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Congenital amusia in speakers of a tone language: association with lexical tone agnosia

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Congenital amusia is a neurogenetic disorder that affects the processing of musical pitch in speakers of non-tonal languages like English and French. We assessed whether this musical disorder exists among speakers of Mandarin Chinese who use pitch to alter the meaning of words. Using the Montreal Battery of Evaluation of Amusia, we tested 117 healthy young Mandarin speakers with no self-declared musical problems and 22 individuals who reported musical difficulties and scored two standard deviations below the mean obtained by the Mandarin speakers without amusia. These 22 amusic individuals showed a similar pattern of musical impairment as did amusic speakers of non-tonal languages, by exhibiting a more pronounced deficit in melody than in rhythm processing. Furthermore, nearly half the tested amusics had impairments in the discrimination and identification of Mandarin lexical tones. Six showed marked impairments, displaying what could be called lexical tone agnosia, but had normal tone production. Our results show that speakers of tone languages such as Mandarin may experience musical pitch disorder despite early exposure to speech-relevant pitch contrasts. The observed association between the musical disorder and lexical tone difficulty indicates that the pitch disorder as defining congenital amusia is not specific to music or culture but is rather general in nature.

Keywords: congenital amusia; tone language; lexical tone; pitch perception
Abbreviation: MBEA = Montreal Battery of Evaluation of Amusia

Introduction

While most humans are naturally endowed to enjoy and produce music, some do not develop this capacity, either in part or at all. This condition affects 4% of the general population (Kalmus and Fry, 1980) and is termed congenital amusia (Peretz, 2001). It is an hereditary disorder (Peretz *et al.*, 2007) and is associated with abnormalities of the grey and white matter that relate the auditory cortex to the inferior frontal region (Hyde *et al.*, 2006, 2007; Mandell *et al.*, 2007; Loui *et al.*, 2009).

At the level of observed behaviour, congenital amusia appears to be domain specific (Peretz and Hyde, 2003). What distinguishes amusic individuals from others is their inability to recognize a familiar tune without the aid of the corresponding lyrics, their inability to know when they are singing out-of-tune and their difficulty in judging if two melodies are the same or different,

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especially with regard to pitch (Ayotte *et al.,* 2002). The associated rhythm deficit that is observed in about half of these individuals seems to result from the presence of pitch variations in melodies. When presented with rhythmic sequences without pitch variations, amusic individuals are able to discriminate them as well as control subjects (Foxton *et al.,* 2006). In summary, the core deficit of amusia concerns the processing of pitch in a musical context.

In speech, the processing of pitch information (intonation) is relatively spared, at least in the majority of the amusic subjects tested so far in non-tonal languages (e.g. Ayotte *et al.*, 2002; Peretz *et al.*, 2002). Amusic individuals can discriminate pitch changes in spoken sentences while failing on the same pitch changes when embedded in a non-speech context (even when preserving the gliding-pitch changes or transforming these into discrete steps; Patel *et al.*, 2005). Recent data have shown that for a minority of amusic cases, the pitch-processing deficit can also affect the processing of speech intonation (Patel *et al.*, 2008). In particular, a slow rate of gliding pitch changes may impair pitch processing in English (Patel *et al.*, 2008). This relative sparing of intonation perception might be related to the fact that pitch variations in non-tonal languages are very coarse as compared with those used in music. Meaningful pitch changes are in the order of 5–12 semitones in both English and French. In contrast, Western melodies have steps of 1 or 2 semitones between consecutive notes (a semitone corresponds to the smallest pitch distance used in Western music; Peretz and Hyde, 2003). These relatively small pitch intervals lie below the abnormally high-pitch threshold of most amusic individuals (Foxton *et al.,* 2004; Hyde and Peretz, 2004). As a result, their pitch deficit is more likely to compromise music perception than intonation perception.

However, this situation might be different with tone languages, which use relatively small pitch variations to alter the meaning of words. In Mandarin Chinese, for example, there are four different tones, each displaying a distinct pitch inflection: level, mid-rising, dipping and high-falling. For instance, the syllable *ma* pronounced with a level tone means 'mother', while the identical syllable pronounced with a dipping tone means 'horse'. The glide size (i.e. the distance between the maximum and minimum pitch heights) in the level tone is less than three semitones apart (Fig. 1). Discrimination of such small glide sizes appears problematic for amusic individuals who speak a non-tonal language (Nguyen *et al.,* 2009).

In contrast, early exposure to small pitch variations in speech may confer an advantage in discriminating musical intervals in speakers whose native tongue is tonal. Speakers of tone languages naturally develop fine-grained pitch categories for the tones of their language. As a result, one might predict that congenital amusia would be quite rare among speakers of a tone language, in that early exposure to a tone language might compensate for the pitch disorder (Peretz, 2008). It should be noted that the type of language (tone language) one speaks has an impact on brain plasticity as reflected by brain-growth related genes (Dediu and Ladd, 2007). It would be interesting to examine whether different language environments (tonal or non-tonal) contribute to variations in the prevalence of congenital amusia and whether such a condition is associated with a deficit in using pitch (along with other features of speech) to discriminate the tones of a language. Testing these predictions was the goal of the present study.

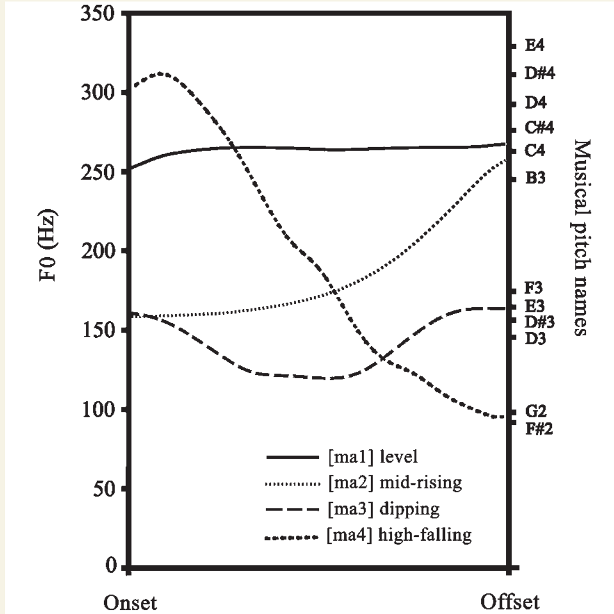

Figure 1 Time by frequency representations of 'ma' uttered in the four lexical tones.

Materials and methods

Participants

We recruited 117 normal and 22 amusic participants from two highly regarded universities in Beijing via advertisements on campus and on the internet. For the first 'normal' sample, the advertisement referred to a survey on musical abilities in general. For the amusic sample, it referred to students who had difficulties with music. Informed consent was obtained from all participants prior to the study. The experimental protocol was approved by the Ethics Committee of Beijing Normal University.

All participants were right-handed and reported no previous history of auditory, neurological or psychiatric disorder. All spoke Mandarin as their native language and none had any formal musical education; that is, they had no music lessons provided by a specialized institution or by music teachers for more than two years. A summary of their characteristics is provided in Tables 1 and 2.

All participants were assessed with the six tests of the Montreal Battery of Evaluation of Amusia (MBEA), following the procedure used by Peretz *et al.* (2003) to screen for amusic cases in the Canadian population. The whole battery, instructions and examples of stimuli can be found at http://www.brams.umontreal.ca/short/MBEA. The MBEA includes three melodic pitch-based tests (scale, contour and interval), two time-based tests (rhythm and meter) and one memory test. The entire battery takes about an hour-and-a-half to complete.

Self-reported amusic individuals were selected based on their MBEA scores. Only 23% of the 96 participants who reported to be amusic scored 2 SD below the mean of the 117 normal participants.

Table 1 Characteristics of 'normal' Mandarin speakers and Canadians, with percentage of correct responses on the MBEA tests

	Mandarin speakers ($n = 117$)	Canadians ($n = 190$)
Mean age (range)	23.4 (18–33)	20.8 (18–33)
Male/female	59/58	102/88
Mean educational year (range)	17.3 (12–24)	14.3 (8–22)
MBEA		
Scale	86.6 (11.2)	87.4 (8.8)
Contour	87.8 (9.1)	87.1 (9.4)
Interval	83.0 (12.0)	86.1 (9.7)
Rhythm	91.3 (9.0)	88.5 (9.1)
Meter	82.7 (14.4)	86.8 (14.5)
Memory	89.8 (9.0)	91.4 (7.6)
Global score	86.9 (7.6)	87.9 (6.6)
Cut-off score	21.5 (71.7%)	22.4 (74.7%)
% Amusia	3.4% (4)	3.2% (6)

Data are percent (SD) unless otherwise stated.
The cut-off score corresponds to 2 SD below the mean global score.

Table 2 Characteristics of the self-declared amusic participants and their matched controls, with mean percentage of correct responses on the MBEA tests

	Control ($n = 22$)	Amusic ($n = 22$)
Mean age (range)	23.1 (18–26)	22.9 (19–30)
Male/female	12/10	9/13
Mean educational year (range)	17.8 (12–22)	16.7 (13–22)
MBEA mean (SD)		
Scale	87.4 (10.3)	64.2 (8.3)
Contour	89.2 (9.0)	65.1 (8.8)
Interval	83.5 (13.4)	57.9 (9.1)
Rhythm	93.5 (6.0)	72.9 (10.5)
Meter	86.8 (16.6)	65.1 (13.8)
Memory	89.8 (9.7)	69.7 (14.1)
Global score	88.4 (8.7)	65.8 (4.5)

Data are percentages (SD) unless otherwise stated.

These 22 amusic participants further reported that they were unable to recognize music and tunes without the help of the lyrics and that they sang out-of-tune. Six reported minor lexical tone problems and two reported emotional prosody recognition difficulties. However, none of them considered these problems as affecting their daily lives.

A subgroup of 22 participants (10 female) taken from the normal sample of 117 participants were matched in age (mean 23.1) and education (mean 17.8) to the amusic group and served as controls in the lexical tone tests (Table 2).

Material and procedures

There were three sets of tasks: lexical tone identification, lexical tone discrimination and lexical tone production. In all tasks, the material consisted of words and pseudo-words that were spoken by a female native Mandarin speaker. Recordings of the words were made in a sound-proof booth using a Sony 60EC digital recorder and an NT1 microphone with a Samson MDR8 mixer. The words were standardized for intensity and used in the tests as follows.

In the tone identification task, 32 monosyllabic words (e.g. hua) were presented with all four possible tones in Mandarin; those are level, mid-rising, dipping and high-falling tones. The task was to identify each tone by pressing the corresponding key (from 1 to 4; 1 = level; 2 = mid-rising; 3 = dipping; 4 = high-falling). It is worthy to note that these codes (1–4) are learnt at school. There were also two bisyllabic conditions, one with 30 meaningful words and one with 30 nonsense words (e.g. 尘他: chen2ta1). For the bisyllabic meaningful words, the task was to identify the first and second tone by pressing the corresponding keys in the same order. Twenty-four words contained two different tones [e.g. mid-rising followed by high-falling, as in the word 实验 (*shi2yan4*), which means 'experiment'], and six words contained the same tones but pronounced on different syllables [e.g. as in 声音 (*sheng1yin1*), which means 'sound', with two level tones]. Monosyllabic and bisyllabic meaningful words were matched in frequency of usage (the Contemporary Chinese Corpus Research Group, 2008) in spoken Mandarin [mean ± SD: 3011 ± 864 for the bisyllabic words and 2797 ± 645 for the monosyllabic words; $t(53) = 2.0$, $P = 0.27$; the degree of freedom 53 was determined by Welch–Satterthwaite equation, due to observed unequal variances between these two types of words, according to a two-sample F-test, $F = 0.6$, $P = 0.06$]. There were also 24 bisyllabic nonsense words, each containing two different tones [e.g. as in 尘他 (*chen2ta1*) includes one mid-rising tone and one level tone] and six bisyllabic nonsense words containing the same tones [e.g. as in 蛋线 (*dan4xian4*) with two high-falling tones]. These nonsense words were made of two meaningful monosyllabic words [e.g. as in 蛋线 (*dan4xian4*), the first character means 'egg' and the second 'thread'], so that they could be pronounced but had no lexical status. As each bisyllabic word could be split into two monosyllabic words, 152 monosyllabic words were used in the tone identification task. In each condition (monosyllabic, bisyllabic meaningful or bisyllabic nonsense words), words were presented in a random order.

For the tone discrimination task, 120 monosyllabic words (109 from the tone identification task) were arranged in same or different pairs. The 30 same word pairs contained 15 pairs of the same word pronounced with the same tones (e.g. *ti2–ti2*; each was based upon a different recording) and 15 pairs of same words pronounced with different tones (e.g. *yu2–yu3*). The different word pairs contained 15 pairs of different words pronounced with the same tones (e.g. *guo3–san3*) and 15 pairs of different words pronounced with different tones (e.g. *shan1–wu4*). The task was to discriminate the tones in each pair irrespective of the words.

Acoustic characteristics of the lexical tone stimuli are summarized in Table 3. These include the onset pitch height, the rate (syllable/s), the minimum and maximum pitch height (in semitone relative to the pitch onset), the pitch glide size (i.e. the distance between the maximum and minimum pitch heights) and the pitch glide rate (semitone/s) for the vowel portion of each syllable. The onset pitch heights were derived from the onsets of the vowels (as done in Chandrasekaran *et al.*, 2007). The stimuli were presented binaurally through earphones to the participants in a quiet room with individually adjusted volume. Each condition (same or different words) was administered separately with all trials presented randomly via E-prime. The tone identification tasks and the discrimination tasks were administered in a counterbalanced order across participants.

Lexical tone production was assessed in a reading and a repetition task in separate sessions. Participants were asked to produce the 30 meaningful and 30 nonsense bisyllabic words that were used in the tone identification test. Thirty of these words were printed and the

Table 3 Acoustic characteristics of the lexical tones

	Rate (syllable/s)	Onset (Hz)	Minimum pitch (semitone)	Maximum pitch (semitone)	Pitch glide size (semitone)	Pitch glide rate (semitone/s)
Level						
(Tone 1, $n = 70$)	2.8 (0.1)	285.2 (4.3)	16.8 (1.1)	18.8 (1.5)	2.0 (0.4)	5.7 (1.4)
Mid-rising						
(Tone 2, $n = 73$)	2.5 (0.1)	188.0 (4.2)	7.7 (3.3)	18.4 (2.0)	10.7 (0.4)	25.9 (1.3)
Dipping						
(Tone 3, $n = 61$)	2.4 (0.1)	190.5 (4.6)	1.5 (4.6)	13.9 (5.1)	9.9 (0.5)	23.4 (1.5)
High-falling						
(Tone 4, $n = 68$)	3.5 (0.1)	313.7 (4.3)	4.9 (5.1)	21.9 (2.7)	16.9 (0.4)	58.2 (1.4)

Rate is defined as the mean number of syllables per second. Onset indicates the mean onset pitch height in hertz. Pitch glide size is the mean difference between minimum and maximum pitch heights within the tone and expressed in semitones. Pitch glide rate is measured in semitones divided by duration. Numbers in parentheses are standard deviations.

participants were asked to read the words out loud. In the repetition task, the participants were invited to repeat the other 30 words, of which half were meaningful bisyllabic words, one at a time. The same recordings as those used in the tone identification test were used here for repetition.

Results

For comparison purposes, the scores obtained on the MBEA by the 117 non-amusic Mandarin speakers were compared with the scores of 190 Canadian subjects who were within the same age range as the norms available on the internet (http://www.brams.umontreal.ca/short/MBEA) and who were matched in music education. Music education in China is very similar to that in Canada, consisting of ~1 h of music per week for a few years during elementary and secondary school. As seen in Table 1, the Mandarin speakers scored higher on the rhythm test, but lower on the interval and meter tests than the Canadians. The scores obtained on the six MBEA tests were analysed with a two-way ANOVA with Test (scale, contour, interval, rhythm, meter and memory) and Group (Mandarin and Canadians) as within- and between-subjects variables, respectively, which revealed a significant interaction [$F(5,1525) = 6.3$, $P < 0.001$]. The *P*-values of all main and interaction effects were corrected using the Greenhouse–Geisser method for repeated measure effects. *Post hoc* comparisons confirmed significant group differences ($P < 0.05$) on the interval, rhythm and metric tests. These results show that speakers of a tone language do not necessarily have superior performance in musical pitch processing.

Out of the 117 musically 'normal' speakers of Mandarin, 4 were found to perform below the cut-off score of 71.7%, which corresponds to 2 SD below the mean. These individuals can be considered as amusic although they seem to be unaware of their deficits. They reported little interest in music but did not declare any problem regarding their musical abilities. These four amusic participants were not tested further. However, this rate suggests that the prevalence of congenital amusia among speakers of a tone language might be as high as 3%.

The MBEA scores obtained by the 22 self-declared amusic participants indicated that all were impaired in the melodic tests,

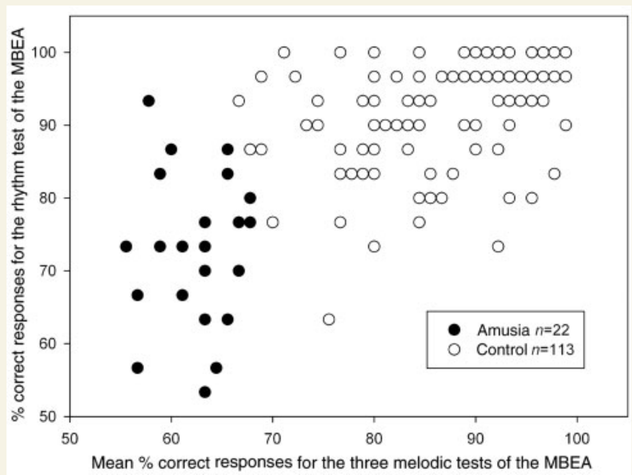

Figure 2 Individual performance on the melodic tests (averaged across the scale, contour and interval tests) as a function of the score obtained on the rhythm test of the MBEA for the amusic and control groups.

whereas about half demonstrated normal performance in the rhythm test (Table 2 and Fig. 2). This pattern is similar to that obtained in Canada and in the UK (Hyde *et al.*, 2006) and suggests the existence of a similar disorder in speakers of a tone language.

The identification of Mandarin tones was easy for control participants. They performed close to ceiling with mean scores above 95% correct (Table 4). The amusic participants, on the other hand, were significantly impaired relative to the controls. This was confirmed by a two-way ANOVA with Condition (monosyllabic, bisyllabic and nonsense words) and Group (amusic and control groups) as factors that yielded a main effect of Group [$F(1,42) = 10.3$, $P < 0.01$]. There was also a significant main effect of Condition [$F(2,84) = 10.9$, $P < 0.001$], but no interaction with Group. *Post hoc* comparisons indicate that the tone of a monosyllabic word is easier to identify than the tones in bisyllabic and nonsense words, irrespective of group.

In the tone discrimination task, the scores were examined separately for the tone pairs that were associated with the same and different words. The amusics did not score significantly below the normal participants when the words were identical, but were impaired when the words were different (Table 4). This was confirmed by the ANOVA with Condition (same versus different words) and Group (amusic versus control) which led to a significant interaction [$F(1,42) = 15.0$, $P < 0.001$]. Tone discrimination is more difficult when words are different than when words are the same, with $F(1,21) = 29.5$ ($P < 0.001$) for amusic participants and $F(1,21) = 11.5$ ($P < 0.001$) for controls. The same results are obtained when d'-scores are considered. A hit was defined as a 'different' response when the tones were different, and a false alarm was defined as a 'different' response when the tones were actually the same. Amusic participants performed better in the same word (mean d'-score = 3.37) than in the different word condition [mean d'-score = 1.88; $F(1,21) = 67.7$, $P < 0.001$]. Similarly, controls obtained higher d'-scores (mean = 3.91) in same word discrimination than in different word discrimination [mean = 2.92; $F(1,21) = 37.1$, $P < 0.001$].

Table 4 **Mean percentages of correct responses (standard deviations) in the tone identification and discrimination tasks for amusic subjects and matched controls**

	Amusic ($n = 22$)	Control ($n = 22$)
Tone identification		
Monosyllabic words	85.4 (21.5)	98.8 (2.3)
Bisyllabic words	80.3 (24.4)	97.6 (2.8)
Nonsense words	79.7 (24.4)	96.5 (2.0)
Tone discrimination		
Same words	97.8 (4.1)	98.5 (2.6)
Different words	84.4 (12.6)	95.4 (5.4)

Data are number of correct responses (SD).

Not all amusic subjects were impaired in the lexical tone tests. As detailed in Table 5, 13 amusic participants scored in the normal range in the tone discrimination task; 12 of these also performed normally in the tone identification task. In contrast, 9 amusic subjects had scores at least 3 SD below the controls' mean (Table 5) in tone identification task; six of them also showed a deficit (3 SD below the controls' mean) in tone discrimination. These six amusic participants who failed in both the tone identification and discrimination tests were further confirmed with k-means clustering analysis and the Grubb's outlier test. This subgroup of six amusic individuals can be qualified as exhibiting 'lexical tone agnosia'. It should be noted that this lexical tone agnosia group performed significantly lower than the other amusic participants on all lexical tone tests (Mann–Whitney tests, all $P < 0.001$) except the tone discrimination in the same word pairs. Yet, there was no significant performance difference between these two groups of amusic subjects on the MBEA tests: the tone agnosia group had a global score of 65.9% and the amusic group without tone agnosia obtained 65.8% (Mann–Whitney test, $P = 0.5$).

Significant correlations between tone identification and discrimination scores were obtained in the amusic group [Spearman rank correlation test: $r_s(20) = 0.90$, $P < 0.001$; the amusic group without tone agnosia: $r_s(14) = 0.79$, $P < 0.001$; and the control group

Table 5 **Individual characteristics, MBEA and lexical tone test scores obtained by the 22 self-declared amusic subjects**

No	Age	Gender	MBEA global score	Tone discrimination in different-word pairs			Tone identification mean		
				% correct	2 SD	3 SD	% correct	2 SD	3 SD
1	25	M	62.8	66.7	↓	↓	59.5	↓	↓
2	24	F	68.9	83.3	↓		95.2		
3	23	M	63.9	53.3	↓	↓	35.3	↓	↓
4	21	M	67.8	93.3			93.0	↓	
5	19	F	70.6	100.0			99.5		
6	30	F	57.2	93.3			99.5		
7	27	F	65.6	96.7			97.8		
8	23	F	71.7	100.0			99.5		
9	24	F	67.8	80.0	↓		81.0	↓	↓
10	22	M	65.0	73.3	↓	↓	27.7	↓	↓
11	20	F	67.2	76.7	↓	↓	67.5	↓	↓
12	23	F	51.1	80.0	↓		81.3	↓	↓
13	23	M	70.6	90.0			98.5		
14	22	F	66.7	70.0	↓	↓	50.3	↓	↓
15	21	M	66.1	80.0	↓		84.3	↓	↓
16	21	F	66.1	87.0			97.8		
17	23	F	63.9	93.00			91.7	↓	
18	23	F	67.8	93.00			97.3		
19	21	M	65.6	97.00			99.0		
20	23	F	66.7	86.7			97.3		
21	25	M	65.6	96.7			99.0		
22	21	M	70.0	66.7	↓	↓	48.0	↓	↓

The lexical tone tests include tone discrimination (different-word pairs only) and tone identification (averaged across the monosyllabic, bisyllabic and nonsense words condition). Performance that is 2 or 3 SD below the mean of the 22 matched controls is indicated by '↓'.

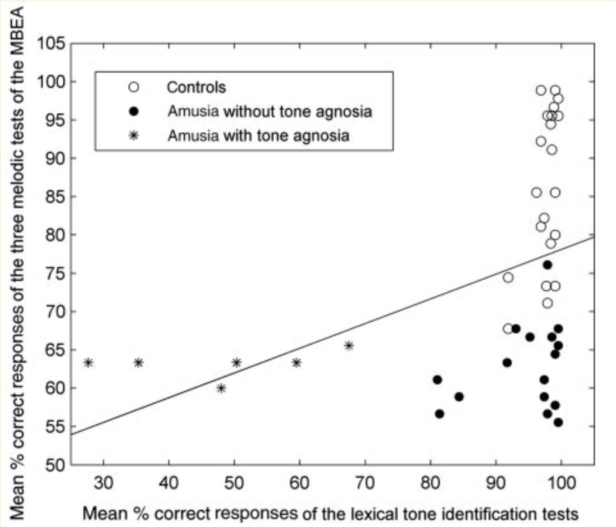

Figure 3 Individual performance in lexical tone identification (across conditions) as a function of the scores obtained in melodic discrimination (averaged across scale, contour and interval tests) of the MBEA for the controls and the amusic groups without lexical tone agnosia and with lexical tone agnosia.

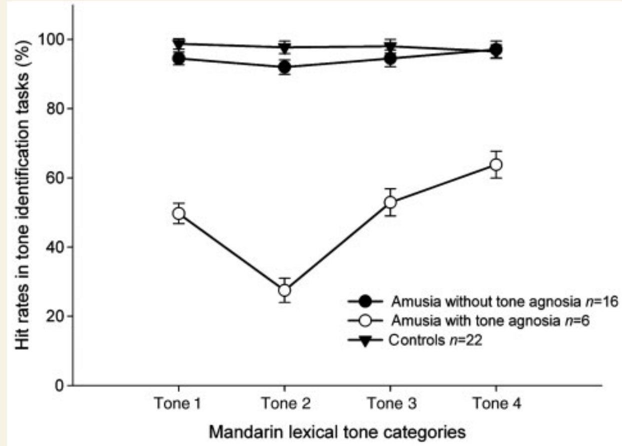

Figure 4 Hit rates in tone identification task for the four lexical tones in controls and in the amusic groups without lexical tone agnosia and with lexical tone agnosia. Error bars represent standard error.

$r_s(20) = 0.50$, $P < 0.05$]. As illustrated in Fig. 3, the correlation between lexical tone processing and melody discrimination was driven mostly by the six amusic participants with lexical tone agnosia. Furthermore, tone identification performance (averaged across the three conditions: monosyllabic, bisyllabic and nonsense words) was significantly related to the MBEA global score [$r_s(42) = 0.47$, $P < 0.01$], but only significantly so in controls [$r_s(20) = 0.54$, $P < 0.01$ whereas in amusic subjects: $r_s(20) = 0.24$, $P = 0.3$].

In order to examine whether some particular tones were more problematic than others in their identification, we conducted a two-way ANOVA considering the four possible tones (level, mid-rising, dipping and high-falling) and the three groups (control $n = 22$; amusic with no tone agnosia $n = 16$; and amusic with tone agnosia $n = 6$) on the hit rates obtained in the tone identification task. The analysis yielded a significant interaction between Tone and Group [$F(6,123) = 14.2$, $P < 0.001$]. Mann–Whitney tests for two independent samples indicated that the tone agnosic group was significantly impaired across the four lexical tones compared with the control group and the amusic participants without lexical tone agnosia (both $P < 0.01$), whereas the latter two groups demonstrated similar normal performance (Fig. 4). Among the four lexical tones, the mid-rising tone (Tone 2) seemed to be the most difficult for all groups of participants; for the amusic subjects with tone agnosia in particular (all $P < 0.05$). Amusic participants with tone agnosia were performing at chance (being 25%) on the mid-rising tone (Tone 2; Fig. 4).

This difficulty for the mid-rising tone might have an acoustical basis. As can be seen in Table 3, the mid-rising (Tone 2) and the dipping tones (Tone 3) share many acoustical characteristics while being different from the other tones. Separate one-way ANOVAs conducted on each acoustical parameter by considering words as random factors indicated significant differences among the four tones, with $F(3,268) = 36.8$ ($P < 0.001$) for rate, $F(3,268) = 221.7$ ($P < 0.001$) for onset pitch height, $F(3,268) = 193.0$ ($P < 0.001$) for pitch glide size and $F(3,268) = 255.7$ ($P < 0.001$) for pitch glide rate. Tukey's *post hoc* comparisons indicate that all pairwise comparisons among the four lexical tones were statistically significant on the four acoustic measures ($P < 0.05$), except the comparisons between mid-rising (Tone 2) and dipping (Tone 3), which did not differ on any of the acoustical parameters considered. This corroborates the patterns of identification errors in controls and amusic subjects without lexical tone agnosia. These participants tended to confuse Tones 2 and 3 most of the time (proportion of lexical tone identification errors: 52.5% for controls, 50.6% for amusic subjects without tone agnosia; both are higher than chance, being 33.3%). However, this was not the case for the amusic participants with lexical tone agnosia. They tended to confuse Tone 2 with the other tones equally often. Thus, the reason why Tone 2 was the most difficult for these amusic individuals with tone agnosia remains unclear.

Tone production performance was examined in the six tone agnosic subjects and their age- and gender-matched controls. The 120 tones produced by each participant were randomly mixed and presented to six independent raters (three males, mean age 25 years, native Mandarin speakers), who classified the produced lexical tones as Tone 1, 2, 3 or 4. When correct, the tone production was considered a hit. Thus, the maximum possible score was 120 tones multiplied by six judges (Table 6). Tone production was highly accurate in both groups, with 98.6 and 99.6% correct in amusic participants with tone agnosia and controls, respectively, and did not differ significantly from each other (all Mann–Whitney tests being non-significant.). In both groups, tone production scores did not differ between reading and repeating tasks or between meaningful and nonsense words (all Wilcoxon signed rank tests for two related samples being non-significant). Taken together, the amusic participants with tone agnosia seemed to be impaired mainly in lexical tone perception, not in tone production.

Table 6 **Percentage of correct responses (lowest and highest scores) in the lexical tone production task for amusic group with lexical tone agnosia and controls**

	Amusia with lexical tone agnosia ($n=6$)	Controls ($n=6$)
Level (Tone 1)	99.9 (99.5–100)	99.8 (99.5–100)
Mid-rising (Tone 2)	98.0 (96.0–100)	99.3 (98.5–100)
Dipping (Tone 3)	97.0 (93.0–99.3)	99.4 (98.0–100)
High-falling (Tone 4)	99.4 (98.3–100)	99.7 (98.9–100)

Discussion

Our results show for the first time that congenital amusia can be observed among speakers of a tone language. Among the 117 Mandarin speakers tested with the MBEA, 3.4% were classified as amusic, with a prevalence rate that is close to the 4% reported in Western countries (Kalmus and Fry, 1980). Moreover, the 22 self-declared amusic participants showed a similar pattern of musical impairment as Western amusic individuals, with a more pronounced deficit in the processing of melodic variations than rhythm. These results suggest that congenital amusia may have a common origin in speakers of tonal and non-tonal languages and that the MBEA might be suitable to identify such a condition in a wide variety of cultures.

In speakers of English and French, the origin of congenital amusia is ascribed to an abnormal encoding of fine-grained pitch variations (Peretz *et al.*, 2002; Foxton *et al.*, 2004; Hyde and Peretz, 2004). We hypothesized that the expression of such a disorder would be less marked in speakers of a tone language. Contrary to expectations, we found no support for an effect of tone language experience on melody discrimination. Mandarin speakers performed below Canadian participants in melody discrimination, especially in the test where a pitch interval was altered. There does not seem to be any transfer effect between fluency in a tone language and music perception. This finding contrasts with the observation that absolute pitch is more frequent among American students who are fluent in a tone language (Deutsch *et al.*, 2009). In the latter case, it is argued that musicians acquire absolute pitch by involving the same processes as those used in the acquisition of the tone language. Similarly, it has been suggested that among speakers of a non-tonal language, musicians outperform non-musicians in the processing of lexical tones (Wong *et al.*, 2007; Lee and Hung, 2008). However, the mechanisms that can account for these positive transfer effects remain undetermined (Schellenberg and Peretz, 2008). One likely explanation for the superior cognitive abilities observed in musicians is that musicians have enhanced attentional or executive control capacities as compared with non-musicians or monolinguals (Bialystok and Depape, 2009).

Although we did not find evidence for an advantage of tonal language experience on melody processing in the normal brain, we did find an association between deficits in the music and language domain. Nearly half the 22 amusic participants were impaired in the identification and discrimination of the lexical tones. Six of them were found to be markedly impaired and were considered as exhibiting lexical tone agnosia. Note that these same amusic individuals with tone agnosia can produce the four lexical tones as well as controls. This relative intact production in the presence of impaired perception suggests dissociation between the neural pathways responsible for pitch perception and production in speech. A similar pattern has been recently reported in Western cases of congenital amusia who were able to correctly reproduce pitch direction between two successive tones without being able to categorize these intervals as falling or rising (Loui *et al.*, 2008). Alternatively, amusic individuals may use non-pitch-based cues such as somatosensory inputs to guide their production, as do profoundly deaf adults when acquiring the capacity for intelligible speech (Nasir and Ostry, 2008).

The common origin of the association found between amusia and lexical tone perception remains to be determined. We hypothesize that the impaired pitch tracking system that characterizes congenital amusia in speakers of non-tonal languages might underpin the observed melodic and lexical tone deficits. Alternatively, it might be unrelated to pitch processing and may instead reflect low executive or attentional control in these individuals. Indeed, the amusic participants had no problem identifying lexical tones when these were carried by the same words. They exhibited a deficit when the tones were embedded in different words. It might be the case that amusic individuals have more difficulty than 'normal' people to filter out irrelevant variations (words in this case). Assessing attentional resources of amusic individuals in Stroop tasks should be considered in future research.

Whether the origin of the musical pitch and lexical tone deficits lies at the level of attentional control or poor pitch resolution, it fits with the existing literature of neural anomalies in the right inferior frontal cortex, the area associated with the processing of musical pitch (Maess *et al.*, 2001) and lexical tone (Liu *et al.*, 2006; Nan *et al.*, 2009). It is possible that the association observed here between musical pitch and lexical tone processing reflects the abnormal functioning of the frontotemporal pathway, as previously identified in Western amusic individuals (Hyde *et al.*, 2007; Loui *et al.*, 2009). Note that this association between musical and lexical tone processing was limited to perception, since lexical tone production was found to be intact. Dissociation between (impaired) tone identification and (spared) tone production has, to our knowledge, never been reported in the language domain. After brain damage, lexical tone production impairments are always associated with tone identification difficulties (Gandour and Dardarananda, 1983; for a review, see Wong *et al.*, 2009). Comparison between tone perception and production should be investigated in future neuroimaging studies.

In summary, speakers of a tone language may experience musical pitch disorders despite early experience with speech-relevant pitch contrasts. The observation of an association between the musical disorder and lexical tone difficulties indicates that the pitch disorder is not confined to the music domain. Further exploration of the functional and neuroanatomical origins as well as the genetic basis of congenital amusia among speakers of a tone language should be pursued so as to improve our current understanding of the causes of congenital amusia in particular, and of pitch-based disorders in music and speech.

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