. Fig. 2 illustrates the arrangement of the stimuli used in the pitch threshold tasks. All stimuli were 250 ms in duration, with an inter-stimulus interval of 250 ms. For identification of discrete pitch patterns (Fig. 2A), the stimuli consisted of a standard stimulus of 120 Hz and 28 target stimuli that varied from 120.07 Hz to 213.82 Hz in steps (ΔF) of 0.01 st (between 120.07 and 120.70 Hz), 0.1 st (between 120.70 and 127.14 Hz), and 1 st (between 127.14 and 213.82 Hz). Thus, the smallest pitch difference (ΔF) between the standard and target stimuli was 0.01 st, and the largest pitch

Table 1
Characteristics of the amusic ($n = 19$) and control ($n = 19$) groups.

Group	Sex	Handedness	Age	Education	Scale	Contour	Interval	Rhythm	Meter	Memory	Pitch composite
Amusic											
Mean	12F	0L	23.32	17.00	18.63	20.05	18.21	23.00	19.84	23.00	56.89
SD	7M	19R	0.89	0.75	2.17	2.30	2.42	2.33	4.35	3.87	4.08
Control											
Mean	12F	1L	23.21	16.95	28.05	27.95	28.37	27.84	23.16	26.58	84.37
SD	7M	18R	1.27	0.78	1.54	1.43	1.67	1.64	5.44	3.20	3.37
t-test											
t			0.30	0.21	−15.44	−12.71	−15.06	−7.40	−2.08	−3.10	−22.63
p			0.77	0.83	<0.0001	<0.0001	<0.0001	<0.0001	0.045	0.004	<0.0001

F = female; M = male; L = left; R = right; age and education are in years; scores on the six MBEA subtests (scale, contour, interval, rhythm, meter, and memory) are in number of correct responses out of 30; the pitch composite score is the sum of the scale, contour, and interval scores; *t* is the statistic of the Welch two sample *t*-test (two-tailed, $df = 36$).

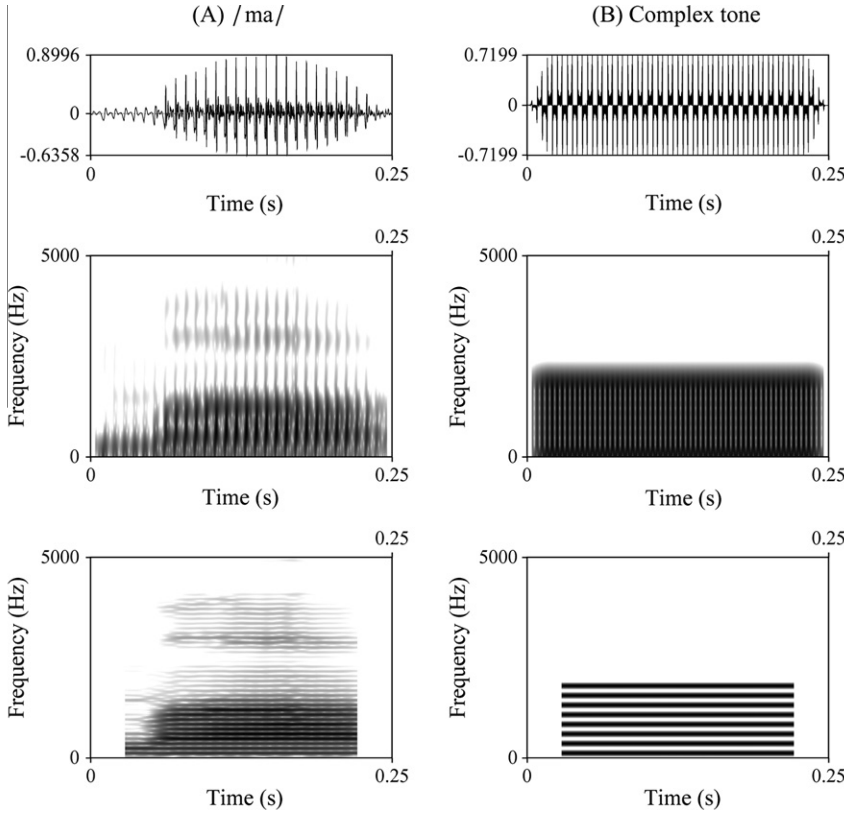

Fig. 1. Waveforms and spectrograms of the Mandarin syllable /ma/ (A) and its complex tone analog (B). Both have a fundamental frequency of 120 Hz. The top panel shows the waveforms of both sounds. The middle panel shows the wide-band spectrograms (window length: 0.0043 s; band-pass filter: 300 Hz) of both sounds, in which the glottal pulses and the formant structure of the speech syllable can be clearly seen. The bottom panel shows the narrow-band spectrograms (window length: 0.029 s; band-pass filter: 45 Hz) of both sounds, in which the spectral components (the fundamental frequency and seven odd harmonics, of the same amplitude and with sine phase) of the complex tone can be easily identified.

difference was 10 st. For identification of gliding pitch patterns (Fig. 2B), the stimuli included 28 rising glides and 28 falling glides with pitch excursion sizes (ΔF) between 0.01 and 10 st. Centered on 120 Hz, the smallest rising glide started at 119.97 Hz and ended at 120.03 Hz ($\Delta F = 0.01$ st), whereas the largest rising glide started at 89.90 Hz and ended at 160.18 Hz ($\Delta F = 10$ st). The falling glides were created using the opposite starting/ending pitches than the corresponding rising glides.

2.3. Procedure

Four two-interval forced-choice (2IFC) tasks (identification of pitch patterns in discrete/gliding /ma/ and complex tone; Fig. 2) were administered to each participant in separate blocks in counterbalanced order. Eight practice trials were given before each task to familiarize the participants with the stimuli and procedure. These practice trials contained stimuli that exhibited the largest pitch differences ($\Delta F = 9$ or 10 st). Participants were instructed to choose between two choices given on the computer screen (via mouse click) to indicate the pitch pattern of the stimulus pair: "高 低 ¯ _" ("high low ¯ _") or "低 高 _ ¯" ("low high _ ¯") for discrete pitches, and "升 降 / \" ("rising falling / \") or "降 升 \ /" ("falling rising \ /") for gliding pitches. Correct responses to all practice trials were ensured before participants proceeded to experimental trials. Depending on the performance on practice trials, participants' experimental trials either began with a 10 or 6 st starting

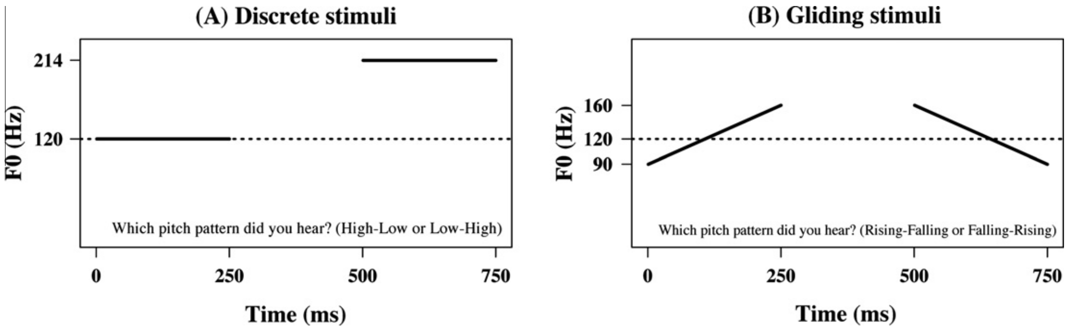

Fig. 2. Illustrations of the pitch threshold tasks: (A) discrete stimuli, and (B) gliding stimuli. The dotted line represents the reference frequency at 120 Hz, and the solid lines represent the auditory stimuli (discrete/gliding /ma/ and complex tones). The stimuli and the silences between them are 250 ms in duration.

ΔF. Experimental trials were presented with adaptive tracking procedures using the APEX 3 program developed at ExpORL (Francart et al., 2008), with an inter-trial interval of 750 ms. As a test platform for auditory psychophysical experiments, APEX 3 enables the user to specify custom stimuli and procedures with eXtensible Markup Language (XML). The "three-down, one-up" staircase method was used in the adaptive tracking procedure (Leek, 2001). Fig. 3 shows a sample data series (ΔF versus trial number) over the course of an entire trial in APEX 3. The experiment ended after 14 reversals, and the threshold was calculated as the mean ΔF (the mean pitch difference between the standard and target stimuli in the case of discrete pitches, and the mean pitch excursion size of the gliding pitches; in st) in the last six reversals. No feedback was given during the experimental trials. All stimuli were presented binaurally through Philips SHM1900 headphones at a comfortable listening level in a soundproof room at Shanghai Normal University, China.

3. Results

Given the non-normal distribution of most of the data, nonparametric Wilcoxon signed rank test (statistic: V, two-sided) and Wilcoxon rank sum test (statistic: W, two-sided) were applied in R (R Development Core Team., 2009) for within- and between-group comparisons, respectively. Kendall's rank correlation τ (two-sided) was used for correlation analysis.

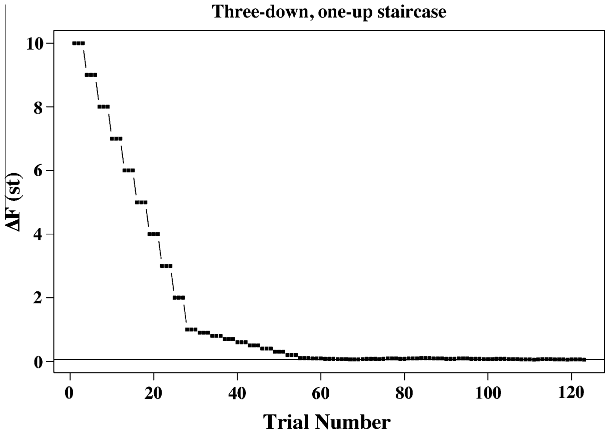

Fig. 3. An example of the adaptive track (ΔF versus trial number) following the "three-down, one-up" staircase procedure, in which the horizontal gray line indicates the calculated threshold (0.06 st) and the reference frequency is 120 Hz. Data from the control C14's performance on identification of pitch patterns in gliding complex tones.

Fig. 4 displays boxplots of amusics' and controls' thresholds (in st) for identification of pitch patterns in the four tasks (see Appendix B for individual thresholds). While the two groups showed comparable thresholds for identification of pitch patterns in gliding /ma/ (Fig. 4A; controls mean (SD): 0.62 (0.37), amusics: 1.42 (1.76), $W = 116$, $p = 0.06$), amusics had significantly higher thresholds than controls for identification of pitch patterns in discrete /ma/ (Fig. 4B; controls: 0.78 (1.25), amusics: 3.67 (3.29), $W = 50$, $p = 0.0001$), gliding complex tone (Fig. 4C; controls: 0.19 (0.08), amusics: 1.90 (2.99), $W = 61$, $p = 0.0005$), and discrete complex tone (Fig. 4D; controls: 0.30 (0.40), amusics: 4.44 (3.18), $W = 14$, $p < 0.0001$). In addition, amusics showed significantly higher thresholds for identification of pitch patterns in discrete than gliding stimuli (/ma/ in Fig. 4A and B: mean difference (SD): 2.26 (3.44), $V = 143$, $p = 0.01$; complex tone in Fig. 4C and D: 2.54 (3.67), $V = 149$, $p = 0.006$), whereas controls' thresholds for discrete and gliding stimuli were highly comparable (/ma/ in Fig. 4A and B: mean difference (SD): 0.16 (1.21), $V = 63$, $p = 0.33$; complex tone in Fig. 4C and D: 0.11 (0.40), $V = 91.5$, $p = 0.89$). Finally, while controls achieved significantly lower thresholds for identification of pitch patterns in complex tone than in /ma/ for both discrete (Fig. 4B and D; mean difference (SD): 0.48 (1.18), $V = 173$, $p = 0.0008$) and gliding (Fig. 4A and C; 0.42 (0.35), $V = 190$, $p < 0.0001$) conditions, amusics' thresholds were not significantly affected by stimulus type (discrete /ma/ versus complex tone in Fig. 4B and D: mean difference (SD): −0.76 (3.31), $V = 84$, $p = 0.66$; gliding /ma/ versus complex tone in Fig. 4A and C: −0.48 (1.67), $V = 93$, $p = 0.94$).

Correlation analysis reveals that controls' thresholds for identification of pitch patterns in discrete and gliding /ma/ were positively correlated ($z = 2.53$, $p = 0.01$, $\tau = 0.43$), and so were their thresholds in gliding /ma/ and complex tone ($z = 2.15$, $p = 0.03$, $\tau = 0.37$). Amusics' thresholds in gliding /ma/ and complex tone were also positively correlated ($z = 4.31$, $p < 0.0001$, $\tau = 0.73$). No other correlations between the sets of tasks reached statistical significance.

Correlation analysis between MBEA scores and pitch thresholds suggests that only amusics showed significant negative correlations between scores on the MBEA interval subtest and thresholds in gliding complex tone ($z = -2.28$, $p = 0.02$, $\tau = -0.40$) and gliding /ma/ ($z = -2.17$, $p = 0.03$, $\tau = -0.38$). No other correlations reached statistical significance.

4. Discussion

Previous studies suggest that amusics are better at simple sensory pitch discrimination than conscious labeling of pitch direction (Foxton et al., 2004; Loui et al., 2008). In order to better understand the nature of "melodic contour deafness" (Patel, 2008) or impaired "pitch awareness" (Loui et al., 2011) in amusia, this study

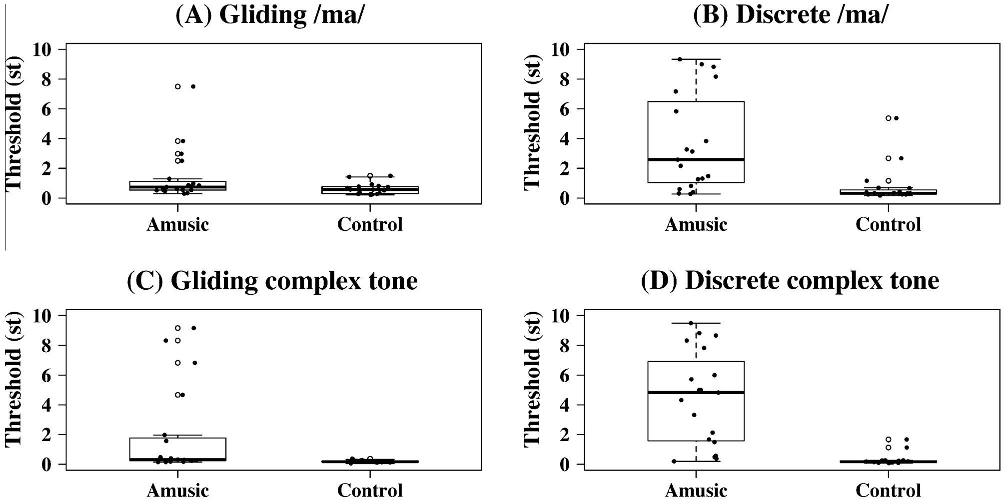

Fig. 4. Boxplots of amusics' and controls' thresholds (in st) for identification of pitch patterns in (A) gliding /ma/, (B) discrete /ma/, (C) gliding complex tone, and (D) discrete complex tone. Individual thresholds are represented by black dots, with those at the same horizontal level having identical values, and those lying beyond the whiskers being outliers (which are further indicated by open circles in the middle).

investigated whether Mandarin amusics have different thresholds for identification of discrete (high–low versus low–high) and gliding (rising–falling versus falling–rising) pitch patterns in the speech syllable /ma/ and in its non-speech complex tone analog. Results show that amusics' pitch direction identification thresholds were not significantly affected by whether the pitches were embedded in speech syllables or complex tones. Rather, it was discrete pitch pattern (high–low versus low–high) that caused amusics the most problems. This is consistent with the report that amusics had smaller (better) thresholds for detecting pitch changes in gliding than discrete pure tones (Foxton et al., 2004). Although controls also achieved better thresholds on gliding than discrete stimuli for both pitch change detection (Foxton et al., 2004) and pitch direction identification (the current study), the difference was not statistically significant. Combining the findings of the current study and Foxton et al. (2004), it seems that amusics' pitch processing deficits (simple pitch change detection, conscious pitch direction identification) are more pronounced for discrete than gliding pitches. This may in part explain the apparent domain specificity of amusia (severely impaired music processing; relatively spared speech processing), since discrete pitches are more commonly employed in music than in speech.

The gliding stimulus advantage for pitch thresholds in amusia may be explained by "perceptual learning" (Goldstone, 1998) or "experience-dependent plasticity" (Bidelman, Gandour, & Krishnan, 2011). There are two discrete (High, Low) and two gliding (Rising, Falling) tones in Mandarin, in terms of underlying phonological forms (Duanmu, 2007). However, in connected speech in Mandarin, pitch is continuously changing because it is in constant transition from one tone to another (Xu, 1997; Xu & Wang, 2001). Consequently, Mandarin speech is characterized by dynamic pitch movements and fast rates of pitch changes (Eady, 1982). Multidimensional scaling studies on linguistic tone perception indicate that Mandarin listeners put more weight on the "direction" (rising versus non-rising) than "height" (average F_0 level) dimension in judging tonal dissimilarity (Francis, Ciocca, Ma, & Fenn, 2008; Gandour, 1983; Guion & Pederson, 2007). Even during pre-attentive pitch processing in the auditory brainstem, Mandarin speakers demonstrated enhanced pitch strength in the rapidly changing part of the Rising tone (Bidelman et al., 2011). Given that only around a quarter of amusics listen to music as frequently as controls (McDonald & Stewart, 2008), it is possible that the perceptual enhancement of gliding versus discrete pitches in amusia is due to the fact that amusics have daily experiences with speech but little exposure to music. It is not clear, however, how perceptual learning based on speech could account for the advantages that amusics show for gliding versus discrete stimuli in non-speech. It could be the case that perceptual learning in one domain has effects that are not limited to that domain. It is worth noting that perceptual learning about gliding pitches in speech is unlikely to be limited to tone languages, given that constant tonal transitions also occur in non-tonal languages (Xu, 2005). Furthermore, studies on psychophysical pitch thresholds of normal listeners (Demany, Carlyon, & Semal, 2009; Lyzenga, Carlyon, & Moore, 2004; Sek & Moore, 1999) and non-native linguistic pitch perception of amusics and controls (Tillmann et al., 2011) have also demonstrated a gliding stimulus advantage. In addition, a recent study by Vuust, Brattico, Seppänen, Näätänen, and Tervaniemi (2012) showed superior neural discrimination of pitch slides in jazz musicians compared with other types of musicians, as a consequence of the diffuse presence of such stylistic feature in jazz music. Therefore, it seems that sensitivity to pitch movement is widespread in audition (perhaps a result of a predisposition of the peripheral auditory system; Demany et al., 2009; Lyzenga et al., 2004; Sek & Moore, 1999) and is employed in speech perception in all types of languages and in music that emphasizes gliding pitches (e.g., jazz, or Indian classical music), while the ability to detect small differences in discrete tones is optional even in a tone language.

To date, there have been mixed findings regarding the effect of stimulus type on pitch processing in amusia. In some studies amusics (both non-tonal language speakers and tone-language speakers) were better able to discriminate speech intonation in natural speech than in complex tone analogs (Ayotte et al., 2002; Jiang et al., 2010; Patel et al., 2005), while other studies observed the opposite (Liu et al., 2010; Patel et al., 2008). Results from the current study indicate that Mandarin amusics have equivalent pitch direction identification thresholds for the speech syllable /ma/ and its complex tone analog. Controls, on the other hand, showed significantly smaller (better) thresholds for complex tones than for the syllables. This is consistent with the finding in Francis and Ciocca (2003), where both English and Cantonese listeners showed higher sensitivity to pitch differences for non-speech complex tones than synthesized speech stimuli. Thus, it is interesting to note that amusics in fact performed slightly better on the syllable /ma/ than on complex tone, although not significantly so, showing a subtle advantage of speech stimulus over complex tone. Tillmann et al. (2011) suggest that amusics' performance on speech versus musical stimuli may be related to their pitch perception thresholds: those with higher pitch thresholds tend to benefit from verbal stimuli versus musical stimuli, whereas those with lower pitch thresholds do not show a stimulus effect. However, given that amusics in the current study show similar pitch thresholds for speech syllables and complex tones, the mixed findings in previous research on the impact of stimulus type on pitch processing in amusia may be due to other factors at play, e.g., linguistic context (Patel, 2008), or amusics' impaired pitch memory for nonverbal sounds (Tillmann, Schulze, & Foxton, 2009; Williamson & Stewart, 2010).

Finally, it is worth mentioning that amusics' pitch direction identification thresholds for gliding stimuli are negatively correlated with their scores on the MBEA interval subtest: the smaller (better) the thresholds, the better the MBEA interval scores. A similar finding was reported in Tillmann et al. (2011), in which a positive correlation was found between French amusics' performance on Mandarin tone discrimination and their MBEA interval scores. This suggests that amusics' pitch processing abilities in psychophysical and non-native speech tasks are linked to their musical interval processing abilities.

In summary, this study assessed Mandarin amusics' pitch direction identification thresholds for different stimulus types. While amusics had comparable pitch thresholds for speech syllables and complex tones, they demonstrated superior recognition of gliding pitch patterns compared with discrete ones. These findings suggest that the ‘‘melodic contour deafness'' in amusia causes similar problems in speech and music processing, but amusics' pitch processing deficits are more severe with discrete pitches in music than with the gliding pitches of speech. This may pave the way for designing rehabilitative programs for congenital amusia, building on residual auditory skills.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandc.2012.03.008.

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