Mem Cogn (2012) 40:1109–1121
DOI 10.3758/s13421-012-0208-2

Impaired categorical perception of lexical tones in Mandarin-speaking congenital amusics

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Published online: 2 May 2012

Abstract The degree to which cognitive resources are shared in the processing of musical pitch and lexical tones remains uncertain. Testing Mandarin amusics on their categorical perception of Mandarin lexical tones may provide insight into this issue. In the present study, a group of 15 amusic Mandarin speakers identified and discriminated Mandarin tones presented as continua in separate blocks. The tonal continua employed were from a high-level tone to a mid-rising tone and from a high-level tone to a high-falling tone. The two tonal continua were made in the contexts of natural speech and of nonlinguistic analogues. In contrast to the controls, the participants with amusia showed no improvement for discrimination pairs that crossed the classification boundary for either speech or nonlinguistic analogues, indicating a lack of categorical perception. The lack of categorical perception of Mandarin tones in the amusic group shows that the pitch deficits in amusics may be domain-general, and this suggests that the processing of musical pitch and lexical tones may share certain cognitive resources and/or processes (Patel 2003, 2008, 2012).

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Keywords Congenital amusia · Mandarin tone · Categorical perception · Identification · Pitch discrimination

Music and language appear in every human society (Ayotte, Peretz & Hyde, 2002; Patel, 2008), and both appear to have developed very early in human history. The oldest known musical instrument, a flute, dates to over 35,000 years ago (Conard, Malina & Münzel, 2009), and language has been suggested to predate the African exodus (Atkinson, 2011). The comparison between music and speech processing has attracted much attention in recent years. On the basis of music-related deficits in brain-damaged patients, it has been suggested that music and language may be processed in separate systems (Peretz, 2006; Peretz & Coltheart, 2003; Peretz & Morais, 1989), although speaking and singing may overlap (Peretz, 2009). Alternatively, others have suggested that music and language share neural resources, on the basis of evidence derived from healthy individuals (Patel, 2003, 2008, 2012). The latter, resource-sharing framework posits that although language and music involve domain-specific representations, similar cognitive operations that share neural resources are conducted on these domain-specific representations (Patel, 2012). For example, pitch is a vital element in both tonal music and speech, and domain-transfer effects suggest a possible connection between musical pitch and lexical tone processing (Gottfried & Riester, 2000; Gottfried, Staby & Ziemer, 2001; Lee & Hung, 2008; Wu & Lin, 2008). As such, examining lexical tone processing in those who are known to have deficits in processing musical pitch should provide valuable evidence toward determining the extent to which music and speech share processing components.

Congenital amusia (simply *amusia*, hereafter; Peretz, 2001) describes a lifelong deficit in the processing of musical pitch variations in the absence of brain injury (Ayotte et al., 2002; Peretz et al., 2002). These pitch deficits manifest as a difficulty in making fine-grained pitch discriminations (Foxton, Dean, Gee, Peretz & Griffiths, 2004; Hyde & Peretz, 2004; Jiang, Hamm, Lim, Kirk & Yang, 2011), processing pitch-change direction (Foxton et al., 2004; Liu, Patel, Fourcin & Stewart, 2010), and deciding whether two sequences of pitches are the same or different (Foxton et al., 2004; Hyde & Peretz, 2004; Jiang, Hamm, Lim, Kirk & Yang, 2010). Some studies have suggested that amusics may also have pitch memory deficits (Gosselin, Jolicœur & Peretz, 2009; Tillmann, Schulze & Foxton, 2009), particularly with shorter tone spans (Williamson & Stewart, 2010). However, whether or not the musical pitch deficits in amusia also manifest as pitch-processing deficits in speech is currently debated. Some have argued that individuals with amusia do not have compromised interpretation and discrimination of Western speech intonation (Ayotte et al., 2002; Peretz et al., 2002), whereas others have suggested that the pitch deficits in amusia extend to the processing of emotional prosody (Thompson, 2007) and speech intonation contours (including gliding-pitch analogues extracted from speech intonation; Hutchins, Zarate, Zatorre & Peretz, 2010; Jiang et al., 2010; Liu et al., 2010; Patel, Foxton & Griffiths, 2005; Patel, Wong, Foxton, Lochy & Peretz, 2008).

It is well known that changes in tone influence word meaning in tonal languages. In Mandarin Chinese, there are four lexical tones, which vary in their contour shapes: high-level (Tone 1), mid-rising (Tone 2), falling-rising (Tone 3), and high-falling (Tone 4) (see Fig. 1). For example, ma[1] means "mother," ma[2] corresponds to "hemp," ma[3] to "horse," and ma[4] indicates "scold." To test whether or not the discrimination of Mandarin pitch changes might be problematic for Western amusic individuals, Nguyen, Tillmann, Gosselin and Peretz (2009) assessed amusic speakers of French on their discrimination of pairs of Mandarin lexical tones. The amusic participants performed worse than

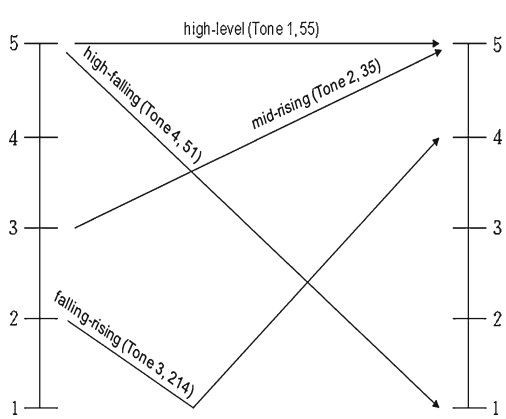

Fig. 1 Pitch contours of Mandarin tones. Note: The numbers in parentheses indicate the pitch values of the tones on a five-level scale

the controls, with 15 % of the amusic group scoring two or more standard deviations below the mean of the controls. Similarly, French-speaking amusics have been shown to be impaired in the processing of Mandarin and Thai lexical tones (Tillmann et al., 2011).

Of course, the French-speaking participants in these studies did not speak Mandarin Chinese, and so the tones would not be processed as meaningful language. Lacking the semantics, and presumably therefore lacking the input of the language-processing system, it may not be surprising that they showed impairments on processing the pitch of these stimuli. It has been speculated that amusics who speak a tonal language might retain normal sensitivity to pitch changes that occur in their native language (Stewart, 2006). However, in our previous study (Jiang et al., 2010), we found that native speakers of Mandarin Chinese with amusia were impaired in Mandarin speech intonation processing during a question-versus-statement discrimination. This result suggests that tonal language experience may not entirely compensate for deficits in intonation processing in amusia. Whether or not Mandarin-speaking amusics also show impairments on the perception of Mandarin tones is of particular interest here.

Some evidence has suggested that this may be the case. Nan, Sun and Peretz (2010) found that amusic Mandarin speakers performed worse than controls in a tone identification task involving monosyllabic and bisyllabic words. In addition, it has been shown that individuals with deficits in musical pitch processing also have impaired phonemic awareness (Jones, Lucker, Zalewski, Brewer & Drayna, 2009a; Loui, Kroog, Zuk, Winner & Schlaug, 2011). This suggests that the deficits with Mandarin tones found by Nan et al. may be related to reduced phonemic awareness in amusia.

Categorical perception of phonemes reflects a fundamental property of speech (e.g., Chang et al., 2010; Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967; Patel, 2008). Previous cross-language studies have indicated that native Mandarin and Cantonese speakers show categorical perception of Mandarin language tones, whereas adults who do not speak Mandarin do not show categorical perception of Mandarin tones (e.g., Chan, Chuang & Wang, 1975; Peng et al., 2010; Wang, 1976; Xu, Gandour & Francis, 2006). Categorical perception is not only found with speech sounds, but has also been found in the processing of musical chords and pitch intervals (Burns & Campbell, 1994; Burns & Ward, 1978; Klein & Zatorre, 2011; McMurray, Dennhardt & Struck-Marcell, 2008; Siegel & Siegel, 1977; Zatorre & Halpern, 1979). It has been suggested that 4- to 6-month-old infants discriminate the sound categories in both Mandarin tones and music (Lynch & Eilers, 1992; Mattock, Molnar, Polka & Burnham, 2008), but if they are not exposed to Mandarin language, or a given musical context, these abilities are lost by 9 months for speech tones (Mattock et al., 2008), and by adulthood for music (Lynch & Eilers, 1992). Furthermore, listeners with music training outperformed those without music training in categorical perception studies involving Mandarin tones (Wu & Lin, 2008) or nonspeech frequency continua (e.g., Howard, Rosen & Broad, 1992; Mirman, Holt & McClelland, 2004; Pisoni, 1977). These studies indicated that experience with tonal language and music may affect the categorical perception of speech and nonlinguistic frequency continua.

It has been suggested that music and language share mechanisms that create and maintain learned sound categories (Patel, 2008). Although the developmental processes for sound categories may be domain-general, the end products of development may be domain-specific (Patel, 2008). Therefore, the ability to learn sound categories in one domain should have some predictive power with regard to sound category learning in the other domain (Patel, 2008, p. 78). From this argument, it follows that deficits with sound categories in one domain, such as the deficits with musical tones shown by amusics, should be associated with deficits with sound categories in another domain, such as Mandarin tones if the deficits are part of the domain-general developmental processes. Conversely, if the deficits in amusia are within the domain-specific representations, there should be no association between the musical deficits in amusia and the categorical perception of Mandarin tones.

To assess categorical perception, two tasks would be required in order to produce unequivocal results (Massaro, 1987). It should be pointed out that we are considering the weak form of categorical perception that Massaro (1987, p. 118) describes, which is captured by the improved discriminations that occur between members of different categories, relative to discriminations between members of the same category that differ by the same physical amount. To determine such discriminations, the first task required is the classification task, in which participants are required to indicate to which of two categories they would assign a given stimulus when it is presented in isolation. A set of stimuli are presented that change along a physical continuum for classification. Provided that the extreme exemplars are distinguishable, it becomes possible to determine a physical stimulus level at which a given participant is equally likely to classify the stimulus as either category. This point of equality will be referred to as the *classification boundary* rather than as the *categorical boundary*, as the latter term may be mistaken to imply that the classification task alone determines categorical perception. The slope of the boundary may be steep or shallow, and it is referred to as the *sharpness* of the classification boundary.

Of course, any classification task will produce a classification boundary, regardless of whether or not there is an accompanying categorical change in perception. This change in decision can reflect training and practice (Livingston, Andrews & Harnad, 1998). While the sharpness of the classification boundary indicates the consistency with which the stimuli near the position of the boundary are assigned into their respective categories, it does not necessarily reflect whether or not a categorical change in perception takes place at that boundary (Massaro, 1987).

The second task is a discrimination task, in which pairs of stimuli are presented for a same/different judgment. On *different* pairs, the two stimuli differ by a constant amount in terms of their physical dimension. If both stimuli of the pair fall on the same side of the classification boundary, they are coded as a *within-category* pair, but if they fall on opposite sides of the classification boundary, they are referred to as a *between-category* pair. The difference between the discrimination of between-category pairs and within-category pairs is referred to as the *peakedness of the discrimination*.

Although the criterion and definition for categorical perception are still a matter of debate (e.g., Francis, Ciocca & Ng, 2003; Gerrits & Schouten, 2004; Liberman, Harris, Hoffman & Griffith, 1957; Massaro, 1998; Repp, Healy & Crowder, 1979; Schouten, Gerrits & van Hessen, 2003), there is consensus that, when stimuli are perceived categorically, two tokens from two different categories are more discernible than are two tokens from the same category with an equivalent acoustic difference between them (Massaro, 1987). Namely, categorical perception can explain why it is easier to discriminate stimuli when the pairing is between categories. This cross-boundary benefit is the defining feature of categorical perception (Massaro, 1987). If there is no benefit for discriminations that cross the boundary relative to within-boundary discriminations, there is no support for asserting that categorical perception occurs.

Because the change in performance for stimuli that cross a boundary is the defining characteristic of categorical perception, knowing the position of this boundary is highly important. Therefore, although the sharpness of the classification boundary is not a critical measure to justify whether or not categorical perception has occurred, the boundary's position during the classification task is a necessary measure in order to test for categorical perception in the subsequent discrimination task.

The purpose of the present study was to investigate the categorical perception of lexical tones in Mandarin-speaking individuals with amusia by employing a traditional categorical-perception paradigm that included both identification and discrimination tasks. The present study also investigated the effects of pitch direction and stimulus context (speech vs. nonlinguistic analogues) on the categorical perception of lexical tones for Mandarin amusics, because it is uncertain whether or not amusics have greater difficulty with detecting rising or falling pitch changes (Hyde & Peretz, 2004; Jiang et al., 2011;

Peretz et al., 2002). As is shown in Fig. 1, Tone 1 is a high-level tone, while the pitch contours of Tone 2 and Tone 4 are rising and falling linear ramps, respectively. Therefore, two types of continua (Tone 1–Tone 2 and Tone 1–Tone 4), using both natural speech and nonlinguistic analogues, were employed in the present study. We hypothesized that if amusia is a domain-general pitch-processing deficit, then amusic individuals would be likely to have greater difficulty in detecting the changes in pitch for language stimuli as well, indicating a shared sound-category learning mechanism for language and music. Alternatively, if the pitch deficits in amusia are domain-specific, then amusic individuals should not be impaired, which would suggest that music and language do not share a common learning mechanism for sound categories.

Method

Participants

The two groups of participants contained 15 amusic adults and 15 control adults. Of these participants, 11 amusic and 10 control adults had participated in our previous studies (Jiang et al., 2010, 2011). All of the participants were recruited by means of advertisements in the bulletin board systems of universities in Beijing. The Montreal Battery of Evaluation of Amusia (MBEA) was to be used to diagnose the presence or absence of amusia in these participants (Nan et al., 2010; Peretz, Champod & Hyde, 2003). The characteristics of each participant group are shown in Table 1. All but two amusics and one control participant were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Moreover, a detailed questionnaire was presented to gather further information about the participants. None of the participants had received extracurricular music training, and none reported difficulties in discriminating Mandarin tones. All had normal hearing, with mean hearing levels of 19.1 and 19.8 dB HL for the right and left ears, respectively, as measured by pure-tone audiometry at 125, 250, 500, 1000, and 2000 Hz. Ethical approval was obtained from the Institute of Psychology, Chinese Academy of Sciences, and informed consent was obtained from all of the participants.

Table 1 Participants' characteristics and individual scores on the Montreal Battery of Evaluation of Amusia (MBEA)

Demographic Characteristics	Amusic (n = 15)	Control (n = 15)	t Test
Mean age	24 (3.3)	23 (1.8)	n.s.
Gender	7 M, 8 F	8 M, 7 F	
Years education	17 (2.3)	16 (1.3)	n.s.
Global score of MBEA	19 (2.3)	27 (1.6)	$p < .001$
Scale subtest	18 (3.4)	27 (2.0)	$p < .001$
Contour subtest	19 (2.7)	26 (2.3)	$p < .001$
Interval subtest	18 (2.7)	27 (1.6)	$p < .001$
Rhythm subtest	21 (4.4)	26 (2.4)	$p < .001$
Meter subtest	21 (3.9)	25 (2.7)	$p = .001$
Memory subtest	20 (4.1)	28 (2.3)	$p < .001$

Parentheses in the data rows indicate standard deviations. F, female; M, male

Stimuli

The speech stimuli were the Mandarin vowel /i/ with a high-level tone (Tone 1) spoken by a male native speaker of Mandarin Chinese. On the basis of the Tone 1 natural-speech template, two tonal continua were synthesized by means of Praat software (Boersma, 2001). These two tonal continua ranged from a high-level tone to a mid-rising tone (yi^1 means "clothing," and yi^2 indicates "aunt"; i.e., Tone 1–Tone 2) and from a high-level tone to a high-falling tone(yi^1 means "clothing," and yi^4 indicates "difference"; i.e., Tone 1–Tone 4), respectively. Each continuum contained 11 stimuli, with a step size of 3 Hz, which is a rather large difference in psychological terms (Wang, 1976). In these two tonal continua, the peak frequency of all stimuli was fixed at 228 Hz, and each stimulus lasted 350 ms (see Fig. 2). The ends of the two tonal continua, Steps 1 and 11, were all judged to be good examples of Mandarin Tone 1, Tone 2, and Tone 4 by six native Chinese (Mandarin) speakers who did not take part in the experiments.

In addition to the speech stimuli, an equal number of nonlinguistic analogues were created. These nonlinguistic analogues were created using Praat software to extract the fundamental frequencies of the speech materials. Essentially, the linguistic information was removed, while the timings of the speech materials remained unchanged. Moreover, the newly created sound was modified to ensure that its acoustic waveform amplitude differed from the original speech sound by no more than ±3 dB in each pair.

For the practice task, 11 stimuli were presented, with linear ramps ranging from Tone 1 to Tone 2 and from Tone 1 to Tone 4 for the speech and nonlinguistic analogues, respectively. The difference between the practice stimuli and the experimental stimuli was that the former were derived from the Mandarin vowel /a/, and the latter from the Mandarin vowel /i/.

Procedure

All participants engaged in the two tonal-continua identification and discrimination tasks for both speech and the nonlinguistic analogue, respectively. The four tasks were presented in separate blocks in a counterbalanced order. In each continuum identification task, each stimulus was repeated four

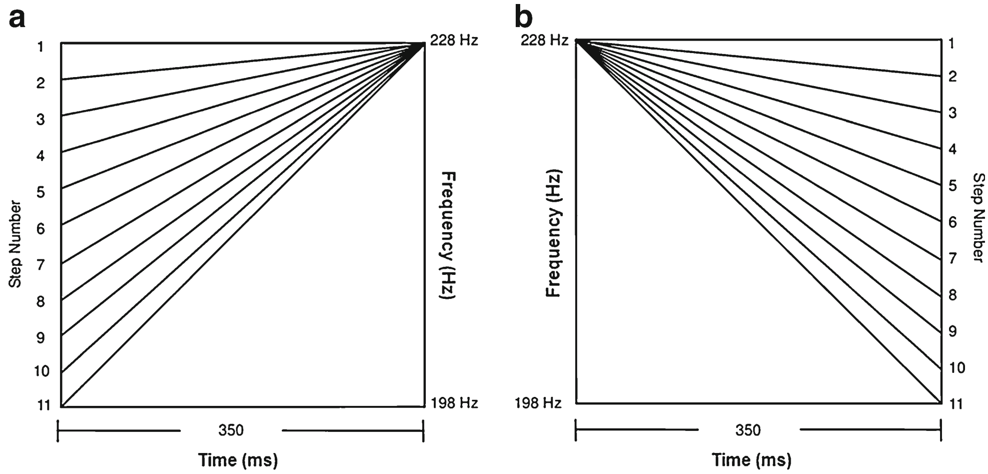

Fig. 2 Pitch patterns of the tonal continua. (**a**) Tone 1–Tone 2 continuum. (**b**) Tone 1–Tone 4 continuum

times, resulting in 44 randomly ordered trials for speech. Furthermore, 44 randomly ordered trials were also presented for nonlinguistic analogues in the two continua. The participants were required to press the "1" key if the stimulus resembled a "high-level tone (Tone 1)," and the "2" key to indicate a "mid-rising tone (Tone 2)" in the Tone 1–Tone 2 continuum for both speech and the nonlinguistic analogue. Similarly, the "2" key was coded as a "high-falling tone (Tone 4)" in the Tone 1–Tone 4 continuum for both speech and the nonlinguistic analogue.

In each tonal continuum discrimination task, nine pairs were derived by combining two stimuli separated by two steps, such as 1–3, 2–4, 3–5, and so on. The *different* pairs included nine pairs for each tonal continuum in the forward (1–3, 2–4, 3–5, 4–6, 5–7, 6–8, 7–9, 8–10, 9–11) and reverse (3–1, 4–2, 5–3, etc.) orders, respectively. Identical pairs were constructed by pairing each stimulus in a tonal continuum with itself. The order of the stimuli in each pair was counterbalanced with a 200-ms interstimulus interval (ISI), and each pair was presented four times. As a result, a total 116 pairs, including 72 *different* pairs and 44 identical pairs, were presented randomly for speech and for the nonlinguistic analogue, respectively, in each tonal continuum. For the four discrimination tasks, the participants were required to judge whether the two stimuli were the same or different by pressing the "1" key if they heard the same stimulus or the "2" key to indicate different stimuli. For the analyses, a hit was defined when a *different* pair was indicated as "different," while a false alarm was defined when an identical pair was indicated as "different."

In the practice task, the 11 stimuli were presented only once in a random order for the identification task. For the discrimination task, eight practice pairs comprising two *different* stimuli separated by three steps were presented randomly. All of the stimuli were presented binaurally through Philips SHM1900 headphones in a soundproofed room.

Results and discussion

Classification task

Identification curves for the two groups are plotted in Fig. 3. As can be seen, the amusic participants show a sharpness of the classification boundary similar to that of the controls. A logistic regression analysis was performed using generalized linear models using the R statistical software package (R Development Core Team, 2009). We calculated the slope (b_1) and intercept (b_0) regression coefficients for each participant, with the slope being used to indicate the sharpness of the classification boundary. The regression equation was used to predict the discrimination value (X) for each stimulus step (1–11). Because logistic regression works in logit space, these predicted values must be transformed back into the data space via the following equation: data = $e^x/(e^x + 1)$. The sum of the squared deviations between these predicted data values and the observed values were then expressed as the percentage reduction in variation relative to the squared deviation about the observed mean. This reduction was used as a measure of the goodness of fit for each participant. The range over all participants and conditions was between 42.4 % and 99.8 %, with a mean percentage reduction of 89.7 %. It was concluded that the logistic regression provided a good fit to the observed data at the individual level, and so an analysis of the b_1 and b_0 parameters was conducted.

In order to determine whether there were any effects on the sharpness of the classification boundary, the slopes were analyzed in a three-way mixed-factor analysis of variance (ANOVA), with Group as a between-subjects factor and Stimulus Context (speech vs. nonspeech analogue) and Continuum (Tone 1–Tone 2 vs. Tone 1–Tone 4) as within-subjects factors. None of the main effects or interactions reached significance (all $ps > .2$).

Although caution is required when interpreting a null result, this is consistent with previous studies, suggesting

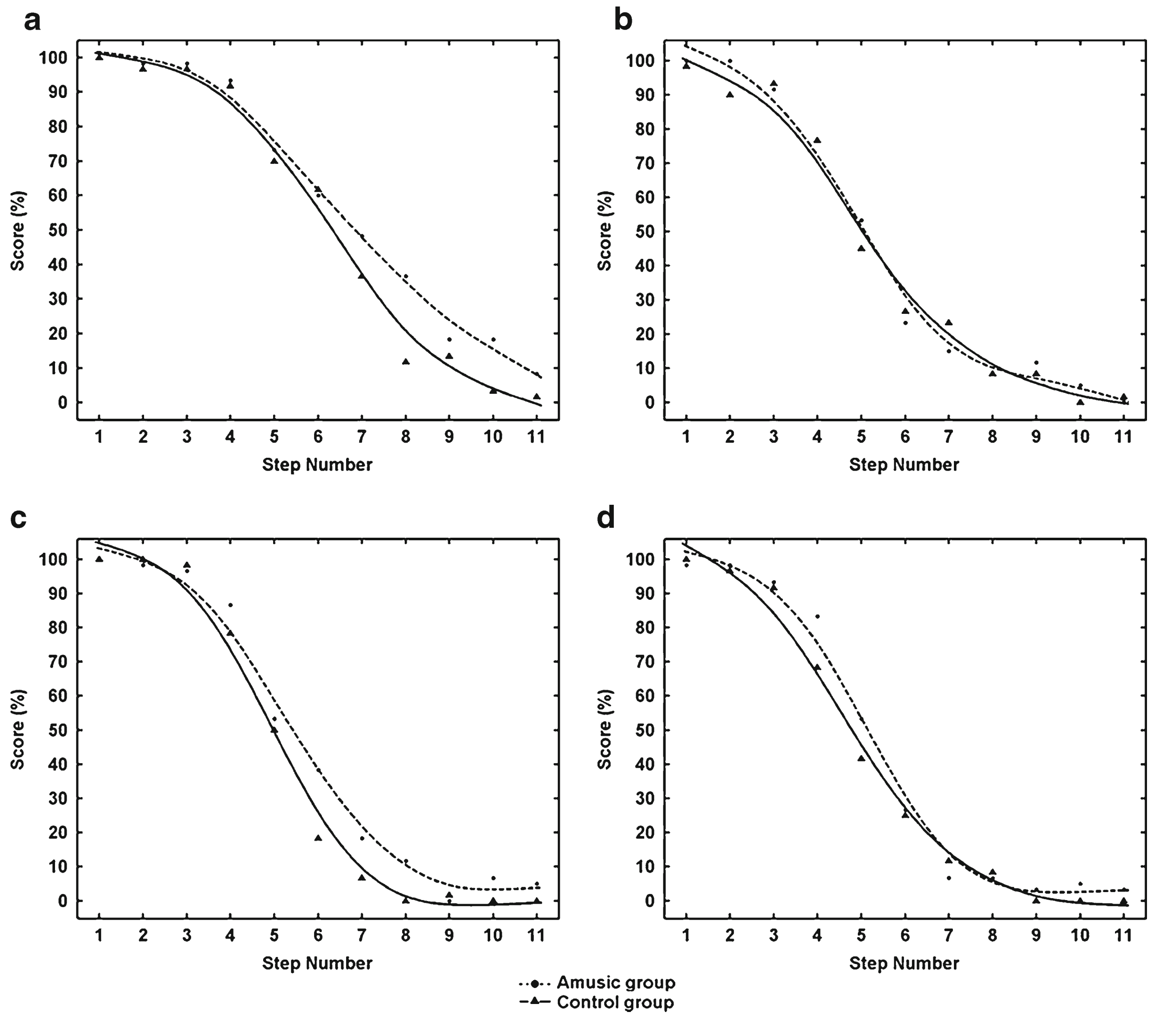

Fig. 3 Identification curves for the two groups in each task. (**a**) Tone 1–Tone 2 continuum for speech. (**b**) Tone 1–Tone 2 continuum for a nonlinguistic analogue. (**c**) Tone 1–Tone 4 continuum for speech. (**d**) Tone 1–Tone 4 continuum for a nonlinguistic analogue

that the identification task reflects the listeners' native language experiences (Chan et al., 1975; Peng et al., 2010; Wang, 1976; Xu et al., 2006) and that phonetic memory is employed to do the identification task (Pisoni, 1973). The phonetic-memory code is thought to be stable, due to contact with representations residing in long-term memory (Xu et al., 2006, p. 1069). The present lack of a difference between amusics and the controls with respect to the sharpness of the classification boundaries is consistent with the suggestion that amusics have normal long-term phonetic memory (Jones, Zalewski, Brewer, Lucker & Drayna, 2009b). A normal long-term phonetic representation in amusia would be consistent with the suggestion that music and language have specialized representations (Patel, 2008).

Although the similar sharpnesses of the boundaries would be consistent with preserved categorical perception of the lexical tones in amusia, this finding does not lead unequivocally to such a conclusion. An alternative explanation would be as follows. The difference in tonal frequency between the beginning and end of the level tone is 0, while the difference between the beginning and end of the rising and falling tones equates to 2.44 semitones at Step 11. Amusics are capable of discriminating musical tones that differ by this amount, although their performance is below that of controls (Jiang et al., 2011). Each step in the tonal continua equates to approximately 0.24 semitones (range = 0.23 to 0.26, due to the exponential relationship between the physical frequency and perceived semitones), which in turn is below their discrimination threshold for individual tones (Jiang et al., 2011). If the amusics compare each presented stimulus with a normal long-term phonetic representation, it might be expected that the stimuli would not be perceived as different from this representation until the tone and representation differ by somewhere between one-half and one semitone (Jiang et al., 2010). As a stimulus moves farther from one end of the continuum, the difference between the stimulus and the long-term phonetic representation would increase and move into the detectable range. At the same time, the stimulus becomes more similar to the alternative long-term phonetic representation and moves quickly into a range that is nondetectable. With these performance pressures working at both ends of the continua, the result could be that the sharpness of the classification boundary reflects these competing forces “squeezing” the boundary into place, rather than indicating a sudden change in the categorical perception of the stimuli. This squeezing due to poor discrimination of lexical tones would also account for the tendency of the boundary position to be more central for the amusics than for the controls.

Unlike the sharpness measure, the position of the classification boundary is a critical measure in order to test for categorical perception in the subsequent discrimination task. On the basis of the formula presented in Xu et al. (2006), the position of the classification boundary (x_{cb}) was calculated for each participant from the logistic regression coefficients (b_0 and b_1) as follows:

$$b_0 + b_1 x_{cb} = \log_e\left(\frac{0.5}{1-0.5}\right) = 0 \Rightarrow x_{cb} = -\frac{b_0}{b_1} \qquad (1)$$

As can be seen in Fig. 2, the higher the value of x_{cb}, the closer the boundary is to Tone 2 or Tone 4. As can be seen in Table 2, the amusic group’s x_{cb} score is higher than the controls’, suggesting that the positions of the classification boundaries for the amusic group may be shifted toward the mid-rising (Tone 2) and high-falling (Tone 4) ends of the two tonal continua. This was confirmed by a mixed-factor three-way ANOVA, which was conducted to determine the impacts of participant group (amusics vs. controls), stimulus context (speech vs. nonlinguistic analogue), and continuum type (Tone 1–Tone 2 vs. Tone 1–Tone 4) on the boundary position, with the participant group as the between-subjects variable, and stimulus context and continuum type as the within-subjects variables. The analysis revealed significant main effects of group [$F(1, 28) = 7.14$, $p < .001$], stimulus context [$F(1, 28) = 15.60$, $p < .001$], and continuum type [$F(1, 28) = 20.54$, $p < .001$], as well as an interaction of stimulus context and continuum type [$F(1, 28) = 22.04$, $p < .001$]. All other interactions were not significant ($p > .05$). Post hoc Bonferroni-corrected *t* tests revealed a significant difference between the groups in the boundary position for the speech stimuli ($p < .001$), but not for the nonlinguistic analogues ($p > .05$).

Cross-linguistic studies (Chan et al., 1975; Francis et al., 2003; Peng et al., 2010; Wang, 1976; Xu et al., 2006) comparing Mandarin- and English-/German-speaking participants on their classification of Mandarin tones have found no significant difference with respect to the position of the classification boundary, although the boundary is shallower for the nonspeakers. Therefore, the present pattern for the amusics is unlike that of nonspeakers of Mandarin and may be due to an insensitivity to pitch contour for the amusics.

As can be seen from Table 2, the boundaries of the amusic group are shifted toward the mid-rising and high-falling tone ends of the two continua. This shift suggests that the amusic participants are less able to detect the change in pitch of the rising and falling tones (Tones 2 and 4), and so classified them as level, or not changing (Tone 1). This is consistent with the notion that Mandarin-speaking amusics have impaired tone processing with speech material. An insensitivity to small pitch changes for the amusics is consistent with the finding of problems in detecting the direction of a small pitch change (Foxton et al., 2004) with fine-grained pitch discriminations (Jiang et al., 2011), and it is also consistent with the finding that Mandarin amusic speakers have problems in processing melodic contour and speech intonation (Jiang et al., 2010).

Discrimination task

On the discrimination task, the amusics were at chance levels for all pairs. The obtained discrimination curves for the amusic group are lower than those of the controls for both speech and the nonlinguistic analogue, as shown in Fig. 4.

On the basis of the position of the classification boundary (x_{cb}), we calculated discrimination scores (the percentage of

Table 2 The regression coefficients (b_0 and b_1) and the derived classification boundary position (x_{cb}) for each group

	Amusic Group			Control Group		
	b_0	b_1	$x_{cb} = -b_0/b_1$	b_0	b_1	$x_{cb} = -b_0/b_1$
T1–T2 S	−6.8 (3.4)	1.0 (0.6)	7.3 (1.6)	−8.9 (4.3)	1.4 (0.8)	6.4 (1.2)
T1–T4 S	−7.6 (3.5)	1.4 (0.7)	5.6 (0.9)	−9.2 (2. 9)	1.9 (0.5)	4.9 (0.6)
T1–T2 NL	−7.0 (2.8)	1.3 (0.5)	5.4 (1.0)	−8.4 (4.0)	1.7 (0.9)	5.2 (1.2)
T1–T4 NL	−8.3 (3.8)	1.6 (0.8)	5.3 (0.8)	−7.9 (3.4)	1.6 (0.7)	4.9 (0.8)

S, speech stimuli, NL, nonlinguistic analogue stimuli; T1–T2, Tone 1–Tone 2 continuum; T1–T4, Tone 1–Tone 4 continuum. The unit of the derived classification boundary position x_{cb} is step number

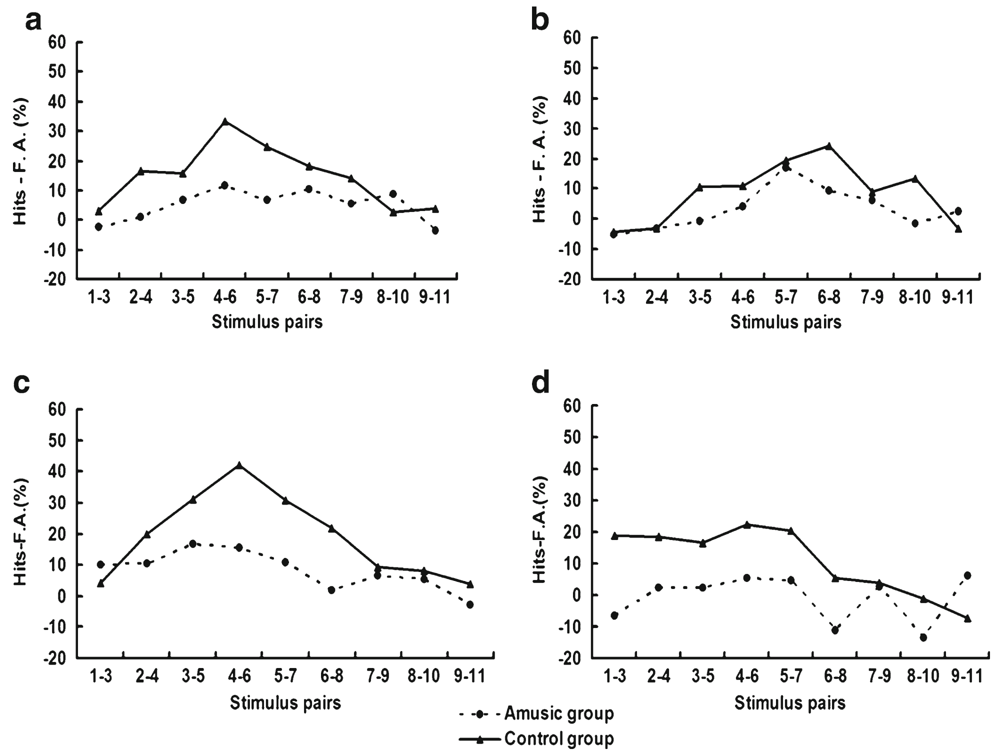

Fig. 4 Discrimination curves for the two groups. (**a**) Tone 1–Tone 2 continuum for speech. (**b**) Tone 1–Tone 2 continuum for a nonlinguistic analogue. (**c**) Tone 1–Tone 4 continuum for speech. (**d**) Tone 1–Tone 4 continuum for a nonlinguistic analogue

hits minus false alarms) for between-category and within-category pairs for each participant. These were calculated as follows. If the classification task indicated that a participant's classification boundary was at position 4.5, then the scores for Stimulus Pairs 3–5 and 4–6 would be averaged and coded as between-category comparisons, while the remaining comparisons would be coded as within-category comparisons. As can be seen in Fig. 5, the performances of both groups were similar on the two continua. Although both groups performed better with speech than with the nonlinguistic analogue, the amusic participants did not benefit from discriminations that crossed the classification boundary for either stimulus type. In contrast, the control participants' discriminations did benefit for both stimulus types when the discriminations crossed the classification boundary.

This was confirmed by a three-way ANOVA performed on the percentage of hits minus the percentage of false alarms for the between- and within-category discrimination for each group, where stimulus context (speech vs. nonlinguistic analogue), category type (between-category vs. within-category), and continuum type (Tone 1–Tone 2 vs. Tone 1–Tone 4) were the within-subjects variables. For the amusic group, we found a main effect of stimulus context [$F(1, 14) = 5.69$, $p < .05$], with all other main effects and interactions being nonsignificant. The controls, however, showed main effects of category type [$F(1, 14) = 28.92$, $p < .001$] and stimulus context [$F(1, 14) = 14.39$, $p < .01$], with all other main effects and interactions being nonsignificant. A four-way mixed-factor ANOVA that included Group as a between-subjects factor confirmed the Group × Category Type interaction implied by the separate analyses above [$F(1, 28) = 5.04$, $p < .05$]. Post hoc Bonferroni-corrected *t* tests revealed that the amusic participants performed worse than the controls in both within-category and between-category discriminations (all *p*s < .05).

Figure 5 shows the mean percentages of hits minus false alarms for both groups on within- and between-category discriminations of Tone 1–Tone 2 and Tone 1–Tone 4 continua of speech and nonlinguistic analogues. Also shown in Fig. 5 are the individual participants' scores, which show an overlap in performance between the groups. Although one or more individual amusic participants did score two or more standard deviations below the mean of the controls in each of the conditions except for the Tone 1–Tone 2 between-category discriminations of the nonlinguistic analogues, *no* individual amusic participant scored two or more standard deviations below the mean of the controls in *all* of the other conditions. However, correlations between an individual's melodic score from the MBEA, which is the average score on the first three subtests, and their discrimination performance revealed significant correlations for both the Tone 1–Tone 2 and Tone 1–Tone 4 speech continua for between-category discriminations [$r(28) = .49$, $p < .05$; $r(28) = .51$, $p < .05$]. The correlation was also significant for the Tone 1–Tone 4 speech continuum on within-category discriminations [$r(28) = .38$, $p < .05$]. These correlations again indicate that performance with musical stimuli on the MBEA

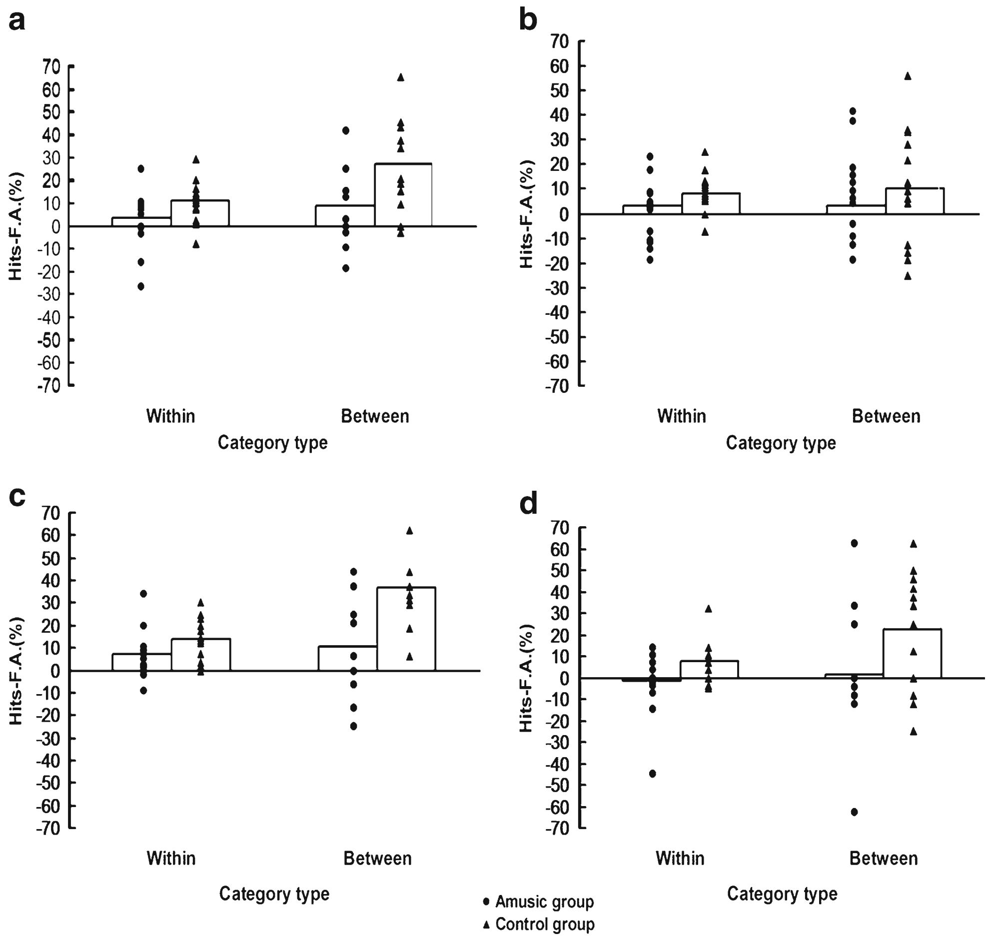

Fig. 5 Percentages of hits minus false alarms for the two groups in discriminating the four stimulus contexts during comparisons that remained within a potential category or that crossed the boundary, as determined by the identification task for each individual participant. (**a**) Tone 1–Tone 2 continuum for speech. (**b**) Tone 1–Tone 2 continuum for a nonlinguistic analogue. (**c**) Tone 1–Tone 4 continuum for speech. (**d**) Tone 1–Tone 4 continuum for a nonlinguistic analogue

predicts performance on linguistic tone discriminations, even for those who speak the language. No other correlation reached significance.

As noted above, the peakedness measure represents the magnitude of the benefit for discriminations that cross the classification boundary. The peakedness of the discrimination performance for each participant was calculated and compared between groups. As can be seen in Fig. 6, the amusic group shows reduced peakedness scores relative to the controls, indicating that they experienced less of a benefit for crossing the classification boundary than the controls did. This is the same effect that was indicated by the Group × Category Type interaction from the analysis of the discrimination scores above. The peakedness values were analyzed with a mixed-factor three-way ANOVA with Group (amusics vs. controls) as a between-subjects factor and Stimulus Context (speech vs. nonlinguistic analogue) and Continuum Type (Tone 1–Tone 2 vs. Tone 1–Tone 4) as within-subjects factors. The results revealed a significant main effect of group [$F(1, 14) = 5.43$, $p < .05$]. No other main effect or interaction reached significance.

Figure 6 shows the mean and individual scores for the peakedness measure for the Tone 1–Tone 2 and Tone 1–Tone 4 continua for both speech and the nonlinguistic analogues. Three amusic participants scored two or more standard deviations below the mean of the controls only for the speech stimuli of the Tone 1–Tone 4 continuum. Correlations with the melodic score and peakedness measures were significant for the speech stimuli in both the Tone 1–Tone 2 [$r(28) = .40$, $p < .05$] and the Tone 1–Tone 4 [$r(28) = .44$, $p < .05$] continua. This again suggests a relationship between music

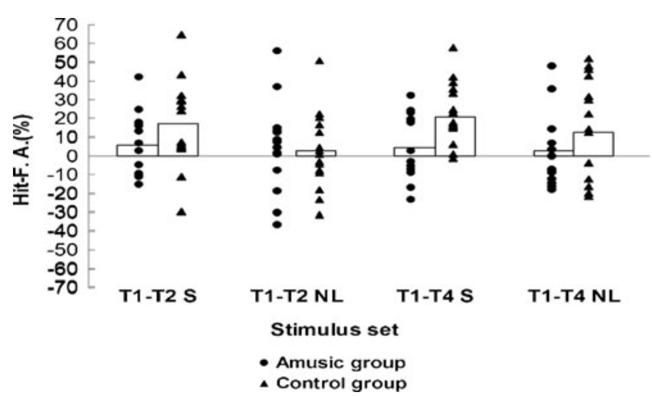

Fig. 6 Peakedness scores for the two groups in the each tonal continuum. T1–T2 S, Tone 1–Tone 2 continuum for speech; T1–T2 NL, Tone 1–Tone 2 continuum for a nonlinguistic analogue; T1–T4 S, Tone 1–Tone 4 continuum for speech; T1–T4 NL, Tone 1–Tone 4 continuum for a nonlinguistic analogue

processing and categorical perception of the Mandarin tones, at least in the context of speech. No other correlation reached significance.

Eleven of the 15 amusic participants in the present study had participated in a two-tone discrimination task in our previous study (Jiang et al., 2011). Correlations between their two-tone discrimination performance and the present three discrimination measures (within-category, between-category, and the peakedness of discriminations) were also calculated for each task. For the Tone 1–Tone 2 continuum, we found significant correlations between the two-tone discrimination performance and the within-category and between-category discrimination of speech stimuli [rs(9) = .61 and .63, respectively; all ps < .05]. The correlations were similar between their two-tone discrimination performance and the within-category and between-category discriminations for the corresponding nonlinguistic analogues, as well [rs(9) = .69 and .71, respectively; all ps < .05]. For the Tone 1–Tone 4 continuum, their two-tone discrimination performance was significantly correlated with the within-category and between-category discriminations of the nonlinguistic analogues [rs(9) = .65 and .62, respectively; all ps < .05]. No other significant correlations were found (all ps > .05). These correlations are consistent with the idea that musical pitch processing and language tone processing share a common underlying deficit in those with amusia.

General discussion

Overall, the participants with amusia showed no improvement for discrimination pairs that crossed the classification boundary, and their peakedness-of-discrimination scores were lower than those of the controls. The present data are consistent with those from previous studies (Liu et al., 2012; Nan et al., 2010) suggesting that Mandarin amusics have an impairment with processing Mandarin lexical tones, and they extend these findings to suggest that individuals with amusia lack categorical perception of Mandarin tones.

According to a multistore model (Xu et al., 2006), sensory, short-term, and long-term forms of categorical memory are involved in categorical perception. As noted above, the similarity in the sharpness of the classification boundary between the amusics and the controls is consistent with the suggestion that amusics may have normal long-term categorical phonetic memory. Therefore, the degraded discrimination for the amusic group could be attributed to deficits in sensory and/or short-term memory. This is consistent with recent studies that have suggested a short-term pitch memory deficit in amusia (Gosselin et al., 2009; Tillmann et al., 2009; Williamson & Stewart, 2010). *Sensory memory* refers to the unanalyzed raw and fine-grain-analyzed sensory codes (Xu et al., 2006), and deficits here could account for the fact that amusics have shown deficits in performing fine-grained pitch discriminations and pitch contour discriminations in previous studies (Ayotte et al., 2002; Foxton et al., 2004; Hyde & Peretz, 2004; Jiang et al., 2010, 2011; Peretz et al., 2002).

Although the participants showed better discrimination for both within- and between-category pairs for speech stimuli as compared to nonlinguistic analogues, this did not lead to a main effect of stimulus context for the peakedness measure. This is because peakedness quantifies the difference between between-category and within-category discriminations, irrespective of the level of performance for each condition individually. The amusic participants did not differ in their discrimination performance between the two tonal continua, which is in line with previous studies that have suggested that individuals with amusia show no difference in impairment in detecting rising or falling pitch changes in pitch (Hyde & Peretz, 2004; Jiang et al., 2011).

Despite the finding that the amusic participants' discrimination performance did not benefit when a stimulus pair crossed the classification boundary for either speech or the nonlinguistic analogues, amusic participants did discriminate speech stimuli better than the nonlinguistic analogue stimuli. This was a pattern similar to that of the controls, and it is consistent with the results reported by Peng et al. (2010), but inconsistent with the data of Xu et al. (2006). This discrepancy in the literature may be attributed to differences between the nonspeech stimuli used in the various studies. For example, the nonlinguistic analogue stimuli in the present study were pure tones rather than the harmonic tones employed by Xu et al. Speech and harmonic tones contain richer harmonic structures, and the "richness of harmonics" facilitates pitch perception, as compared to pure tones (e.g., Bernstein & Oxenham, 2003; Lütkenhöner, Seither & Seither-Preisler, 2006; Peng et al., 2010; Tervaniemi et al., 2000). It is also possible that linguistic information may facilitate pitch perception for speech stimuli relative to nonlinguistic analogues.

Interestingly, the pattern of discrimination shown by the Mandarin amusic participants with the Mandarin speech stimuli was similar to that shown by English participants (Xu et al., 2006), who also failed to show a cross-boundary benefit in their discrimination of Mandarin tones. It is assumed that the English participants could perform the tone discrimination up until the age of 6 months, and that they then lost this ability due to lack of early exposure to the tones (Mattock et al., 2008). It may be that congenital amusia effectively negates the preserving effect that exposure provides. However, it remains unknown whether or not amusic individuals could initially discriminate the tones up to the age of 6 months and later lost this ability, similar to the English participants (Mattock et al., 2008). Alternatively, congenital amusia may interfere with tonal processing at all ages, to the point that the amusic participants would have failed this discrimination at any age. Both of these possibilities would result in failing to preserve categorical perception of the Mandarin tones, so the present discrimination results are consistent with the possibility that congenital amusia is present from birth (Peretz, 2008). A developmental study in amusia would be necessary to address these possibilities.

Conclusion

In contrast to the controls, the amusic group did not show the expected benefit in performance when the speech tone pairs crossed the classification boundary. This impaired categorical perception of Mandarin tones may be attributed to deficits in processing pitch and pitch contours in amusia. Together with those from previous studies (Jiang et al., 2010, 2011; Liu et al., 2012; Nan et al., 2010), these findings indicate that tonal language experience does not compensate for the pitch deficits in amusia, or if it does, it does not do so completely. The impaired categorical perception of lexical tones in amusia supports the "shared sound category learning mechanism hypothesis" (Patel, 2008). Moreover, the normal long-term phonetic representations yet poor discrimination performance in amusia indicate that language and music may involve domain-specific representations but share domain-general mechanisms (Patel, 2003, 2008, 2012). Overall, the present findings provide further evidence for the resource-sharing framework, suggesting that pitch processing of musical pitch and of lexical tones may share certain cognitive resources and/or processes (Patel, 2003, 2008, 2012).

Author note We are grateful to our participants for their continued cooperation. We also thank the two anonymous reviewers and the editor, Prof. Markus Damian, for their insightful comments.

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