Impaired Explicit Processing of Musical Syntax and Tonality in a Group of Mandarin-speaking Congenital Amusics

Cunmei Jiang

Shanghai Normal University, Shanghai, China

Fang Liu

University of Essex, Essex, United Kingdom

William Forde Thompson

Macquarie University, Sydney, Australia

Abstract

We examined explicit processing of musical syntax and tonality in a group of Han Chinese Mandarin speakers with congenital amusia, and the extent to which pitch discrimination impairments were associated with syntax and tonality processing. In Experiment 1, we assessed whether congenital amusia is associated with impaired explicit processing of musical syntax. Congruity ratings were examined for syntactically regular or irregular endings in harmonic and melodic contexts. Unlike controls, amusic participants failed to explicitly distinguish regular from irregular endings in both contexts. Surprisingly, however, a concurrent manipulation of pitch distance did not affect the processing of musical syntax for amusics, and their impaired music-syntactic processing was uncorrelated with their pitch discrimination thresholds. In Experiment 2, we assessed tonality perception using a probe-tone paradigm. Recovery of the tonal hierarchy was less evident for the amusic group than for the control group, and this reduced sensitivity to tonality in amusia was also unrelated to poor pitch discrimination. These findings support the view that music structure is processed by cognitive and neural resources that operate independently of pitch discrimination, and that these resources are impaired in explicit judgments for individuals with congenital amusia.

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Key words: congenital amusia, musical syntax, tonality perception, pitch deficits, chord and melody

Congenital amusia (hereafter amusia) is a neurogenetic disorder of music processing, diagnosed by melodic, rhythmic, and memory subtests of the Montreal Battery of Evaluation of Amusia (MBEA, Peretz, Champod, & Hyde, 2003). It has been characterized by deficits in fine-grained pitch discrimination (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Hyde & Peretz, 2004; Jiang, Hamm, Lim, Kirk, & Yang, 2011) and melodic contour and pitch direction discrimination (Foxton et al., 2004; Jiang, Hamm, Lim, Kirk, & Yang, 2010; Liu, Patel, Fourcin, & Stewart, 2010). These impairments are thought to have a cascade effect such that amusic individuals exhibit reduced sensitivity to anomalous pitches ("wrong notes") and dissonant chords in conventional music (Ayotte, Peretz, & Hyde, 2002). Their disorder also extends to subtle aspects of prosodic processing in speech, such as perceiving speech intonation (Jiang et al., 2010; Liu et al., 2012; Liu et al., 2010; Patel, Wong, Foxton, Lochy, & Peretz, 2008), decoding emotion in speech prosody (Thompson, Marin, & Stewart, 2012), and detecting syntactic violation during speech comprehension (Jiang et al., 2012).

The perception of music reflects low-level processes responsible for pitch discrimination and higher-level processes responsible for structural properties of music such as tonality and syntax (Koelsch, 2012). Amusic individuals may have both low-level and high-level impairments, but the extent to which they are related to one another remains unclear. Figure 1 illustrates a simplified model of pitch processing in music with three stages: feature extraction, mental representation, and syntactic processing. Following the process of feature extraction, the mental representation stage encodes the hierarchy of stability of chords and tones (Krumhansl, 1990), which reflects sensitivity to tonality. Syntax refers to the structural regularities of music (Patel, 2003), and syntactic processing at the third stage allows perceivers to predict subsequent events in music. In Western music, both tonality and syntax play especially prominent roles in music perception and experience, presumably because semantic processing is less specific for music than for language (Koelsch, 2005; Koelsch, Gunter, Wittfoth, & Sammler, 2005; Schmuckler & Tomovski, 2005; Steinbeis & Koelsch, 2008). As such, exploring syntax and tonality perception in amusia is essential for clarifying the relationship between (low-level) pitch discrimination and (higher-level) musical structure processing.

Insert Figure 1, about here.

A challenge in investigating musical syntax and tonality among amusic individuals is that most pitch intervals in Western melodies are small – being less than or equal to two semitones (Vos & Troost, 1989). These pitch distances are frequently below the pitch change and pitch direction detection thresholds of amusic individuals (Hyde & Peretz, 2004; Jiang, Lim, Wang, & Hamm, 2013; Peretz et al., 2002). As such, it has been speculated that low-level processing difficulties in amusia result in higher-level structure processing difficulties, such as syntax and tonality processing (Cousineau, McDermott, & Peretz, 2012; Stewart, 2011). These latter difficulties may account for a lower self-reported appreciation for music by the amusic group than by their nonamusic counterparts (McDonald & Stewart, 2008).

The aim of the present study was to examine musical syntax processing and tonality perception in a group of Han Chinese Mandarin speakers with congenital amusia. Experiment

1 focused on the processing of musical syntax whereas Experiment 2 examined the perception of tonality. We also evaluated the extent to which pitch discrimination impairments in amusia are predictive of musical syntax and tonality processing, given recent discussions of the complex relationship between the processing of tonal music structure and physical properties of sound (Bigand, Delbé, Poulin-Charronnat, Leman, & Tillmann, 2014; Collins, Tillmann, Delbé, Barrett, & Janata, 2014). If the processing of musical structure is based on the extraction of acoustic features (Huron & Parncutt, 1993; Leman, 2000; Parncutt & Bregman, 2000), then low-level pitch processing deficits in amusia should predict difficulties in processing syntax and tonality. In contrast, if the processing of musical structure relies on knowledge of conventional structural relations (Bigand & Pineau, 1997; Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003; Tekman & Bharucha, 1998; Tillmann, Bigand, & Pineau, 1998), then the processing of syntax and tonality should not be predicted by pitch discrimination deficits in amusia.

Experiment 1: Music-syntactic Processing

Previous research has revealed that amusic individuals implicitly differentiate the functions of subdominant and tonic chords, suggesting that they have internalized syntactic-like functions of chords (Tillmann, Gosselin, Bigand, & Peretz, 2012). Employing both implicit and explicit tasks, however, Omigie, Pearce, and Stewart (2012) reported that amusic individuals were impaired at differentiating between high and low probability melodic events, despite intact implicit processing. The dissociation between implicit and explicit performance of musical structure has also been reported for individuals with acquired amusia (Peretz, 1993; Tillmann, Peretz, Bigand, & Gosselin, 2007). These findings suggest that these two forms of knowledge are accessed using independent strategies.

Indeed, implicit strategies involve automatic, spontaneous, and effortless responses, whereas explicit strategies involve conscious and effortful judgements (Brattico, 2013; Schacter, 1995; van Zuijen, Simoens, Paavilainen, Näätänen, & Tervaniemi, 2006). The two mechanisms are indexed by different behavioral outcomes and are associated with distinct electrical brain activities (van Zuijen et al., 2006). A functional magnetic resonance imaging (fMRI) study reported by Brattico (2013) points to a primary difference between implicit and explicit processing of music emotion: whereas implicit processing of music emotion activates cortical areas that are implicated for other modalities, explicit processing of music emotion predominantly recruits cortical areas specific to cognitive processing of music.

Experiment 1 employed explicit tasks to investigate the processing of musical syntax in amusia and the extent to which pitch discrimination impairments in amusia are related to musical syntax processing. To examine whether sensitivity to musical syntax is associated with pitch discrimination ability in amusia, sequences were constructed such that there were two different pitch distances (small or large) between the fourth and the fifth positions in the top voice.

Given that tonal implications of melody and chord sequences arise through partially independent processes (Thompson, 1993; Thompson & Cuddy, 1989), we also evaluated whether amusic individuals perceive melodic and harmonic syntax differently. As in Koelsch and Jentschke (2010), melodic sequences in the present study were derived from the top voices of the chord sequences for the sake of comparison. Musical excerpts were constructed to end on the tonic chord (regular ending) or a Neapolitan chord (in C major: D^b – F – A^b, irregular ending) for the harmonic task, or end with the root notes of these two chords for the melodic task. The Neapolitan chord is consonant and is a variation of the subdominant chord that has a root-note on the flattened supertonic. In Western tonal music, ending a passage on the Neapolitan chord or the root note of the Neapolitan chord indicates a syntactic violation.

Tonal expectancies should be the strongest when key structure remains constant from trial to trial within a block, because repeated exposure to the same key should give rise to a strong auditory sensory memory trace for in-key scale tones (Koelsch, Jentschke, Sammler, & Mietchen, 2007). Conversely, transposition from trial to trial should prevent accumulation effects on tonal expectancies. Therefore, sequences in the present study were also presented in blocks such that all were either in the same key (single-key condition) or in different keys (mixed-key condition).

We hypothesized that, for both single- and mixed-key conditions, amusic individuals would have difficulty discriminating between sequences ending on the tonic and Neapolitan chord or root notes, and that impaired music syntactic processing would not be related to pitch discrimination, given that pitch impairment in amusia does not disrupt prediction of the probability of the occurrence of melodic events (Omigie et al., 2012).

Method

Participants. Twenty-eight postgraduate students (14 amusics and 14 matched controls) were recruited by means of an advertisement posted on the bulletin board system of universities in Shanghai. Only participants of the Han Chinese ethnicity were included in order to control for the effects of musical enculturation and exposure to Western tonal music.

The six subtests of the MBEA were used to assess musical abilities of these participants (Peretz et al., 2003). Participants were diagnosed as amusic if they scored 65 or below on the three pitch-based subtests, i.e., scale, contour, and interval subtests (Liu et al., 2010), and below 78% correct on the MBEA global score, which represents two standard deviations below the mean score of normal controls (Peretz et al., 2003). None of the participants reported any learning or memory problems with their university studies, or history of neurological/psychiatric disorders and hearing problems. None had received extracurricular music training. All were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971).

As shown in Table 1, the two groups were matched on age, sex, handedness, hours of voluntary music listening per day, and years of education. Pitch change detection and pitch direction discrimination thresholds were also measured for each participant using a two-alternative forced choice AXB procedure as reported in Jiang et al. (2013). The amusic participants showed higher pitch thresholds and performed significantly worse than control participants on the MBEA (Table 1). Ethical approval was granted by Shanghai Normal University in China, and written informed consents were obtained from all participants before testing.

Insert Table 1, about here.

Stimuli. There were two music-syntactic tasks: harmony and melody. For the harmonic task, 44 original five-chord sequences in C major were arbitrarily assigned to be transposed to two different major keys (D and B^b), yielding 132 sequences. Each of these 132 sequences was given regular and irregular endings, resulting in a total of 264 experimental sequences.

Consistent with the procedures employed by Koelsch, Gunter, Friederici, and Schroeger (2000), the first chord was always the tonic of the key. The second chord was one of the following: tonic (I), mediant (iii), submediant (vi), subdominant (IV), dominant to the dominant (II), secondary dominant to mediant (VII), secondary dominant to submediant (III), or secondary dominant to supertonic chord (VI). The third chord was the subdominant (IV), dominant (V), or dominant six-four chord (K_4^6). The fourth chord was always a dominant seventh chord (V_7). The final chord was either a tonic chord (I) or a Neapolitan chord (^{b}II). Half of the sequences ended with a tonic chord and the other half ended with a Neapolitan chord (Figure 2A and B). The tonic chord ending is regular and represents the most expected chord, whereas the Neapolitan chord ending is irregular and creates an unexpected harmonic event.

The melodic sequences were derived from the top voices of the chord sequences, yielding 132 melodic sequences. The first tone was always the first, third, or fifth scale degree. Half of the sequences ended with the tonic and the other half ended with the root tone of the Neapolitan chord (Figure 2C and D). That is, the regular melodic sequences ended with the tonic note, whereas the irregular sequences ended with a nonscale tone, namely, the root tone of the Neapolitan chord (flattened supertonic). Since the fourth chord was always a dominant seventh chord, the supertonic, subdominant, or leading tone (the second, fourth, or seventh scale tone) was possible in the top voice of the chord. There were 51 sequences with the subdominant tone, 51 sequences with the leading tone, and 30 sequences with the supertonic tone at the top voice of the dominant seventh chord. As such there were two different pitch distances (small or large) between the fourth and the fifth positions in the top voice: 1) large: pitch distance of five semitones for the tonic ending and four semitones for the Neapolitan ending when the top voice of the dominant seventh chord was the subdominant tone, and 2) small: pitch distance of one semitone for the tonic ending and two semitones for the Neapolitan ending when the top voice of the chord was the leading tone. It is worth noting that the first four tones of the melodic sequences always contained the subdominant and leading tones in major scale so as to ensure strong expectancy for the tonic as the final event in the sequences.

Insert Figure 2, about here.

Each of the first four chords or tones lasted 500 ms, while the final chord or tone was 1000 ms in duration. There was no silent period between chords, tones, or sequences. All sequences were generated with a grand piano sound using Pianissimo (Acoustica, Inc.) at an approximate intensity of 70 dB.

Procedure. There were six blocks for both the harmonic and melody tasks: three single-key and three mixed-key blocks. The three single-key blocks contained trials in a single key, C, D, or B^b major key. In the three mixed-key blocks, trials in C, D, and B^b major keys were mixed. That is, the key of sequences did not remain constant from trial to trial but varied between C, D, and B^b major keys. Within the single-key blocks, the trials were presented in a pseudo-randomized order with the constraint that a given ending (regular or irregular) was not repeated more than three times in succession and a given sequence with different endings was separated by more than five trials. Similarly, there were three constraints for the three mixed-key blocks: 1) sequences in succession were not within the same key, 2) a given sequence with different endings was not distributed in the same block, and 3) a given ending was not repeated more than three times in succession.

As the participants had no prior music training, they were informed of the meaning of music expectation before testing. Specifically, they were instructed that if the five events (tones or chords) in a music sequence followed one another in an expected manner, they would feel a sense of completeness when the sequence ended. Participants rated each sequence for expectedness on a 7-point Likert scale, with 1 being least expected (incongruent) and 7 most expected (congruent). They were encouraged to use the full range of the response scale. Eight practice trials were given before the experimental session to familiarize the participants with the stimuli and procedure. No feedback was provided. As in the procedure used by Koelsch and Jentschke (2010), the melodic blocks were always presented before the harmonic blocks so as to prevent participants from mentally harmonizing the melodies. All stimuli were presented binaurally through Philips SHM1900 headphones in a soundproof room.

Results and Discussion

Mean and individual ratings of the regular and irregular endings in the melodic and harmonic tasks were computed for both groups. As shown in Figure 3, individuals with amusia exhibited difficulty in detecting violations in melodic syntax in both single- and mixed-key conditions, as compared with the controls. This finding was confirmed by a three-way mixed-factor analysis of variance (ANOVA) with group (amusics versus controls) as the between-subjects factor, and regularity (regular versus irregular) and key (single-key versus mixed-key) as the within-subjects factors. There were significant main effects of group, $F(1, 26) = 8.18$, $p < .01$, $\eta_p^2 = .24$, and regularity, $F(1, 26) = 40.30$, $p < .001$, $\eta_p^2 = .61$. An interaction between key and regularity was significant, $F(1, 26) = 24.25$, $p < .001$, $\eta_p^2 = .48$, reflecting that participants distinguished regular from irregular endings more easily in the single-key condition, $F(1, 26) = 44.86$, $p < .001$, $\eta_p^2 = .63$, than in the mixed-key condition, $F(1, 26) = 25.73$, $p < .001$, $\eta_p^2 = .50$. There was a significant interaction between group and regularity, $F(1, 26) = 48.00$, $p < .001$, $\eta_p^2 = .65$, reflecting that controls distinguished irregular from regular melodic endings, $F(1, 12) = 88.13$, $p < .001$, $\eta_p^2 = .77$, while individuals with amusia did not show significant difference in ratings between regular and irregular melodic endings, $F(1,12) = .17$, $p > .05$.

Insert Figure 3, about here.

Mean and individual ratings for music-syntactic processing in the harmonic task are displayed in Figure 4. Similar to the melodic syntactic processing task, ratings by individuals with amusia for regular and irregular endings were not significantly different in either the single- or mixed-key condition, in contrast to ratings by the control group. A three-way ANOVA revealed main effects of group, $F(1, 26) = 9.55$, $p = .005$, $\eta_p^2 = .27$, and regularity, $F(1, 26) = 109.92$, $p < .001$, $\eta_p^2 = .81$, and an interaction between group and regularity, $F(1,$

26) = 71.55, $p < .001$, $\eta_p^2 = .73$. Planned comparisons revealed that mean ratings for regular and irregular endings were significantly different for control participants, $F(1, 12) = 179.42$, $p < .001$, $\eta_p^2 = .87$, but not for amusic participants, $F(1, 12) = 2.05$, $p > .05$.

Insert Figure 4, about here.

As stated, there were 51 sequences with the subdominant tone and 51 sequences with the leading tone at the top voice of the dominant seventh chord. In order to facilitate the analysis, we used large and small pitch distances to identify the two conditions of top voice of the dominant seventh chord. The small pitch distance was identified to the condition that the pitch distance between the fourth and final positions was one semitone for the regular ending and two semitones for the irregular ending when the leading tone was at the top voice of the dominant seventh chord, whereas the large pitch distance was assigned to the condition that the pitch distance was five semitones for the regular ending and four semitones for the irregular ending when the subdominant was at the top voice of the dominant seventh chord. Table 2 presents mean ratings for melodic and harmonic endings for amusic and control groups. As can be seen, while controls showed different ratings on regular and irregular endings, amusic individuals did not differentiate the two endings. This was confirmed by a three-way ANOVA with group (amusics versus controls) as the between-subjects factor, and regularity (regular versus irregular) and pitch distance (small versus large) as the within-subjects factors for both melodic and harmonic tasks.

Insert Table 2, about here.

For the melodic task, the analysis revealed main effects of regularity, $F(1, 26) = 33.41$, $p < .001$, $\eta_p^2 = .56$, pitch distance, $F(1, 26) = 24.63$, $p < 0.001$, $\eta_p^2 = .49$, and group, $F(1, 26) = 7.73$, $p = .01$, $\eta_p^2 = .23$. There was a significant interaction between regularity and pitch distance, $F(1, 26) = 15.02$, $p = .001$, $\eta_p^2 = .37$, due to the fact that participants distinguished regular from irregular endings better for the small distance condition, $F(1, 26) =36.79$, p $< .001$, $\eta_p^2 =.59$, than for the large distance condition, $F(1, 26) =11.54$, p $< .01$, $\eta_p^2 = .31$. A significant interaction between regularity and group, $F(1, 26) = 45.84$, $p < .001$, $\eta_p^2 = .64$, reflected that control participants, but not amusic participants, showed a significant difference in ratings between regular and irregular endings: $F(1, 12) = 78.73$, $p < .001$, $\eta_p^2 = .75$ for the control group, and $F(1, 12) = 0.49$, $p > .05$ for the amusic group. There was an interaction between regularity, group, and pitch distance, $F(1, 26) = 5.04$, $p < .05$, $\eta_p^2 = .37$, reflecting that controls rated irregular and regular endings differently for both the large, $F(1, 12) = 39.23$, $p < .001$, $\eta_p^2 = .60$, and the small pitch distance conditions, $F(1, 12) = 73.20$, $p < .001$, $\eta_p^2 = .74$, whereas individuals with amusia did not distinguish irregular from regular endings for either condition, *p*s > .05. Other effects were not significant.

For the harmonic task, there were main effects of regularity, $F(1, 26) = 95.24$, $p < .001$, $\eta_p^2 = .79$, and group, $F(1, 26) = 7.94$, $p < .01$, $\eta_p^2 = .23$. A two-way interaction between regularity and group was significant, $F(1, 26) = 51.42$, $p < .001$, $\eta_p^2 = .66$, indicating that mean ratings for regular and irregular endings were significantly different for control participants, $F(1, 12) = 143.31, p < .001, \eta_p^2 = .85$, but not for amusic participants, $F(1, 12) = 3.35, p > .05$. A significant three-way interaction between regularity, group, and pitch distance was also observed, $F(1, 26) = 4.27, p < .05, \eta_p^2 = .14$. Specifically, controls showed significantly different ratings for regular versus irregular endings, for both the large pitch distance, $F(1, 12) =108.70, p < .001, \eta_p^2 = .81$, and the small pitch distance conditions, $F(1,12) =174.72, p < .001, \eta_p^2 = .87$, whereas individuals with amusia did not distinguish irregular from regular endings for either condition, *p*s > .05. Other effects were not significant.

We further explored whether performance on musical syntax was related to scores on the pitch thresholds and MBEA. Because there were differences in average ratings for the participants, the differences in rating for regular and irregular endings on each trial were individually normalized to *z*-scores in both melodic and harmonic tasks and subjected to correlation analysis. For the amusic group, there was only a significant correlation between performance on music-syntactic processing in the harmonic task and scores on the metric subtest of the MBEA, $r(12) = .55, p < .05$. No other correlations were significant for the amusic group, *p*s > .05.

The present findings corroborate previous research showing that nonamusic individuals without music training can readily process musical syntax, presumably using skills developed through long-term passive exposure to music (Koelsch et al., 2000). In contrast, amusic individuals failed to distinguish between these two endings in melodic and harmonic tasks, and in both single- and mixed-key conditions. This failure could not be explained by deficits in pitch discrimination. Amusic individuals exhibited poor performance on musical syntax even when the pitch distance between the final two tones or between the top voices of the final two chords was well above pitch change detection thresholds of amusic individuals: five and four semitones for the regular and irregular endings, respectively.

Correlation analyses confirmed this point by showing that melodic syntax processing of the amusic group was not related to their thresholds for pitch change detection or pitch direction discrimination, or any of the MBEA subtests or global scores, although amusics' performance on the harmonic syntax task was exclusively correlated with their scores of the MBEA metric subtest. The reason for the correlation between the harmonic syntactic performance and the score of metric subtest in amusia may be because both harmonic syntax and meter reflect the hierarchical structures in Western tonal music. As Prince, Thompson, and Schmuckler (2009) stated, a strong positive correlation between the tonal and metric hierarchies reflects the fact that metrically stable temporal positions usually contain tonally stable tones in Western tonal music.

However, compared with harmonic sequences, melodic sequences were more ambiguous in tonal information. This notion is further supported by the present results that participants were more prone to be affected by transposition in mixed-key conditions for melodies than for chords. This may account for the nonsignificant correlation between amusics' syntactic performance on the melodic task and the metric subtest.

The present data revealed that control participants distinguished irregular from regular endings not only in the harmonic task but also in the melodic task. This is consistent with previous electrophysiological evidence that the human brain responds to irregular tone/chord endings by eliciting an early anterior negativity, an ERP component of music-syntactic processing (Koelsch & Jentschke, 2010; Miranda & Ullman, 2007). These findings indicate that listeners can readily extract key structure from isolated melodies, even though they can be harmonized in multiple ways (Thompson, 1993; Thompson & Cuddy, 1989).

Compared with the mixed-key condition, the single-key condition would result in the effect of an auditory sensory memory trace for in-key scale tones (Koelsch et al., 2007). Conversely, the mixed-key condition should have prevented accumulation effects on key structure. This may account for our finding that participants showed better music-syntactic processing for the single-key condition than for the mixed-key condition in the melodic task. In contrast, participants showed comparable music-syntactic performance on single- and mixed-key conditions in the harmonic task. This suggests that an auditory sensory memory trace for in-key scale tones cannot affect the processing of harmonic syntax. This finding may be understandable in that a five-chord progression provides sufficient tonal information for listeners to establish a key and make a music-syntactic judgment, and provides further evidence in support of the notion that harmonic syntax can be perceived regardless of whether chord sequences in a block are within a single key (Koelsch et al., 2000) or transposed to different keys (Koelsch & Jentschke, 2010; Koelsch et al., 2007). Therefore, our findings indicate that although listeners can extract tonal information from melody, sensitivity to melodic syntax is somewhat less stable than sensitivity to harmonic syntax.

Experiment 2: Tonality Perception

The results of Experiment 1 revealed that amusic individuals exhibited deficits in explicit processing of music syntax, and this impairment was not associated with pitch change detection or pitch direction perception in amusia. Because the sense of tonality is the basis for the processing of chord and key structures (Patel, 2008; Schmuckler & Tomovski, 2005), and tonality reflects an important component of tonal music grammar (Steinke, Cuddy, & Holden, 1997), it is reasonable to expect that amusia is also associated with poor tonality processing in explicit tasks.

Indeed, previous evidence shows that amusic individuals do not explicitly benefit from tonality when memorizing tonal sequences to the extent observed for typical listeners (Albouy, Schulze, Caclin, & Tillmann, 2013), and fail to elicit an N200 response, an ERP component indexing the neural response to unexpected pitch in melodic context, when detecting out-of-key tones (Peretz, Brattico, Jarvenpaa, & Tervaniemi, 2009). Therefore, the aim of Experiment 2 was to explore this hypothesis by evaluating explicit tonality perception in individuals with amusia, and investigating the extent to which sensitivity to tonality is related to their deficits of pitch discrimination.

Method

Participants. The same participants in Experiment 1 took part in Experiment 2.

Stimuli. The probe-tone method developed by Krumhansl and colleagues was employed in Experiment 2 (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). An ascending scale and a cadence (IV-V-I) in both major and minor keys were used as key-defining contexts. Each context was followed by a probe tone. The set of probe tones were composed of 12 chromatic scale tones. Each probe-tone was randomly presented only once in each context, which resulted in 12 trials for each block. There were eight blocks in which the contexts of scales and cadences in both major and minor keys were equally distributed. In each trial, the context and the probe tone were separated by a silence of 1000 ms. Each probe tone lasted 700 ms. In keeping with Krumhansl and Kessler (1982), the tonic tones in both major and minor scales were 700 ms in duration, and the remaining scale tones lasted 350 ms, with a 50 ms pause between scale tones. Each chord in the cadence was 700 ms in duration, with a 50 ms pause between chords. Tones were generated with a grand piano sound using Pianissimo (Acoustica, Inc.) at an approximate intensity of 70 dB.

Procedure. There were four blocks in which the contexts were scales in major and minor keys (D major, A major, F minor, and B^b minor); four other blocks consisted of cadences in major and minor keys (C major, $F^\#$ major, E minor, B minor). To minimize the carry-over effect of the key of the preceding block, the stimuli of each block were presented in a different key from those of the preceding blocks. The order of blocks using a scale or a cadence as contexts was counterbalanced. In a pilot study, it was observed that participants had difficulty understanding the concept of a "musical context" due to lack of music training. Therefore, prior to the experiment, the context of a major scale or a minor cadence in a key different from those of the experimental stimuli was used as examples for explanation of the concept of a musical context to the participants. Participants were required to rate how well each probe tone fit with the musical context on a 7-point Likert scale (1 = *fit poorly*, and 7 = *fit well*). They were encouraged to use the full range of the response scale. Twelve practice trials were given before the first blocks of each task (scale or cadence). All stimuli were presented binaurally through Philips SHM1900 headphones in a soundproof room.

Results and Discussion

The hierarchical system of pitch relations in Western tonal music is fundamental to tonality. As such, tonality perception is inferred by the extent to which probe-tone profiles exhibit a hierarchy of stability of chords and tones. Figure 5 displays the average goodness-of-fit ratings of each probe tone for major and minor key contexts, and for the two groups. As illustrated in Figure 5, for the control group, mean ratings for both major or minor key contexts were the highest for the tonic (displayed as C in both major and minor keys), followed by the third (E for the major key, and $D^{\#}$ for the minor key) and fifth scale tones (G in both major and minor keys), and then the remaining diatonic tones (D, F, A, and B in major key, and D, F, and $G^{\#}$ in minor key, although B was slightly lower than other diatonic tones in the minor). Non-diatonic tones ($C^{\#}$, $D^{\#}$, $F^{\#}$, $G^{\#}$, and $A^{\#}$ in major key, and $C^{\#}$, E, $F^{\#}$, $G^{\#}$, and $A^{\#}$ in minor key) were assigned the lowest ratings.

Correlation analyses were next performed to examine whether the rating profiles of the amusic and controls groups were correlated with the standard key profile reported by Krumhansl and Kessler (1982). For the control group, correlations were very high for the major key context, $r(10) = .94$; and for the minor key context, $r(10) = .94$, *p*s < .05. However, this hierarchy was not as clearly evident in probe-tone ratings by amusic participants. Although amusics' mean ratings for major key contexts were significantly correlated with the standard major key profile, $r(10) = .73$, $p < .05$, their mean ratings for minor key contexts were not correlated with the standard minor key profile, $r(10) = .07$, $p > .05$. That amusic individuals would exhibit such a striking difference in the recovery of major and minor tonal hierarchies is surprising, but may relate to the inherent ambiguity of the minor key. For example, unlike the major key, the minor key is associated with three competing scales: natural, harmonic, and melodic minor (Vuvan, Prince, & Schmuckler, 2011). Quite possibly, amusic individuals are especially impaired at forming stable representations of ambiguous musical materials.

Insert Figure 5, about here.

Given the importance of the hierarchy of stability of tones in tonality, to further assess whether there are different performances on the rating profiles between amusic and control groups, we calculated the mean rating for each of the four categories of probe tones based on their relative stability in the tonal hierarchy for both the major and minor key contexts: (1) tonic; (2) mean of third and fifth scale tones; (3) mean of other diatonic tones; (4) mean of nondiatonic tones, according to previous studies (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979). A three-way ANOVA with group (amusics versus controls) as the between-subjects factor and category of probe tone and task (major versus minor) as the within-subjects factors revealed main effects of group, $F(1, 26) = 6.71$, $p < .05$, $\eta_p^2 = .21$, and category, $F(2.23, 57.92) = 31.82$, $p < .001$, $\eta_p^2 = .55$, and an interaction between category and task, $F(2.31,60.05) = 3.58$, $p < .05$, $\eta_p^2 = .12$, reflecting that participants assigned different ratings to most categories except for the ratings between the tonic and third and fifth scale tones in the major key context, whereas they only differentiated the stabilities between nondiatonic tones and all diatonic tones in the minor key context. The different performance on major and minor key contexts for participants may be due to the ambiguity of tonal percepts for minor context (Vuvan et al., 2011). There was a significant interaction between group and category, $F(2.23, 57.92) = 21.47$, $p < .001$, $\eta_p^2 = .45$. Mean ratings for the four categories of probe tones were significantly different for control participants, *p*s < .05, but not for amusic participants, *p*s > .05. Other effects were not significant.

These results were corroborated in a subsequent correlation analysis. For each participant, we calculated the correlation between their key profiles and the standard key profile reported by Krumhansl and Kessler (1982). These correlation values may be considered as an index of an individual's sensitivity to tonality, with higher correlation values indicating greater sensitivity. Correlation values were subjected to a two-way ANOVA with group (amusics versus controls) as the between-subjects factor and task (major versus minor) as the within-subjects factor. The analysis revealed a main effect of group, $F(1, 26) = 38.10$, $p < .001$, $\eta_p^2 = .76$, confirming lower tonality perception in amusic participants (major: M = 0.20, SD = 0.33; minor: M = 0.05, SD = 0.29) than in controls (major: M = 0.67, SD = 0.30; minor: M = 0.61, SD = 0.19). No other effects were significant.

For each participant, the correlation values for major and minor key contexts were next averaged to create a composite tonality perception score (there was no significant effect of mode on these values). We calculated the correlation between the composite tonality perception scores and the scores on the pitch thresholds and MBEA. Tonality perception was only correlated with scores on the metric subtest of the MBEA for the amusic group, $r(12) = .72$, $p < .05$, but not with other subtests of the MBEA or pitch thresholds, *p*s > .05. Furthermore, although tonality perception scores for the control group were not related to normalized *z*-scores of music-syntactic performance for either the melodic or the harmonic task, *p*s > .05, whereas for the amusic group, there were significant correlations between tonality perception and melodic syntactic performance, $r(12) = .54$, $p < .05$, and harmonic syntactic performance, $r(12) = .62$, $p < .05$. These correlations were driven by the performance of an amusic participant who obtained the highest scores for musical syntax and tonality among the amusic group, which represented two standard deviations above the mean score of this group. When this participant was removed from the analysis, no significant correlations were found in the amusic group, $r(11) = .36$, $p > .05$ for the melodic task, or $r(11) = .11$, $p > .05$ for the harmonic task. To check whether the above findings were affected by the performance of this amusic participant, we performed the same analysis of syntax and tonality as above by excluding this amusic participant. The results showed the same pattern as above.

The present findings showed that while controls rated the probe tones based on their relative stability in the tonal hierarchy, amusic individuals did not rate in terms of this hierarchy for either the major or minor key context. This may not be attributed to pitch deficits of amusia since amusics' tonality perception was not correlated with their performance on any pitch-based subtests of the MBEA, or with their pitch change detection and pitch direction thresholds. However, similar to their performance on harmonic syntax, amusics' tonality perception was significantly related to metric processing in the MBEA. This may be also due to the consistency of the hierarchical structures of tonality and meter. Metrically stable temporal positions usually correspond to those of tonally stable tones in Western tonal music (Prince et al., 2009).

Consistent with previous studies (Krumhansl & Kessler, 1982; Krumhansl & Shepard, 1979; Steinke et al., 1997), the present data confirmed that typical individuals were highly sensitive to tonality by exhibiting a tonal hierarchy. This provides further evidence that musicians and nonmusicians have a common representation of tonality that develops through repeated exposure to Western tonal music (Koelsch, 2012; Krumhansl & Cuddy, 2010).

General Discussion

This investigation used explicit tasks to examine musical syntax and tonality processing in a group of Mandarin-speaking congenital amusics. Although previous evidence suggested that amusic individuals could *implicitly* perceive harmonic structure (Tillmann et al., 2012) and predict the probability of musical events in a melodic context (Omigie et al., 2012), our findings revealed that they exhibited significant impairments with *explicit* processing of syntax and tonality. Specifically, amusic individuals were unable to detect the difference between regular and irregular endings, whereas controls readily distinguished regular from irregular endings in both melodic and harmonic tasks. A probe-tone study further revealed that amusic individuals had reduced sensitivity to tonality compared with control participants. This reduced sensitivity to syntax and tonality cannot be attributed to poor pitch discrimination in amusia. Taken together, the present study provides the first behavioral evidence that individuals with amusia have reduced sensitivity to musical syntax and tonality in explicit tasks, and that musical structure processing as reflected by tonality and syntax cannot be explained by low-level pitch discrimination.

In contrast to the findings based on an implicit task (Tillmann et al., 2012), individuals with congenital amusia showed difficulty in processing musical syntax using explicit judgments for both melodic and harmonic contexts. The present finding is consistent with previous evidence that amusic individuals are impaired in consciously differentiating between high and low probability events in a melodic context (Omigie et al., 2012).

Furthermore, consistent with a case study of a patient with acquired amusia (Steinke et al., 1997), congenital amusics exhibited lower sensitivity to tonality compared with controls. This can account for the observations that amusic individuals lack a short-term memory advantage for tonal over atonal sequences (Albouy et al., 2013). Taken together, the impaired explicit processing of musical syntax and tonality may be attributed not only to a neural anomaly underlying processing of pitch, such as abnormal N2 elicited by an unexpected out-of-key tones in a melodic context (Peretz et al., 2009) and the absence of P3b indexing inability to perceive small pitch changes (Moreau, Jolicœur, & Peretz, 2013; Peretz, Brattico, & Tervaniemi, 2005), but also to an impoverished connectivity between the auditory cortex and the inferior frontal cortex (Hyde, Zatorre, & Peretz, 2011). These findings suggest that individuals with amusia have deficits not only at an early stage of pitch discrimination, but also at later stages where a hierarchy of tonal stability and musical expectancies are represented.

Musical syntax and tonality play important roles in the enjoyment of Western tonal music (Lerdahl & Jackendoff, 1983; Patel, Gibson, Ratner, Besson, & Holcomb, 1998; Schmuckler & Tomovski, 2005). During a listening experience, listeners draw on their knowledge of the tonal functions of musical events in order to predict subsequent events. Musical expectancies (e.g., expectancy build-up, violation or fulfillment of expectancies, resolution), together with scale structure, underlie the perception of tension and relaxation and affect emotional aspects of music listening (Koelsch, 2014). From this perspective, reduced sensitivity to syntax and tonality in the present study may account for why some amusic individuals have problems with appreciating music (McDonald & Stewart, 2008).

Amusic participants performed poorly on syntactic processing of sequences containing both small (1-2 semitones) and large (4-5 semitones) pitch distances. Correlation analyses further revealed that neither syntax nor tonality performance was related to the scores of the MBEA, or the pitch change detection and pitch direction thresholds in amusia. These findings are consistent with previous studies suggesting that deficits of pitch discrimination do not affect statistical learning of tonal materials (Omigie & Stewart, 2011), short-term memory for tone sequences (Albouy et al., 2013), or consciously differentiating between high and low probability events in a melodic context (Omigie et al., 2012).

In Western tonal music, pitch distance is confounded with tonal function since large and small pitch distances may have the same tonal function. The perceived psychological distance between the leading tone and tonic was larger than that between the subdominant tone and tonic. This is because the leading tone occupies a lower position than the subdominant tone in the tonal hierarchy (Krumhansl, 1990). Although participants were able to distinguish regular endings from irregular endings in the melodic task regardless of whether the subdominant or leading tone was at the fourth position, the effect size was larger when the stimuli involved a small pitch distance (leading tone to tonic) than when the stimuli involved a large pitch distance (subdominant tone to tonic) [η_p^2 = .31 (medium effect size) and .59 (large effect size) for large and small distance conditions, respectively, see Cohen, 1998]. The present findings support the view that processing of musical structure is based on conventional structural relations rather than on psychoacoustic relations of the sounds (Bigand & Pineau, 1997; Bigand et al., 2003; Tekman & Bharucha, 1998; Tillmann et al., 1998).

In Experiment 1, the Neapolitan chord was employed to disrupt the syntactic hierarchy of musical sequences, but it is also less stable tonally than the tonic chord (Koelsch, 2012; Rohrmeier, 2011). For this reason, it was important to evaluate tonality perception more directly in Experiment 2 using the probe-tone method. We observed no significant correlation between the findings of Experiments 1 and the tonality perception results of Experiment 2, suggesting that performance in Experiment 1 was unrelated to tonality perception. These results highlight the distinction between syntax and tonality. Tonality is established from knowledge-free structure, whereas musical syntax is formed on the basis of a context-free grammar (Koelsch, 2012). The former may be based on psychoacoustic principles and information stored in the auditory sensory memory, while the latter may be based on long-term memory and exhibits features of recursion, hierarchical organization, and long-distance dependencies (Koelsch, 2012; Rohrmeier, 2011).

To conclude, amusic individuals exhibited significant impairment in the conscious perception of musical syntax, and as well as reduced capacity to recover the major and minor tonal hierarchies. This reduced sensitivity to both syntax and tonality was not associated with poor pitch discrimination in amusia, suggesting that the processing of such regularities in music may be cognitively and neurally distinct from mechanisms that handle low-level pitch discrimination.

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Correspondence concerning this article should be addressed to either Dr. Cunmei Jiang, Music College, Shanghai Normal University, Shanghai, 200234, China. E-mail: cunmeijiang@126.com, or Professor William Forde Thompson, Department of Psychology, ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Sydney, Australia. E-mail: bill.thompson@mq.edu.au

TABLE 1.

Participants' Characteristics and Mean Scores from the MBEA for Amusic and Control Groups

	Amusic (*n* = 14)	**Control (*n* = 14)**	***t*-test**
Demographic characteristics			
Mean age (*SD*)	24 (0.91)	24 (0.80)	*ns*
Sex	7M, 7F	7M, 7F	
Handedness	14R	14R	
Hours music listening per day (*SD*)	0.38 (0.32)	0.33 (0.36)	*ns*
Years education (*SD*)	18 (1.20)	18 (0.94)	*ns*
Mean scores of MBEA			
Scale subtest (*SD*)	19 (3.42)	28 (1.20)	$p < .001$
Contour subtest (*SD*)	19 (3.23)	28 (1.35)	$p < .001$
Interval subtest (*SD*)	17 (2.43)	28 (2.17)	$p < .001$
Rhythmic subtest (*SD*)	22 (3.56)	28 (1.67)	$p < .001$
Metric subtest (*SD*)	17 (3.26)	27 (2.93)	$p < .001$
Memory subtest (*SD*)	21 (2.99)	29 (0.98)	$p < .001$
Melodic subtests (*SD*)	18 (1.70)	28 (1.32)	$p < .001$
Global score (*SD*)	19 (1.22)	28 (1.20)	$p < .001$
Direction threshold (*SD*)	3.38 (2.09)	0.85 (0.58)	$p < .001$
Detection threshold (*SD*)	1.02 (0.80)	0.28 (0.14)	$p < .01$

Note: F = female; M = male; R= right-handed.

Table 2.

Mean Ratings for Melodic and Harmonic Endings for Amusic and Control Groups in the Large and Small Pitch Distance Conditions

	Melodic sequences				Harmonic sequences			
	Large		Small		Large		Small	
	Regular	Irregular	Regular	Irregular	Regular	Irregular	Regular	Irregular
usic group	4.42 (0.75)	4.71(0.74)	4.93 (0.57)	4.93 (0.65)	4.89 (0.61)	4.35 (0.87)	4.79 (0.58)	4.41 (0.72)
ıtrol group	4.28 (1.02)	3.01 (0.98)	5.68 (0.70)	3.29 (1.22)	5.54 (0.70)	2.59 (0.88)	5.59 (0.69)	2.45 (0.73)

Note: "Large" indicates pitch distances between the fourth and final positions (five semitones for the tonic ending and four semitones for the Neapolitan ending) when the subdominant was at the top voice of the dominant seventh chord (the fourth chord). "Small" indicates pitch distances between the fourth and final positions (one semitone for the tonic ending and two semitones for the Neapolitan ending) when the leading tone was at the top voice of the dominant seventh chord.

Figure Captions:

Figure 1. A simplified model of pitch processing in music.

Figure 2. Examples of the stimuli used in the study. There were regular and irregular chord endings: regular ones ended on a tonic chord (A) and irregular ones ended on a Neapolitan chord (B). The melodic sequences were derived from the top voices of the chord sequences, with regular sequences ending with a tonic (C) and irregular sequences ending with the root tones of the Neapolitan chord (D).

Figure 3. Mean and individual ratings for melodic endings of the amusic and control groups.

Figure 4. Mean and individual ratings for harmonic endings of the amusic and control groups.

Figure 5. The major key profile (upper graph) contains the average rating for each probe tone for the major scale and cadence by the amusic and control groups. The minor key profile (lower graph) contains the average rating for each probe tone for the minor scale and cadence by the amusic and control groups. The profiles are shown with respect to C major and minor, respectively.