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Abstract

Congenital amusia is a neurodevelopmental disorder of music perception and production, which has been attributed to a major deficit in pitch processing. While most studies and diagnosis tests have used explicit investigation methods, recent studies using implicit investigation approaches have revealed some unimpaired pitch structure processing in congenital amusia. The present study investigated amusic individuals' processing of tonal structures (e.g., musical structures respecting the Western tonal system) via three different questions. Amusic participants and their matched controls judged tonal versions (original musical excerpts) and atonal versions (with manipulated pitch content to remove tonal structures) of 12 musical pieces. For each piece, participants answered three questions that required judgments from different perspectives: an explicit structural one, a personal, emotional one and a more social one (judging the perception of others). Results revealed that amusic individuals' judgments differed between tonal and atonal versions. However, the question type influenced the extent of the revealed structure processing: while amusic individuals were impaired for the question requiring explicit structural judgments, they performed as well as their matched controls for the two other questions. Together with other recent studies, these findings suggest that congenital amusia might be related to a disorder of the conscious access to music processing rather than music processing per se.

Keywords: music perception deficit, tonal knowledge, implicit processing, consciousness

1. Introduction

Research in cognitive psychology and neurosciences has provided increasing evidence for non-musician listeners' musical knowledge and sophisticated tonal structure processing, in particular when studied with implicit (indirect) investigation methods (e.g., Bigand & Poulin-Charronnat, 2006; Tillmann, 2005). These findings contrast with the phenomenon of congenital amusia, a life-long impairment of music perception and production (e.g., Peretz, 2013; Tillmann, Albouy, & Caclin, 2015; Williamson & Stewart, 2013). Amusic individuals have difficulties to detect mistuned tones and out-of-key tones as well as to detect when someone sings out-of-tune, including themselves (e.g., Ayotte, Peretz, & Hyde, 2002). Experimental evidence has confirmed that the major deficit in congenital amusia concerns the processing of the pitch dimension, notably with elevated pitch discrimination thresholds (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Hyde & Peretz, 2004; Peretz, et al., 2002) and impaired short-term memory for pitch, both with isolated tones and tone sequences (Albouy, Mattout, et al., 2013a; Gosselin, Jolicoeur, & Peretz, 2009; Tillmann, Schulze, & Foxton, 2009; Williamson, McDonald, Deutsch, Griffiths, & Stewart, 2010; Williamson & Stewart, 2010). The deficit affects less systematically the processing of the time dimension (rhythm, meter), but it can also be impaired (e.g., Peretz, Champod, & Hyde, 2003).

While the condition of amusia has been described for a long time (e.g., Allen, 1878), scientific research investigating this condition is still relatively recent, benefitting in particular from the diagnostic battery proposed by Peretz, et al. (2003). In the Montreal Battery for the Evaluation of Amusia (MBEA), six sub-tests address various components of music perception and memory, notably the pitch dimension (detection of an out-of-key note, a contour violation or interval changes), the time dimension (concerning rhythm and meter) and incidental memory (for melodies used in the preceding subtests). In four of the subtests, participants hear two melodies separated by a delay and have to explicitly indicate whether the two melodies are the same or different (i.e., they differ by a single tone). The most distinctive subtest of this battery is the scale test, in which the changed tone is an out-of-key note: While this task is relatively simple for control participants (the changed notes are particularly salient due to their out-of-key nature), amusic participants perform distinctively worse, further confirming their deficit in tonal structure processing (Peretz, et al., 2008).

As for the diagnostic battery, most research has used explicit investigations methods (e.g., out-of-key tone detection task, structural judgments, memory tasks; e.g., Hyde & Peretz, 2003; Ayotte et al., 2002). However, recent studies have revealed some spared pitch processing as well as tonal structure processing in congenital amusia due to the benefit of implicit investigation methods (e.g., Omigie & Stewart, 2011; Peretz, Brattico, Jarvenpaa, & Tervaniemi, 2009; Tillmann, Gosselin, Bigand, & Peretz, 2012). These findings have led to the hypothesis that congenital amusia might impair conscious access to music processing rather than music processing per se (e.g., Stewart, 2011).

Previous research has shown for various neurological disorders (e.g., alexia, agraphia, aphasia, prosopagnosia as well as acquired amusia) that indirect investigation methods can reveal spared implicit processing in the presence of severe impairments in tasks requiring explicit processing (e.g., Mimura, Goodglass, & Milberg, 1996; Schacter & Buckner, 1998; Tillmann, Peretz, Bigand, & Gosselin, 2007). For the condition of congenital amusia, recent studies have reported some implicit tonal knowledge and pitch processing, but not yet by directly comparing implicit and explicit judgments on the same musical pieces to investigate tonal structure processing. Electrophysiological measurements revealed that the amusic brain detects mistuned notes in melodies, while the behavioral performance of the amusic individuals indicate that they fail to detect them explicitly (Peretz, et al., 2009). However, this observation did not extend significantly to the detection of out-of-key tones, which would suggest processing of tonal structures. Indirect behavioral investigation methods (i.e., the priming paradigm) have shown some sensitivity of congenital amusics for the syntactic-like functions of chords in the tonalities of the Western musical system (Tillmann, et al., 2012) as well as for melodic structures (tonal structures combined with other features, such as melodic contour, see Omigie, Pearce, & Stewart, 2012). However, Tillmann et al. (2012) did not compare their findings to explicit judgments, and while Omigie et al. (2012) compared priming data to explicit judgments, their manipulations did not focus on tonal structures. Similarly, three other studies suggest some implicit processing, but without testing explicit processing in comparison and/or without focusing on tonality: Albouy et al. (2013b) reported that tonal structures in tone sequences allowed for faster response times in a short-term memory paradigm than did atonal tone sequences (Albouy et al., 2013b). In a related vein, a recent study investigating amusics' perception of musical emotions also suggest some spared musical structure processing, in particular related to mode (major, minor; Gosselin, Paquette, & Peretz, 2015). Finally, probing for the feeling of familiarity (instead of for explicit recognition) revealed that amusic individuals have stored knowledge about musical pieces in long-term memory, but explicit recognition was not tested (Tillmann, Albouy, Caclin, & Bigand, 2014).

Taken together, these findings raise the hypothesis that amusics might have less impaired pitch and tonal structure processing than previously shown in tasks requiring explicit judgments. However, none of the studies compared directly amusics' processing of tonal and atonal musical structures when investigated with implicit vs. explicit subjective judgments, that is judgments that require different degrees of conscious evaluation of the musical pieces and their features. To further our understanding of congenital amusia and potentially spared processes, the present study required amusic and control participants to judge musical pieces with three questions shifting from explicit structural judgments to more implicit ones. For that aim, we tested amusics' processing of the pitch dimension at the level of tonal structures in real piano pieces and modified versions thereof.

In the original versions of the piano pieces, the pitch content installs a clear tonal center (i.e., tonality, key). A tonal center is notably characterized by the use of a subset of tones (7 tones selected from the possible 12 tones of the chromatic scale) with a characteristic pattern of different frequencies of occurrence in their use (e.g., Krumhansl, 1990; see also Method). To investigate tonal structure processing, we created "atonal" counterparts of these pieces (without tonal center and tonal structures) by manipulating the pitch content (i.e., removing the characteristic patterns of the tones' frequencies of occurrence) while keeping the same rhythm, tempo, dynamics and thematic structures as in the original tonal versions (procedure adapted from Lalitte et al., 2009). The tonal and atonal versions thus differed only by the used tone sets, and thus by the presence versus absence of tonality.

Amusic participants and their matched controls judged these tonal and atonal versions with three questions requiring judgments from different perspectives: an explicit structural focus, a personal, emotional focus and a more social focus (judging the perception of others). Question 1 (Q1) required evaluating the degree the excerpt is in agreement with what we are used to hear as music respecting the musical system of our culture. Question 2 (Q2) required evaluating the degree to which participants would buy a CD with this kind of music. Question 3 (Q3) required participants to estimate the ranking that a given excerpt would reach in a hit-parade, which is based on the opinion of the general French population.

The aim of Q1 was to obtain information about amusics' perception of what is well-constructed music, thus reflecting their perspective about the musical system of their own culture. This question involved the highest degree of explicit judgments as it suggests that an objectively correct (or incorrect) response can be defined. As the experimental manipulation only modified the tonal structures of the musical pieces (while keeping constant other potential features related to the culture, such as the tuning system, the used instrument, the metrical structures, typical rhythmic cells etc.), responses to Q1 should inform us about listeners' perception about tonal structures in particular.

The aim of Q2 was to tap into amusics' personal preferences for music, also including some emotional aspects (under the hypothesis that one prefers listening to music that one considers pleasant or likes). This task was similar to the one used by Karno and Konecni (1992) who required participants to judge their desire to own a copy of the musical piece aiming to investigate whether listeners process tonal structures not only at a local level, but also at a global level (comparing musical pieces that were either in their original version or with an altered structure after reordering some segments). This task was also similar to the procedure used by Salimpoor et al. (2013) where participants were asked to purchase previously unheard music with their own money in an auction paradigm. This task was used as an indication of whether participants wanted to hear a musical piece again and to assess musical reward value objectively. Their findings show that the degree of activity in cortical reward circuitry and emotion-related networks predicts the amount of money listeners are willing to spend in the auction paradigm. In our present material, responses to Q2 should be influenced by the differences in tonal structures (that is, their presence vs. absence in the tonal vs. atonal versions) beyond personal preferences for other feature implementations (e.g., tempo, rhythm), which were kept constant between the two versions. This testing approach is also similar to the procedure used by Peretz et al. (1998) who manipulated musical features (mode, tempo) and investigated its influence on perceivers' emotional judgments (see also Gosselin et al., 2015).

The aim of Q3 was to invite participants to take the perspective of the "others", that is how would the French population rank the different pieces. Q3 thus follows the same rationale as Q2, suggesting that participants' responses should reflect processing of tonal (vs. atonal) structures, which were the only features differing between the two versions and which should thus indirectly influence their judgments. Q2 and Q3 required participants to judge the musical material from different perspectives (either on an individual or societal) level, but not to directly judge the musical structures. They thus allowed for two types of more indirect and implicit investigations of musical structure processing.

Based on the data suggesting some spared implicit processing of tonality in amusia (eg., Albouy, Schulze, Caclin, & Tillmann, 2013; Tillmann, et al., 2012), we aimed to test whether amusics have acquired at least some sparse tonal knowledge (via implicit learning) that might influence their judgments and thus allow separating the tonal from the atonal pieces. We hypothesized that this knowledge influences most strongly the judgments of own emotional preferences (Q2) and of the perception and preference of others (Q3) as these judgments might tap into more implicit processing. These judgments might also be less obscured by missing confidence in their music perception (because of their amusic condition) as might be the case for explicit, structural judgments (Q1), which should show their previously reported deficit.

2. Material and methods

2.1. Participants

Eleven amusic adults (seven women; mean age, 36.90 ± 10.98 years, ranging from 20 to 54; mean education, 14.90 ± 1.44 years; musical education 0.95 ± 1.73 years) and eleven matched non-musician controls (seven women; mean age, 36.18 ± 10.10 years, ranging from 24 to 51; mean education, 15 ± 2.60 years; musical education 0.36 ± 0.80 years) participated in the study. Each group was composed of ten right-handed participants and one left-handed participant. Moderate or severe peripheral hearing loss was excluded using standard audiometry, and all participants reported no history of neurological or psychiatric disease. Participants gave their written informed consent, and were paid for their participation.

All participants were tested with the MBEA (Peretz, et al., 2003). To be considered as amusic, participants had to obtain an average score two standard deviations below the average of the normal population on the MBEA. Amusics obtained scores below the cut-off score (23.4 on average across the six tasks, maximum score = 30), except one with a borderline score of 23.5. All controls obtained scores higher than the cut-off score. The average scores of the amusic group (mean = 21.24; SD = 1.68, range: 18 to 23.5) differed significantly from the scores of the control group (mean = 27.65; SD = 0.72; range: 26.2 to 28.7, $t(20) = 11.17$, $p < .0001$).

Pitch discrimination thresholds were determined using a two-alternative forced-choice task with an adaptive tracking, two-down/one-up staircase procedure (see Tillmann et al., 2009, for task and details). Pitch discrimination thresholds of the amusic group (ranging from 0.13 to 4 semitones) was higher than that of the control group (ranging from .06 to 0.95 semitones, $t(20) = 2.68$, $p = .01$). We observed an overlap in pitch thresholds between amusic and control groups, in agreement with previous findings (Foxton, et al., 2004; Tillmann, et al., 2009).

2.2. Material

Twelve piano pieces were selected from romantic and early twentieth century piano repertory (see Appendix for a complete list). The duration of the excerpts ranged from 22 sec to 34 sec (average duration of 26 sec, SD = 3.86). For the creation of the atonal counterpart of each of these tonal excerpts, the pitch content (i.e., the used pitches and intervals) was entirely reorganized with a pseudorandom process with constraints (see Lalitte et al., 2009, for details). The manipulation resulted in twelve atonal excerpts that shared with their tonal counterparts the same rhythm, tempo, dynamic, and thematic structure (see Figure 1 for an example). The atonal versions were composed in a free, but constraint atonal style (neither the twelve-tone technique, nor a random algorithm were used): Full and half cadences were not included; major, minor, and dominant seventh chords were avoided in order to remove tonal relationships; pitch contours were preserved for the melody and as closely as possible for the harmonic accompaniment. For the tonal versions, all excerpts had a clearly established tonality, and frequencies of occurrence of pitch classes showed the typical tonal hierarchy profile: pitches fulfilling important tonal functions, such as the tonic or the dominant, occur more often in the musical excerpts than pitches fulfilling weaker tonal functions or being out-of-key (as previously reported by Krumhansl, 1990). In contrast, for the atonal versions, the frequencies of occurrence did not differ between the pitch classes, leading to a rather flat profile, which is confirming the missing tonal center. To illustrate this change, Figure 2 plots the average frequency distribution for the 12 pitch classes (i.e., pitches independently of octave) as used in the tonal pieces in major mode and their atonal counterpart. We confirmed the difference in tonal center establishment by using the Krumhansl and Schmuckler (see Krumhansl, 1990) key-finding algorithm (as implemented in the MIR toolbox; https://www.jyu.fi/hum/laitokset/musiikki/en/research/coe/materials/mirtoolbox), which analyses the strength of the tonal center by correlating these frequency distributions with the tone profiles of the 12 major and 12 minor keys, respectively[1]. Among the 24 keys, the maximum positive correlation is taken as an indicator of the most strongly established key. The maximum positive correlations averaged over the 12 tonal excerpts and over the 12 atonal excerpts of our study clearly indicated a strongly established tonal centre for the tonal

[1] The major and minor key tone profiles reflect the functional hierarchy defined by tonal theory for a given key (with highest values for the tonic tone, followed by the tones on the fifth and third scale degrees, then by the remaining in-key tones, and finally the out-of-key tones, see Figure 2 for the light grey line), and result from subjective judgments of listeners (Krumhansl & Kessler, 1982).

excerpts (average *r* (10) = .76), but not for the atonal excerpts (average *r* (10) = .49). These two correlations differed significantly (p <.001).

INSERT FIGURES 1 and 2 about here

To further describe the musical pieces in terms of acoustic and tonal features, and to use this information to further investigate participants' performance (see Results), we analyzed the 24 sound files with the MIR toolbox (Lartillot, Toiviainen, & Eerola, 2008). This toolbox allows for the extraction of multiple acoustic and musical features from audio files, which have been previously linked to various behavioral data (e.g., Lalitte, 2015; Trochidis & Bigand, 2013). The retained parameters cover low-level acoustic-feature information and higher-level, more global, cognitive features related to tonality. For the low-level acoustic-feature information, we have retained the following parameters:

- standard deviation of intensity (as measured by the SD of the root-mean-square energy RMS), note that up to now, no published study had reported a deficit on loudness processing in amusia,

- mean roughness (or sensory dissonance; based on (Plomp & Levelt, 1965), related to the beating phenomenon when overtones are close in frequency)[2], as amusics have been reported to be sensitive to this acoustic feature (Cousineau et al., 2012, Marin et al., 2015),

- spectral novelty (based on the similarity of the harmonic spectrum between time point *t* and *t-1*) and spectral flux (related to the rate of change of the spectral shape (Lerch, 2012), as both are tapping into the pitch dimension, which is manipulated between our tonal and atonal versions.

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[2] Another indicator of dissonance that could be used is based on the irregularity of the spectrum (i.e., the degree of variation of successive peaks of the spectrum, cf. Jensen, 1999). However, this indicator was highly correlated with roughness, $r(22) = -.82$, $p < .0001$, and tonal and atonal excerpts did not differ in irregularity, $p = .37$ (as it is observed for roughness, Table 1). We thus did not add this parameter in our subsequent analyses.

For the higher-level, more global, cognitive features related to tonality, we used the following parameters:

- key clarity (associated to the average strength of the best fitting keys over time; based on Krumhansl, 1990),

- mean Harmonic Change Detection Function (HCDF; flux of the tonal centroid; Harte, Sandler, & Gasser, 2006),

- chromagram novelty (based on the similarity of the chromagram between time point *t* and *t-1;* the chromagram is defined as the pitch-class distribution based on the number of occurrences of the specific pitch class in a time frame and its energy throughout the analysis block).

The overview presented in Table 1 shows that the tonal and atonal excerpts differed significantly for all cognitive features related to tonality, as intended by the material construction. For the acoustic features, tonal and atonal excerpts did not differ in SD of intensity and in roughness, but differed significantly only in spectral flux (for spectral novelty, the difference failed to reach significance). This acoustic difference, which is related to the pitch content, can be explained by the pitch manipulation and the strongly entwined relationship between sensory and tonal features in Western tonal music (e.g., Bigand, Delbé, Poulin-Charronnat, Leman, & Tillmann, 2014; Bigand, Tillmann, & Poulin-Charronnat, 2006).

INSERT TABLE 1 about here

The twelve original (tonal) and twelve altered (atonal) versions were recorded in MIDI format with Steinberg Cubase SX 2 Software and exported in audio format (aiff) with The

Grand VST plug-in, which provides a realistic piano timbre. The experiment was run using Psyscope software (Cohen et al., 1993).

2.3. Procedure

Participants were informed that they would listen to 24 short piano excerpts presented over headphones in a sound-attenuated testing booth. For each excerpt, they were required to respond to three questions (Q1 to Q3), presented successively on the screen (note that participants did not have the possibility to replay the piano excerpts). Q1 required evaluating on a scale from 1 (little) to 10 (strong) the degree the excerpt is in agreement with what we are used to hear as music respecting the musical system of our culture. Q2 required evaluating on a scale from 1 (no, not at all) to 10 (yes, certainly) the degree to which they would buy a CD with this kind of music. Q3 required estimating the ranking that a given excerpt would reach in a hitparade, which would be based on the opinion of the general French population; one of four possibilities had to be chosen: 1 – the excerpt would be ranked among the last three of the hit parade, 2- the excerpt would be ranked among the 11th and 20th position of the hit parade, 3- the excerpt would be ranked among the 4th and 10th position of the hit parade, 4 - the excerpt would be ranked among the first three of the hit parade. Participants responded by pressing a key on the computer keyboard corresponding to the number of their choice. Participants pressed the space bar to start the presentation of the next musical excerpt. The 24 excerpts were presented in random order for each participant.

2.4. Post-test

Ayotte et al. (2002) showed that amusics' and controls' performance in a pitch anomaly detection task was higher for familiar melodies than for unfamiliar melodies, suggesting an indirect influence of listeners' knowledge about familiar melodies on tonal structure processing. Based on this finding and the observation that amusics judged familiar and unfamiliar excerpts similarly to controls (Tillmann et al., 2014), we ran a post-test to check for the potential familiarity of the tonal stimuli used here. Note that we had aimed for a selection of unfamiliar musical pieces for the purpose of this experiment, in order to minimize familiarity effects.

Thirteen participants (mean age: 22.54 year (SD = 3.28); 7 women; musical training as measured by years of instrumental or voice classes: 0.54 (SD = 1.45)) judged the familiarity of each musical excerpt of the tonal condition on a 10-point subjective rating scale (from 1 unfamiliar to 10 familiar). Participants were asked to judge how familiar each of the excerpts sounded to them (i.e., whether they knew a given musical excerpt and whether it evoked a feeling of familiarity). Familiarity was defined as referring to the musical piece itself, but not to the musical style or instrumental configuration. It was further explained that participants were not required to identify the excerpt, title or composer. To familiarize participants with the subjective scale, participants first judged their feeling of familiarity for four musical excerpts (also played with a piano timbre; taken from Plailly et al., 2007, selected on the basis of a pretest with a larger item pool), with two excerpts having been classified previously as familiar and two as unfamiliar. Note that the four excerpts used to familiarize the participants with the rating scale have been also used in Tillmann et al. (2014) where amusics performed as well as controls in classifying familiar and unfamiliar excerpts. The excerpts of the training and of the experimental phase were presented in random order for each participant[3]. The experiment was run on PsyScope software.

Familiarity judgments were averaged across participants (analyses by item) for each of the four example sequences and for each of the twelve experimental sequences. The results of the example sequences showed that participants understood the use of the scale and the task: the familiar excerpts and the unfamiliar excerpts received average judgments of 9.77 and 3.23, respectively (SD across participants = 0.48 and 1.39, respectively). The twelve experimental sequences received an average judgment of 3.71 (SD across participants = 1.42 and across excerpts = 0.79), which was thus closer to the average judgment of the unfamiliar example sequences. The results thus confirm that the musical pieces selected for the tonal condition (and which served as the basis for the creation of the pieces of the atonal condition) were rather unfamiliar to non-musician listeners.

3. Results

3.1. Rating analyses for the three questions

For each question, ratings were averaged over the 12 tonal excerpts and the 12 atonal excerpts for each participant, and average ratings were analyzed by a 2x2 ANOVA with Tonality (tonal/atonal) as within-participants factor and Group (amusic/control) as between-participants factor.

For ratings of Q1 (Figure 3), the main effect of Tonality was significant, $F(1,20) = 27.26$, $p<.0001$, $MSE = 1.07$, with higher ratings for tonal excerpts than for atonal excerpts,

[3] Two other tonal excerpts (which had not been retained for the main experiment) were included in the experimental phase due to a programming error. The average judgments of these excerpts were 2.31 and 3.15, respectively, and were thus in the range of the judgments of the other twelve excerpts (data in the main text).

indicating that the tonal excerpts were judged as more strongly respecting the cultural system than the atonal excerpts. In addition, the interaction between Tonality and Group was significant, $F(1,20) = 4.88$, $p = .039$, MSE = 1.07: The difference between tonal and atonal pieces was rather large for the control participants, $F(1,20) = 27.61$, $p < .0001$, and just reached significance for the amusic participants, $F(1, 20) = 4.53$, $p = .046$. The two participant groups did not differ for the tonal excerpts ($p = .947$), but differed for the atonal excerpts, which the amusic participants did not rate as strongly as 'not conform' as did the controls, $F(1,20) = 6.73$, $p = .017$. Finally, the main effect of group was not significant, $p = .287$.

INSERT FIGURE 3 about here

For ratings of Q2 (Figure 4), only the main effect of Tonality was significant, $F(1,20) = 47.27$, $p < .0001$, MSE = .74, with higher values for the tonal excerpts than for the atonal excerpts. Participants of both groups were less willing to buy a CD with atonal excerpts than with tonal excerpts. The main effect of Group ($p = .79$) and the interaction between Group and Tonality ($p = .11$) were not significant.

INSERT FIGURE 4 about here

For ratings of Q3 (Figure 5), only the main effect of Tonality was significant, $F(1,20) = 39.26$, $p < .0001$, MSE = .14, with higher values for the tonal excerpts than for the atonal excerpts. Both participant groups estimated that the tonal excerpts would reach higher rankings in the hit-parade than would the atonal excerpts. The main effect of Group ($p=.64$) and the interaction between Group and Tonality ($p=.82$) were not significant.

INSERT FIGURE 5 about here

3.2. Correlation and Regression analyses

For correlation and regression analyses, we averaged (separately for amusic and control participants) participants' judgments for each of the 24 items (12 tonal pieces and 12 atonal pieces) for each of the three questions.

a) Correlations between the questions. The special status of Q1 (in comparison to Q2 and Q3) for amusics, and the finding that amusics seemed to behave similarly to controls for Q2 and Q3 found further support in the correlations between the tasks for each group. Judgments across the 24 musical pieces correlated between Q1 and Q2 for amusics ($r(22)=.61$, $p = .002$) and for controls ($r(22)=.94$, $p < .0001$), between Q1 and Q3 for amusics ($r(22)=.66$, $p < .0001$) and for controls ($r(22)=.90$, $p < .0001$), as well as between Q2 and Q3 for amusics ($r(22)=.88$; $p < .0001$) and controls ($r(22)=.89$; $p < .0001$). However, most importantly, the correlation between Q1 and Q2 as well as the correlation between Q1 and Q3 (i.e., the two correlations involving Q1) were significantly lower for amusics than for controls (Q1 and Q2: $p = .0008$; Q1 and Q3: $p = .03$), while the correlation between Q2 and Q3 for amusics did not differ from that for controls ($p=.88$). This result further confirmed that amusics' behavior differed from controls for Q1, but was similar to that of controls for Q2 and Q3.

b) Correlations between amusics and controls' judgments. To test whether amusics and controls judged similarly the 24 musical pieces (12 tonal, 12 atonal), we calculated the correlations of the pieces' average judgments between amusics and controls for each question. These correlations were significant for Q1 ($r(22) = .45$, $p<.05$), Q2 ($r(22) = .73$, $p<.001$) and Q3 ($r(22) = .75$, $p<.001$), suggesting that amusics judged about the same musical pieces as being more in agreement with the cultural system, more likely to buy a CD and in a higher hit-parade position than did the controls. However, the correlation between amusics' and controls' judgments for Q1 was significantly weaker than the correlation between amusics' and controls' judgments for Q2 ($p = .01$) and for Q3 ($p = .009$), respectively, while the correlation between amusics' and controls' judgments for Q2 did not differ significantly from the correlation between amusics' and controls' judgments for Q3 ($p=.99$). These correlation analyses thus further confirmed the special status of Q1 (in comparison to Q2 and Q3) for the amusics whereas they performed similarly to controls for Q2 and Q3.

c) Regression analyses: Predicting participants' judgments with acoustic and tonal features. Here, we further investigated whether amusic participants are using acoustic and/or tonal features for their judgments in the three questions as done by control participants. For each question and participant group, we ran regression analyses aiming to predict these average judgments with either the low-level acoustic-features or the higher-level, cognitive features related to tonality (see Methods). To ensure that there was no collinearity between predictors, we calculated the correlations between the predictors. None of the correlations between predictors was significant, neither for the low-level acoustic-features (all *p*s > .14) nor for the higher-level features linked to tonality (all *p*s > .10).

For the regressions with the acoustic predictor variables, only for amusic participants for Q1, the overall model fit was significant [$F(4,19) = 3.6$, $p=.02$, $R^2 = .43$]; there were significant contributions of Roughness [beta = -.37; $t(19) = -2.11$; $p < .05$] and Spectral Novelty [beta = .39; $t(19) = 2.09$; $p = .05$].

For the regressions with the cognitive, tonality-related predictor variables, the overall model fits were significant for amusic and control participants for Q2 and Q3. For Q2 for amusic participants [$F(3,20) = 5.97$, $p = .004$, $R^2 = .47$], there were significant contributions of Key Clarity [beta = .71; $t(20) = 3.78$; $p = .001$] and HCDF [beta = .60; $t(20) = 3.31$; $p = .003$]. For Q2 for control participants [$F(3,20) = 4.4$, $p = .02$, $R^2 = .40$], there was a significant contributions of Key Clarity [beta = .44; $t(20) = 2.21$; $p = .04$]. For Q3 for amusic participants [$F(3,20) = 4.00$, $p = .02$, $R^2 = .38$] and control participants [$F(3,20) = 4.45$, $p =$

.02, R^2 = .40], there was a significant contribution of Key Clarity [beta = .69; t(20) = 3.38; p = .003 for amusics; beta = .71; t(20) = 3.58; p = .002 for controls]. Note that for Q1, the overall model fits were weak and not significant for either group (R^2 = .12. p = .46 for amusics; R^2 = .19, p=.23 for controls], but only for controls (and not for amusics; p = .51), there was a significant contribution of Key Clarity [beta = .48; t(20) = 2.06; p = .05]. This data pattern across the participant groups and the three questions can be also seen in the correlation between key clarity and ratings: Even though this correlation was significant for the three questions in amusics and controls (ps < .05), it was weaker for amusics for Q1 only (amusics: r (10) = .48; controls: r (10) = .73), but not for Q2 (amusics: r (10) = .74; controls: r (10) = .64) or Q3 (amusics: r (10) = .66; controls: r (10) = .73).

d) Correlations between participants' ratings and their scores in the MBEA and their pitch discrimination thresholds. We calculated correlations between participants' ratings and their scores in the MBEA as well as their pitch discrimination thresholds. We calculated these correlations 1) across all participants, and 2) for each participant group separately (this is particularly important for correlations involving the MBEA as the MBEA score had served to create the groups, thus correlations across all participants might be created by group differences only). For each of the three questions, we calculated difference scores between the ratings for the tonal and atonal versions and correlated these difference scores first with the overall MBEA score and the pitch discrimination thresholds. None of the correlations were significant (all p>.05), neither across all participants (df = 20), nor for each participant group separately (df = 9). As a second step, we calculated the correlations between the tonal/atonal difference scores and the scores at the subtests of the MBEA that are related to pitch processing (as this is the relevant dimension manipulated here; i.e., scale, interval, contour). Across all participants, the correlations with the subtest "interval" reached significance for the difference score of Q2 ($r(20) = .43$; $p < .05$). However, this correlation was not significant for each of the participant groups separately.

3.3. Inter-rater agreement in amusic and control groups

To check that inter-rater agreements within the amusic group was not weaker than that within the control group, we calculated Cronbach's α (alpha) as a coefficient of internal consistency for the judgments over the 24 musical pieces (12 tonal, 12 atonal) for each of the three questions. Results showed rather good inter-rater agreements for each of the three questions for amusic participants (Q1: .84; Q2: .97; Q3: .95) and for control participants (Q1: .94; Q2: .92; Q3: .83). The difference between Cronbach's α of the participant groups was not significant for any question (all *p*s > .14).

Discussion

The aim of the present study was to investigate amusics' tonal structure processing with three judgments shifting from a more explicit structural one (Q1) to more implicit ones (Q2, Q3), which differ from the required perspectives. The specificity of our study was to investigate amusics' tonal structure processing in full-blown music by comparing tonal and atonal (highly controlled) versions of musical excerpts with subjective scales that tap into implicit vs. explicit judgments. The results contribute to our understanding of the condition of congenital amusia and support the hypothesis of an altered access of consciousness to the perceived musical information.

Our data reveal that despite a deficit in processing the pitch dimension, as shown by the scores of the MBEA and the pitch discrimination thresholds, amusics' judgments can differ between tonal and atonal musical pieces. They can do so even though the tonal and atonal pieces had the same complexity, the same rhythmic and metric structures, the same number of notes, similar contours and melodic lines. Furthermore, the atonal versions were not distinguishable based on an emerging dissonance as the tonal versions also contained dissonances (as they were chosen from the repertoire of the 19th century and the beginning of the 20th century). The tonal and atonal versions differed in the used tones, notably with tone sets leading to the installation of a tonal center with a tonal hierarchy in the tonal versions, but no tonal center and no tonal hierarchy in the atonal versions (see Methods). The results showed that amusic participants perceived this difference in tone use despite their pitch discrimination difficulties, tonal structure deficits and the complexity of the musical material used here. These findings suggest that some pitch-processing capacities are preserved in amusic participants, even though they are impaired in explicit pitch discrimination and memory tasks (e.g., Hyde & Peretz, 2004; Tillmann, et al., 2009). Interestingly, the tonal structure processing was observed for rather unfamiliar tonal music, thus without the potential benefit of tonal versions being stored in long-term memory, as previously reported for Ayotte et al. (2002) with a pitch anomaly detection task (e.g., higher performance for familiar melodies than for unfamiliar melodies).

In our study, amusic participants' judgments reflect their capacity to perceive the differences in tone use between tonal and atonal versions for all three questions, but the difference between tonal and atonal versions was less pronounced for amusics than for controls for Q1. The present data pattern excluded amusics' deficit being caused by the previously reported impaired short-term memory for musical material. If this short-term memory deficit influenced amusics' performance (but not controls' performance), one would rather expect differences between amusics and controls for Q2 and Q3 (presented after Q1, which directly followed the music), while the reverse was observed (amusics performed like controls for Q2 and Q3). It is also worth noting that the previously reported short-term memory deficits were observed with delayed-matching-to-sample paradigms and not subjective judgments to the musical excerpts, which are less demanding on memory.

Using three questions aimed to investigate tonal structure processing in amusia with judgments differing in their degree of required explicit processing. While Q1 requires an explicit structural judgment (in reference to the musical system of their culture), Q2 and Q3 refer to more subjective judgments – tapping either in participants' personal and emotional preference (buying a CD with this music, Q2, see also Karno & Konecni, 1992; Salimpoor et al., 2013) or in using a more social perspective, that is, the perception of others (ranking the pieces in a French hitparade, Q3). The results show that amusics performed as well as controls for Q2 and Q3, while they were impaired for Q1. This data pattern suggests that amusics' deficit mainly lies in accessing and using the tonal information for direct explicit tasks (Q1), while still being able to process this information (as reflected in the more indirect questions here, Q2 and Q3). This interpretation is supported by the regression analyses, revealing that amusics' judgments' rely on tonal features (key clarity) for Q2 and Q3, as do the control participants, but not for Q1. For Q1, amusics showed a shift in processing or in strategy to use the auditory material. Here, the regression analyses revealed the influence of sensory feature processing, notably roughness and spectral novelty. Previous research has also provided evidence for amusics' capacity to process roughness, notably in explicit judgments required in psychophysics tasks (Cousineau, McDermott, & Peretz, 2012).

Asking for more subjective judgments on either an individual or a societal level, Q2 and Q3 also include judgments of preference and musical emotions. The link between tonal structures, musical expressivity, and emotions has been investigated previously (e.g., Meyer, 1956). Musical structure knowledge allows listeners to follow the tension-relaxation schemas in Western tonal music (Lerdahl & Jackendoff, 1983) as well as to developp musical expectations (Meyer, 1958), which both influence emotional responses (e.g., Krumhansl, 1996; Steinbeis, Koelsch, & Sloboda, 2006). As tonal structures are the only features differing between the two versions (tonal, atonal), the hypothesis is that Q2 and Q3 allow for an indirect investigation of tonal structure processing in amusia, and preference as well as emotion processing might come into play here. This is in agreement with previous data on acquired and congenital amusia. A severe case of acquired amusia (IR, Peretz, Belleville, & Fontaine, 1997) has shown intact emotional responses to music (Peretz, Gagnon, & Bouchard, 1998) and some tonal structure knowledge, which was revealed by an implicit investigation method (musical priming paradigm), but not seen in a task requiring explicit judgments (Tillmann, et al., 2007). For congenital amusia, spared processing of musical emotion has been shown, even though with some impairments (Ayotte, et al., 2002). Interestingly, some of the data on emotion perception also suggest spared tonal structure processing, in particular related to mode (major, minor; Gosselin et al., 2015).

Our results obtained with the three questions suggest that the amusic brain can process tonal structures, but lacks access to this knowledge, as revealed by explicit tasks directly requiring participants to report this. These findings integrate in previous research suggesting that the performance of amusic individuals in pitch-based tasks may depend on the way in which the knowledge is probed, such as the work of Omigie, et al. (2012) on melodic features and of Peretz, et al. (2009) on mistuning, which both however did not show tonal structure processing. Most recently, Zendel, Lagrois, Robitaille, & Peretz (2015) reported congruent EEG data: evoked potentials reflected amusics' detection of out-of-key tones only when the task required a judgment on a different dimension (i.e., the detection of unrelated clicks), but not when the task required to detect the pitch deviances directly. This neurophysiological data pattern thus mirrors our behavioral data pattern: amusics used tonal structures (notably, key clarity as revealed by the regression analyses) in their judgments only when the focus of the question was on other features (personal or social group preference; Q2 and Q3), but not when the task required them to directly judge the tonal structures (Q1).

Taken together, these findings suggest that congenital amusia might – at least partially – be related to some disorder of awareness or consciousness. This observation is similar to other cases reported in neuropsychology (e.g., prosopagnosia, aphasia, and also acquired amusia), with impaired explicit processing, but spared implicit processing. Amusics' and controls' performance differences might not necessarily suggest that there are separate implicit and explicit knowledge representations for tonal structures, with only the later one being impaired in amusia. The difference might be caused by differences in its accessibility to consciousness, which might be related to a "difference in degree, rather than in kind" of the involved representation or knowledge, as suggested by Cleeremans and colleagues in another research domain (Cleeremans & Jimenez, 2002; Destrebecqz & Cleeremans, 2002). Research investigating the cerebral correlates of consciousness further suggests that specific states of consciousness occur when numerous subsystems interact in a coordinated way (e.g., Boly & Seth, 2012). As explicit processes are linked to conscious access to the stored knowledge or memory traces, explicit processes might require increased interactive coordination of areas in the neural network, with a central role of the frontal cortex. For congenital amusia, anatomical and functional brain imaging data have revealed abnormalities in the auditory and inferior frontal cortices, associated with decreased connectivity between these structures (e.g., Albouy, Mattout, et al., 2013a; Hyde, Zatorre, & Peretz, 2011; Loui, Alsop, & Schlaug, 2009). The altered temporo-frontal connectivity has been observed during passive listening (Hyde, et al., 2011), for short-term memory with its associated steps of encoding, maintenance and retrieval (Albouy, Mattout, et al., 2013a; Albouy, Mattout, Sanchez, Tillmann, & Caclin, 2015), as well as during resting state (without associated task; Lévêque, et al., in revision). This altered temporo-frontal connectivity might be linked to the abnormalities in the conscious access of tonal information processing in congenital amusia. Combining different types of behavioral tasks, as in our present study, with neurophysiological measurements will allow furthering our understanding not only of the music-specific disorder of congenital amusia, but also of the neural correlates of consciousness.

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Table 1. Mean, standard deviation (SD) as well as minimum (Min) and maximum (Max) values for the excerpts in the tonal and atonal conditions for each of the low-level acoustic features and the features linked to tonality (as calculated by MIR); with their difference being tested with paired, two-sided t-tests

.			Tonal	Atonal	T-test
Low-level acoustic information	Intensity (SD)	Mean (SD)	0.48 (0.10)	0.49 (0.11)	*p* = *.44*
		[Min; Max]	[0.29; 0.61]	[0.27; 0.62]	
	Roughness	Mean (SD)	27591 (7676)	28216 (7261)	*p* = *.47*
		[Min; Max]	[11437; 41090]	[12445; 41937]	
	Spectral Novelty	Mean (SD)	0.044 (0.02)	0.06 (0.02)	*p* = *.07*
		[Min; Max]	[0.01; 0.08]	[0.02; 0.09]	
	Spectral Flux	Mean (SD)	420.29 (76.29)	452.46 (65.08)	*p* < *.0001*
		[Min; Max]	[290.86; 521.64]	[335.55; 532.93]	
Information linked to tonality	Key clarity	Mean (SD)	0.66 (0.05)	0.56 (0.02)	*p* < *.0001*
		[Min; Max]	[0.60; 0.76]	[0.51; 0.59]	
	HCDF	Mean (SD)	0.13 (0.03)	0.14 (0.03)	*p* = *.0001*
		[Min; Max]	[0.08; 0.16]	[0.09; 0.17]	
	Chromagram Novelty	Mean (SD)	0.12 (0.05)	0.15 (0.04)	*p* = *.004*
		[Min; Max]	[0.05; 0.22]	[0.10; 0.22]	

Figure Captions

Figure 1. Scores of the beginning of one of the twelve tonal excerpts used in the present experiment: the first measures of F. Poulenc's First movement (Assez modéré) from Trois Mouvements perpétuels opus 14 (top) and its atonal counterpart (bottom) are presented to illustrate the matching of the tonal and atonal versions on various features, such as rhythm, contour, tempo, dynamic and thematic structure. (See supplementary online material for an audiofile of each excerpt).

Figure 2. Relative frequencies (see y-axis on the left) of each of the twelve chromatic tones for tonal and atonal excerpts (here averaged only for the ten tonal excerpts in major key and their atonal counterparts) plotted together with the subjective probe-tone judgements (see y-axis on the right) reported by Krumhansl & Kessler (1983; exact values taken from Krumhansl, 1990); referred to as the tonal hierarchy profile. Note that for the purpose of the illustration all frequencies were presented in reference to the C Major key.

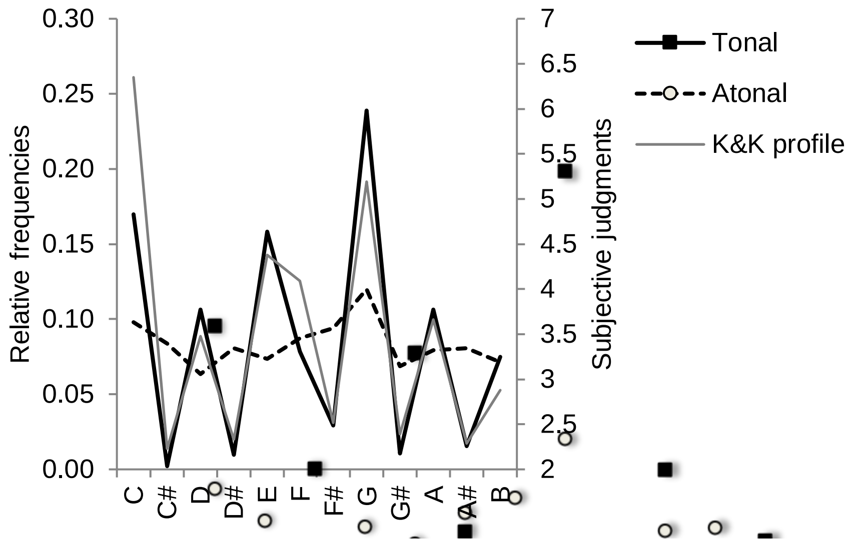
Figure 3. Average ratings given for Question 1 presented as a function of Tonality (tonal/atonal versions) and Participant groups (amusics/controls). Q1 required participants to evaluate on a scale from 1 (little, "peu") to 10 (strong, "beaucoup") the degree the excerpt is in agreement with what we are used to hear as music respecting the musical system of our culture. Error bars represent between-participant standard errors.

Figure 4. Average ratings given for Question 2 presented as a function of Tonality (tonal/atonal versions) and Participant groups (amusics/controls). Q2 required participants to evaluate on a scale from 1 (no, not at all) to 10 (yes, certainly) the degree to which they would buy a CD with this kind of music. Error bars represent between-participant standard errors.

Figure 5. Average ratings given for Question 3 presented as a function of Tonality (tonal/atonal versions) and Participant groups (amusics/controls). Q3 required participants to estimate the ranking that a given excerpt would reach in a hit parade, which would be based on the opinion of the general French population; one of four possibilities had to be chosen: 1 – the excerpt would be ranked among the last three of the hit parade, 2- the excerpt would be ranked among the 11th and 20th position of the hit parade, 3- the excerpt would be ranked among the 4th and 10th position of the hit parade, 4 - the excerpt would be ranked among the first three of the hit parade. Error bars represent between-participant standard errors.


Assez modéré
♩ = 144
Piano
p
5
En général, sans nuances
mf
En dehors


Assez modéré
♩ = 144
Piano
p
5
En général, sans nuances
mf
En dehors



0.30
0.25
0.20
0.15
0.10
0.05
0.00
Relative frequencies
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
Subjective judgments
C
C#
D
D#
E
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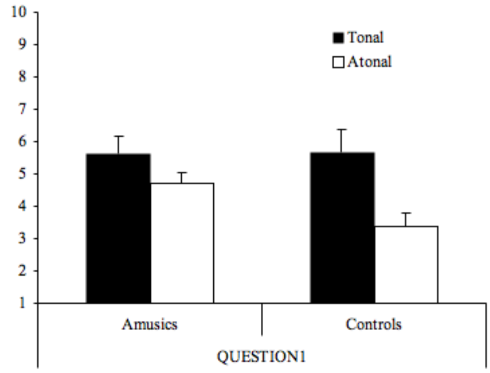
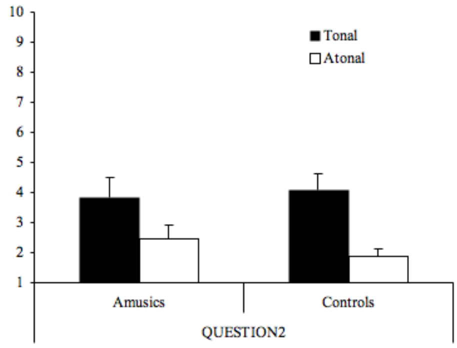
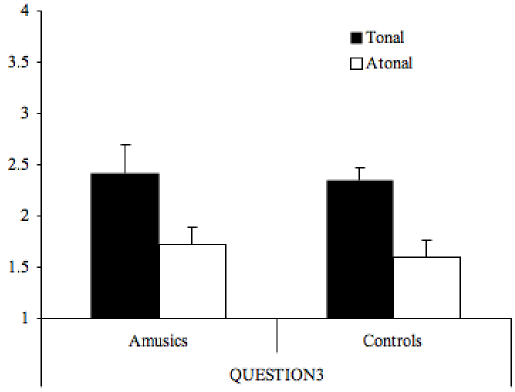
F#
G
G#
A
A#
B
Tonal
Atonal
K&K profile


10
9
8
7
6
5
4
3
2
1
Tonal
Atonal
Amusics
Controls
QUESTION1



10
9
8
7
6
5
4
3
2
1
Tonal
Atonal
Amusics
Controls
QUESTION2



4
3.5
3
2.5
2
1.5
1
Tonal
Atonal
Amusics
Controls
QUESTION3

Appendix

Composers, titles and durations of the tonal pieces (with same duration for the created atonal versions):

Beethoven, van, L: 1st movement of Piano Sonata opus 31 n° 53 ("Waldstein") (24 sec)

Brahms, J.: Intermezzo opus 117 n° 1 (34 sec)

Chopin, F.: Ballade n°2 opus 38 (20 sec)

Elgar, E.: Imperial March (piano version) opus 32 (23 sec)

Liszt, F.: First Study from Six Paganini Studies (26 sec)

Moussorgsky, M.: Promenade from Pictures at an exhibition (24 sec)

Moussorgsky, M.: Tuileries from Pictures at an exhibition (25 sec)

Poulenc, F.: 1st movement (Assez modéré) from Trois Mouvements perpétuels opus 14 (22 sec)

Prokofiev, S.: Gavotte (Allegretto) from Ten Piano Pieces opus 12 (23 sec)

Satie, E.: Sonatine bureaucratique (29 sec)

Sibelius, J.: The Lonely Pin from Five Piano Pieces Op.75 (27 sec)

Sinding, C.: Rustle of Spring opus 32 n° 3 (32 sec)

Supplementary data

Example sound files for the excerpts displayed in Figure 1; the tonal excerpt is the beginning of F. Poulenc's First movement (Assez modéré) from Trois Mouvements perpétuels opus 14; its atonal counterpart.