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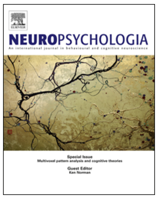

Affective evaluation of simultaneous tone combinations in congenital amusia

Manuela M. Marin [a,*], William Forde Thompson [b], Bruno Gingras [c], Lauren Stewart [d,e,**]

[a] Department of Basic Psychological Research and Research Methods, University of Vienna, Liebiggasse 5, A-1010 Vienna, Austria
[b] Centre for Cognition and its Disorders, Macquarie University, Sydney, NSW 2109, Australia
[c] Institute of Psychology, University of Innsbruck, Innrain 52f, A-6020 Innsbruck, Austria
[d] Department of Psychology, Goldsmiths, University of London, New Cross, London, SE14 6NW, United Kingdom
[e] Center for Music in the Brain, Dept. of Clinical Medicine, Aarhus University & The Royal Academy of Music Aarhus/Aalborg, Denmark

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ABSTRACT

Congenital amusia is a neurodevelopmental disorder characterized by impaired pitch processing. Although pitch simultaneities are among the fundamental building blocks of Western tonal music, affective responses to simultaneities such as isolated dyads varying in consonance/dissonance or chords varying in major/minor quality have rarely been studied in amusic individuals. Thirteen amusics and thirteen matched controls enculturated to Western tonal music provided pleasantness ratings of sine-tone dyads and complex-tone dyads in piano timbre as well as perceived happiness/sadness ratings of sine-tone triads and complex-tone triads in piano timbre. Acoustical analyses of roughness and harmonicity were conducted to determine whether similar acoustic information contributed to these evaluations in amusics and controls. Amusic individuals' pleasantness ratings indicated sensitivity to consonance and dissonance for complex-tone (piano timbre) dyads and, to a lesser degree, sine-tone dyads, whereas controls showed sensitivity when listening to both tone types. Furthermore, amusic individuals showed some sensitivity to the happiness-major association in the complex-tone condition, but not in the sine-tone condition. Controls rated major chords as happier than minor chords in both tone types. Linear regression analyses revealed that affective ratings of dyads and triads by amusic individuals were predicted by roughness but not harmonicity, whereas affective ratings by controls were predicted by both roughness and harmonicity. We discuss affective sensitivity in congenital amusia in view of theories of affective responses to isolated chords in Western listeners.

1. Introduction

Affect in music and speech is communicated by modulating attributes such as pitch, loudness, rate, and timbre (Ilie and Thompson, 2006, 2011; Juslin and Laukka, 2003). In music, even single events such as tone combinations of two or three pitches presented simultaneously (dyads and triads respectively) can have aesthetic and emotional connotations. Such combinations play a central role in musical communication and may be perceived as pleasant or unpleasant according to their degree of consonance (e.g., Kameoka and Kuriyagawa (1969a, 1969b), Plomp and Levelt (1965)), and can also evoke emotional connotations such as happiness and sadness (Crowder, 1984, 1985; Heinlein, 1928). The study of the affective evaluation of tone combinations, often tightly linked to music-theoretical considerations, can be traced back to the beginning of psychophysics in the 19th century and has remained a topic of interest to psychologists and neuroscientists since then (here and elsewhere the term “affective” refers to all evaluative (e.g., valenced) states, cf. Juslin and Västfjäll, 2008).

Two main theories have been advanced to explain why consonant tone combinations are deemed as pleasing in Western tonal music. According to the *roughness model*, first proposed by Helmholtz (1863/1954), dissonant intervals of pure tones (i.e., sine tones), such as the minor and major second, are perceived as unpleasant due to roughness, which refers to the presence of rapid beating (amplitude modulations) that occurs when two concurrent tones are similar in frequency (Plomp and Levelt, 1965; Terhardt, 1974a, 1974b). This model can be extended to combinations of complex tones (i.e., sounds that consist of harmonically related frequencies) (Kameoka and Kuriyagawa, 1969b; Sethares, 1993) and applied to intervals such as the augmented fourth (tritone), in which the perceived dissonance is due to beats

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[*] Corresponding author. Fax: +43 1 42779471.
[**] Corresponding author. Fax: +44 20 7919 7873.

E-mail addresses: manuela.marin@univie.ac.at (M.M. Marin), bill.thompson@mq.edu.au (W.F. Thompson), brunogingras@gmail.com (B. Gingras), l.stewart@gold.ac.uk (L. Stewart).

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produced by nearby partials (overtones or harmonics) of the two combined tones. However, neuroimaging studies suggest that roughness may not be sufficient to explain consonance perception when considering pure-tone (Itoh et al., 2010) and complex-tone (Bidelman and Krishnan, 2009) dyads in isolation.

According to the *tonal fusion model* (Stumpf, 1890, 1898), the degree to which two or more tones tend to be perceptually fused into a single auditory object is linked to the perception of consonance. Stumpf's theory, which later received empirical support (DeWitt and Crowder, 1987), is comparable to current models of consonance according to which the better the partials of pitch combinations match a single harmonic series (*harmonicity*), the higher the degree of perceived consonance (McDermott et al., 2010; Plack, 2010). However, some studies have challenged both roughness and tonal fusion models, suggesting instead that familiarity with commonly used musical chords underlies consonance perception (Guernsey, 1928; McLachlan et al., 2013). Although familiarity may indeed play a role in judgements of consonance, it is likely that perception of consonance and dissonance are determined by a convergence of both learned and psychoacoustic factors, including roughness and harmonicity.

Affective responses to isolated chords have been studied less frequently than the effects of mode and tempo on the perception of happiness and sadness in melodies (e.g., Dalla Bella et al. (2001), Gabrielsson and Juslin (1996), Hunter et al. (2010), Leaver and Halpern (2004), Peretz et al. (1998)). Regarding the affective connotations of triads, the major triad (consisting of a minor third superimposed on a major third) is generally associated with happiness in the Western tonal system, whereas the minor triad (consisting of a major third superimposed on a minor third) is associated with sadness (Crowder, 1984, 1985; Lahdelma and Eerola, 2014). There is evidence that major triads are perceived as more pleasant than minor triads (Crowder, 1985; McDermott et al., 2010; Roberts, 1983). However, it is still a matter of debate whether these associations are constrained by innate mechanisms or are culturally learned (Peretz, 2010). On the one hand, evidence of enculturation processes regarding affective associations with chord quality has been reported in pre-schoolers and older children (Dalla Bella et al., 2001; Gerardi and Gerken, 1995; Gregory et al., 1996; Kastner and Crowder, 1990), and Crowder (1984) argued that the preference for major over minor triads was driven by the mere-exposure effect (Zajonc, 1968). On the other hand, recent findings suggest that innate mechanisms are involved in the emotional appraisal of major and minor triads (Bakker and Martin, 2015; Cook, 2007).

In the present study, we investigated the extent to which individuals with congenital amusia differ from controls in terms of their affective evaluations of tone combinations. Congenital amusia is a rare neurodevelopmental disorder in which individuals show deficits in melodic processing and production which cannot be explained by hearing impairment, neurological or intellectual deficiency, or a lack of exposure to music in early life (Ayotte et al., 2002; Mignault-Goulet et al., 2012; Kalmus and Fry, 1980; Peretz et al., 2002). Among the core perceptual deficits of amusic individuals are difficulties in detecting fine-grained pitch changes and out-of-key notes in melodies (Ayotte et al., 2002; Hyde and Peretz, 2004; Jiang et al., 2011; Jones et al., 2009; Peretz et al., 2002) as well as difficulties in the processing of contours of pitch sequences (Dalla Bella et al., 2009; Foxton et al., 2004; Jiang et al., 2010; Liu et al., 2012). These deficits also extend to the perception of speech intonation contours (Foxton et al., 2004; Liu et al., 2010; Loui et al., 2008; Patel et al., 2008) and emotional prosody (Thompson et al., 2012). However, it should be noted that in everyday situations the observed perceptual pitch deficits relate mainly to music rather than speech (Tillmann et al., 2011), which may be partly due to amusic individuals' difficulty in recognising pitch direction in discrete compared to gliding pitches (Liu et al., 2012), and due to the relatively large pitch intervals that normally occur in speech (compared to music) as well as to the presence of additional cues to meaning in speech.

Interestingly, the extent to which individuals with congenital amusia differ from controls in terms of the affective judgements of tone combinations is not well understood, though two studies in particular provide foundations for investigating this question. In terms of the perception of consonance and dissonance, Ayotte et al. (2002) found that although amusic individuals judged consonant melodies (with accompaniment) and their pitch-shifted dissonant versions as significantly different in perceived pleasantness, this difference was much smaller in magnitude than in controls, who rated consonant melodies as more pleasant. Cousineau et al. (2012) further investigated the perception of consonance and dissonance in amusia, using isolated tone combinations instead of whole melodies. They collected pleasantness ratings of consonant and dissonant dyads and triads composed of notes sung by a vocalist or played on a saxophone, as well as pleasantness ratings in response to synthetic stimuli varying in roughness and harmonicity. Whereas controls showed preferences for consonant over dissonant dyads and chords, for harmonicity over inharmonicity, and for smooth (non-beating) over rough (beating) stimuli, amusic individuals only showed a preference for smooth over rough stimuli. Cousineau et al. thus concluded that the perception of harmonicity and roughness is clearly dissociated in congenital amusia, and that the preference for consonance over dissonance displayed by typical listeners (but not those with amusia) cannot, therefore, be driven by roughness alone. Preserved sensitivity to roughness in congenital amusics was also noted by Gosselin et al. (2015), who investigated whether amusics are able to perceive emotions communicated by music.

Building on these previous studies, we sought to investigate more fully the extent of amusics' reduced preference for consonance over dissonance. Specifically, we collected pleasantness ratings in response to isolated dyads (built of either sine tones or complex tones in piano timbre) varying in their degree of consonance/dissonance. We specifically ensured that stimuli within a block did not vary in timbre or tone type so that differences in pleasantness ratings would not be affected by these factors. We also included the octave (a dyad in which the higher note's frequency is exactly twice the frequency of the lower note) in our stimulus set. The octave is regarded as a very harmonious and pleasant interval that generates a highly salient and unambiguous pitch sensation, evoking a stronger percept of tonal fusion and consonance (Thompson and Parncutt, 1997). Moreover, we conducted acoustical analyses of our stimuli in order to assess more specifically the role of roughness and harmonicity. This approach differs from the one followed by Cousineau et al. (2012), who did not correlate pleasantness ratings of voice and saxophone stimuli with acoustical measures of roughness *and* harmonicity obtained on the same stimuli. Furthermore, based on the results of Cousineau et al. (2012), we predicted that amusic individuals' pleasantness ratings would not correlate with the harmonicity of the musical stimuli but rather with their roughness.

Amusics have been shown to be impaired in sorting sounds according to instrumental categories, which partly differ in their harmonic spectra (Marin et al., 2012). Since the harmonic spectra of sine-tone dyads/triads differ considerably from those of complex-tone dyads/triads, we also correlated the participants' pleasantness ratings obtained on the dyads/triads with their questionnaire data obtained in a previous study involving the same sample of amusics, as well as their performance in a musical timbre categorisation task (Marin et al., 2012). The questionnaire data included information on the general liking for music, aversiveness of music as well as music listening time.

We predicted that amusics' preserved sensitivity to roughness (Cousineau et al., 2012) would lead to lower pleasantness ratings in response to rough dyads such as the minor and major seconds, in comparison to smooth dyads such as the octave or the fifth. This pattern of results was hypothesised for both sine-tone and complex-tone stimuli. However, owing to possible effects of exposure and familiarity on pleasantness ratings of dyads (McLachlan et al., 2013; Plantinga and Trehub, 2014) and given the fact that complex tones occur more frequently in the natural environment than sine tones, we surmised that amusics' sensitivity to variations in roughness across intervals might be more evident for pleasantness ratings of complex-tone dyads than for ratings of sine-tone dyads.

In addition to investigating responses to consonance and dissonance, we also sought to determine whether amusic individuals are sensitive to the well-established emotional associations of isolated major and minor chords. Whereas Ayotte et al. (2002) showed that individuals with amusia associated major- and minor-mode melodies with happiness and sadness respectively, they were unable to rule out a contributing influence of tempo. Recently, Gosselin et al. (2015) investigated the emotional responses of amusic individuals to manipulated musical clips and showed that their responses were largely based on the tempo and timbre of the music. In the present study, we collected happiness/sadness judgements in response to isolated triads (sine-tone vs. complex-tone), for which tempo is not a factor. Given that previous work has demonstrated that amusics have implicit knowledge of harmonic structure but to a lesser extent than controls (Tillmann et al., 2012), we hypothesized that the typical association between mode and emotional valence would be preserved, but reduced, in amusia.

2. Methods

2.1. Participants

Twenty-six participants (13 amusic individuals and 13 matched controls), all enculturated to Western tonal music, took part in the study for modest monetary compensation. All participants were recruited by means of an online test that included the scale subtest of the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003). Participants were considered for the study if they completed the test twice and scored in the amusic (22/30 or less) or normal range and reported an absence of any neurological, psychiatric disorder or dyslexia. Further on-site testing comprised four MBEA subtests (scale, contour, interval and rhythm) to confirm the presence or absence of congenital amusia. Due to the fact that previous research has shown that congenital amusia is primarily characterized by poor performance in the pitch-based subtests of the MBEA (scale, contour and interval) (Peretz et al., 2003), a composite score was calculated for the three pitch-based subtests, using 65 as a cut-off score, i.e., the sum of the cut-off scores for the three subtests (Peretz et al., 2003). Amusic individuals were defined as those participants who had a pitch-composite score of 65 or less.

The following background measures were used to match amusic individuals and controls: age, sex, handedness, years of education, years of musical training, National Adult Reading Test (NART, Nelson and Willison (1991)), and digit span tests (Wechsler, 1997). In addition, participants completed two pitch threshold tasks, namely a pitch change detection task and a pitch direction discrimination task (see Liu et al. (2010), Williamson and Stewart (2010) for further details). Table 1 provides background information on the two groups, whereas Table 2 provides scores on the MBEA subtests and pitch thresholds. The two groups performed significantly differently in all three MBEA pitch-based subtests, the MBEA rhythm subtest and the pitch direction discrimination task. The results further revealed that amusic individuals had higher pitch direction discrimination thresholds than controls.

To ensure that poor performance on the MBEA or on the affective evaluation tasks was not due to hearing loss, hearing tests were administered. Pure tone thresholds were determined using a manually operated Amplivox 2160 pure tone diagnostic audiometer and following a standardized procedure for the measurement of hearing thresholds. Participants were required to have a mean hearing level, in at least one ear, of less than or equal to 20 dB HL, as measured at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz. These frequencies covered the range of frequencies used in the listening tasks. One amusic individual and one control did not fulfil this criterion. However, data inspection revealed that these two participants were not outliers in any of the tasks; therefore, we decided not to exclude them from the sample and the main analyses. The two groups did not differ in their hearing abilities.

2.2. Materials

The auditory stimuli were created by means of Sibelius 6 (Avid Technology, Inc.) and Audacity 1.3.11 software. For the two tasks involving pleasantness ratings of dyads varying in consonance/dissonance, tone combinations of two pitches, ranging between 1 and 12 semitones in interval size, were built from single tones of the equal-tempered scale (A4=440 Hz). Each of these 12 intervallic dyads i.e., minor second (m2), major second (M2), minor third (m3), major third (M3), perfect fourth (P4), tritone (Tri), perfect fifth (P5), minor sixth (m6), major sixth (M6), minor seventh (m7), major seventh (M7) and the octave (P8) was constructed above one of 4 lower pitches (G3, Bb3, C#4, or E4), resulting in a set of 48 dyads. The length of each dyad was 1.5 s, including a 25 ms fade in and a 25 ms fade out. Two sets of 48 dyads, one built from sine tones and the other built from complex

Table 1
Amusic and control participant characteristics I. Summary of the two groups in terms of their mean age, sex, handedness, years of musical training and education, NART and total digit span (forward and backward).

Group	Age	Sex	Handedness	Yrs. musical training	Yrs. education	NART	Digit span
Amusic							
M	49.53	8 F	12 R	.92	16.31	40.69	20.38
SD	13.00	5 M	1 L	2.06	2.81	4.5	3.97
Control							
M	47.54	8 F	12 R	1.38	16.23	43.69	21.08
SD	11.24	5 M	1 L	1.89	2.00	4.23	3.45
t-tests							
t	.420			−.595	.080	−1.752	−.475
p	.678			.558	.937	.093	.639

Note. M=mean, *SD*=standard deviation, F=female, M=male, R=right, L=left, *t*=test statistic of the independent samples *t*-test, *p*=calculated probability, Yrs.=years, all *dfs*=24. Mann–Whitney *U*-tests revealed a similar pattern of results.

Table 2
Amusic and control participant characteristics II. Mean scores on the Montreal Battery of Amusia (MBEA): scale, contour, interval and rhythm and on two pitch threshold tasks (pitch change detection, pitch direction discrimination).

Group	MBEA scale	MBEA contour	MBEA interval	MBEA rhythm	MBEA pitch composite	Pitch change detection threshold [ST]	Pitch direction discrimination threshold [ST]
Amusic							
M	19.46	20.46	18.23	25.54	58.15	.19	.84
SD	2.93	2.79	2.49	3.62	6.35	.08	.82
Control							
M	27.61	27.85	27.54	28.85	83.00	.16	.17
SD	2.21	2.15	2.37	.90	5.39	.06	.08
t-tests							
t	−7.99	−7.56	−9.78	−.320	−10.76	1.23	2.95
p	<.001	<.001	<.001	.007	<.001	.231	.012

Note. *M*=mean, *SD*=standard deviation, *t*=test statistic of the independent samples *t-test*, *p*=calculated probability, ST=semitone; all *dfs*=24. The pitch composite score is the mean score based on the scale, contour and interval subtests of the MBEA. The maximum score for each subtest is 30. The cut-off score to be considered as congenitally amusic is 22 or less for the scale, contour and interval MBEA subtests and 65 for the pitch composite score (Peretz et al., 2003). Mann–Whitney *U*-tests revealed a similar pattern of results.

tones in piano timbre (Sibelius Sounds Essentials, Steinway piano sound), were created. Both sets were globally normalised at the mean intensity level of all original dyads of each set using the software Adobe Audition 3.0. Mean root-mean square normalisation was performed, such that the average intensity was the same for all dyads in each set. In a similar vein, 12 major and 12 minor triads in root position (i.e. a chord which has the root [fundamental] as the lowest note and two thirds stacked on top of it) were created using a range of chord roots encompassing G3 to F#4. The triads were 1.5 s long. Each triad was also built from either sine or complex tones in piano timbre, resulting in two sets of 24 triads that were equalized for intensity as described above.

2.3. Procedure

The experiment was conducted in a sound-attenuated booth, and sounds were presented through an external sound card (Edirol UA-4FX USB Audio Capture) at a fixed loudness level of 73 dB SPL (C-weighted, peak) using Sennheiser headphones HD 202. The programs for stimulus presentation and the collection of ratings were written in Matlab 7.1 (The Mathworks, Inc., Natick, Massachusetts, United States). Prior to the experiment, participants gave written consent to participate in the experiments, according to the Declaration of Helsinki. The study was approved by the Ethics Committee of Goldsmiths, University of London (UK).

Participants completed four tasks varying in the type of presented sounds (dyads or triads) and in the composition of these sounds (sine tones or complex tones). We collected pleasantness ratings of dyads and happy/sad ratings of triads (in both cases with separate blocks for sine tones and complex tones). We considered it as crucial to block sounds of the same type to ensure that participants' affective responses to variations in consonance/dissonance and major/minor chord quality were measured, rather than responses to differences between sine and complex tones per se. The order of the tasks involving either dyads or triads was counterbalanced across participants. Within each condition (dyads or triads), the order of blocks involving different tone-types (sine tones or complex tones) was also counterbalanced across participants. A subsequent analysis showed that block order did not significantly affect ratings of dyads and triads.

In the tasks involving the presentation of dyads, each trial started 5 s after the appearance of a text indicating that the next sound would start shortly. Participants were asked to indicate whether the stimulus was pleasant or unpleasant. After stimulus presentation, participants indicated their ratings via a 7-point Likert scale (1=very unpleasant, 4=neutral, 7=very pleasant) by clicking on the appropriate button on the screen. In general, the procedure of the tasks involving the presentation of triads was the same as that used for the dyads, except that participants were asked to indicate whether the sound was happy or sad via a 7-point Likert scale (1=more sad, 4=neutral, 7=more happy). For each of the four tasks, two practice trials were run to familiarise participants with the procedure. There was no time limit associated with the ratings. The completion of all four tasks took around 20 min.

2.4. Statistical and acoustical analyses

Statistical analyses were conducted using IBM Statistics SPSS 20. Unless otherwise indicated, all assumptions for the statistical tests were fulfilled and the alpha level was set to.05. All statistical tests were run as two-tailed tests and the Bonferroni–Holm correction (Holm, 1979) was applied in order to control for multiple comparisons. In case of non-normal distributions of data, non-parametric correlation analyses were used. In such cases Kendall tau rank correlations were used because the sample size was small (Field, 2009). In repeated-measures ANOVAs, Greenhouse–Geisser corrections were applied as appropriate. For *t*-tests, effect sizes were estimated as a function of the observed *t*-value and the degrees of freedom on which it is based, $r=\sqrt{(t^2/(t^2+df))}$ (Rosenthal, 1991, p. 19). The effect size thresholds of *r* are as follows: small: $r=.1$; medium: $r=.3$; large: $r=.5$, and very large: $r=.7$. If effect sizes are reported using Cohen's *d* (Cohen, 1988), the thresholds are as follows: small: $d=.2$; medium: $d=.5$; large: $d=.8$, and very large: $d=1.3$. Assumptions for multiple linear regression analyses were checked following conventional methods and comprised the absence of multicollinearity between predictors (determined by checking the correlation matrix ($r<.8$) and the variance inflation factor), the homoscedasticity of the errors, independent and normally distributed errors, as well as the linear relationship between predictors and the outcome variable (Field, 2009).

The perceptual roughness of the sounds was estimated using an algorithm developed by Vassilakis and Fitz (2008) [http://musicalgorithms.ewu.edu/algorithms/roughness.html], based on a model developed by Vassilakis (2005, 2007). Here, we computed the mean roughness over the entire duration of the stimuli by averaging over the roughness values obtained every 20 ms, using a frequency resolution of 10 Hz and no amplitude normalization. Harmonicity was calculated using the harmonics-to-noise ratio (HNR), which represents the degree of acoustic periodicity, or the amount of acoustic energy found in the periodic part of the signal. Because HNR is based on a single pitch or fundamental frequency f_0, it corresponds to the amount of energy found in partials (or overtones) whose frequencies are integer multiples of f_0, a definition which is consistent with the use of the term “harmonicity” in McDermott et al. (2010) and Cousineau et al. (2012). In this study, HNR values (in dB) obtained using the algorithm developed by Boersma (1993) were converted to a harmonicity index corresponding to the percentage of energy found in the periodic part of the signal.

3. Results

Results for affective judgements are presented in the following way: first, we computed the inter-rater reliability of ratings to assess whether the two groups (amusics and controls) gave reliable and consistent ratings. Second, we assessed the similarity of controls' and amusics' rating profiles across all types of dyads. Third, we grouped the types of dyads into consonant versus dissonant tone combinations and used ANOVA to compare pleasantness ratings for these two categories, as a function of group (amusics versus control), and tone type (sine-tone versus complex-tone). Fourth, to ascertain that the effects we observed were not due to pitch height, which covaried for each stimulus, we also assessed effects of pitch height on affective ratings (Ilie and Thompson, 2006). Fifth, we computed linear regression models with roughness and harmonicity values as predictors to examine whether acoustical parameters predict affective ratings to a similar or different degree in amusics and controls. This analysis was performed separately for each task, tone type and group. Lastly, we present an analysis of the relationships between affective sensitivity and pitch-related measures used to describe amusic individuals as well as questionnaire and experimental data on timbre perception (Marin et al., 2012).

3.1. Pleasantness ratings of dyads

Inter-rater reliability of pleasantness ratings for sine- and complex-tone dyads was assessed by means of intraclass correlations (McGraw and Wong, 1996; Shrout and Fleiss, 1979), in which class refers to the group of raters (i.e. the group of amusics and controls, respectively) and raters to all members of a class. Two types of intraclass correlation coefficients (two-way random effects model, type consistency) are reported in Table 3: the single measure ICCs refer to the reliability of an individual rater i.e., the level of consensus and consistency of a randomly selected rater from the population of raters in comparison to the mean score obtained from the sample of raters (Bliese, 2000), whereas the average measure ICCs refer to the reliability of the mean of the raters i.e., the level of consensus and consistency of two sets of means if a new set of raters evaluated a new set of targets (James, 1982). Both single and average ICC measures were lower for the amusic group than for the control group. However, for single ICC measures, which can also be interpreted as a measure of effect size revealing the extent to which individual ratings are attributable to group membership, we observed a medium effect for the sine-tone condition and a large effect for the complex-tone condition in the amusic group (following the traditional convention when interpreting effect sizes, i.e. percentage of variance explained, see Murphy and Myors (1998)). Similarly, the current data suggests that average ICC measures of both tone conditions for the amusic group exceeded Nunnally's (1978) cut-off point of .7 (indicating that 70% of the variance of raters' judgments is systematic). Taken together, these findings suggest that amusic individuals showed significantly above-chance agreement with regard to pleasantness ratings of dyads.[1]

Table 3
Intraclass correlation coefficients (ICCs) for pleasantness ratings of 12 conditions of sine-tone and complex-tone dyads varying in consonance/dissonance.

Group	ICC(2,13) Sine tones average	ICC(2,1) Sine tones single	ICC(2,13) Complex tones average	ICC(2,1) Complex tones single
Amusic	$r=.72$	$r=.17$	$r=.87$	$r=.34$
	CI [.41, .90]	CI [.05, .42]	CI [.73, .96]	CI [.17, .62]
Control	$r=.94$	$r=.56$	$r=.97$	$r=.74$
	CI [.88, .98]	CI [.36, .79]	CI [.95, .99]	CI [.57, .90]

Note. ICC(2,k)=two-way random average measure, type consistency, ICC(2,1)= two-way random single measure, type consistency, CI=95% confidence interval.

Having established that amusic individuals show a pattern of responses that is consistent, we next computed the average pleasantness ratings in response to sine-tone and complex-tone dyads varying in consonance/dissonance. A repeated-measures ANOVA with type of dyad (12 levels) and tone type (sine vs. complex) as within-subjects factors and group (amusic vs. control) as between-subjects factor was computed. We observed a significant main effect of type of dyad, $F(4.21, 101.02)=41.39$, $p<.001$, $\eta_p^2=.63$, and a significant interaction between type of dyad and group, $F(4.21, 101.02)=10.42$, $p<.001$, $\eta_p^2=.30$. There was also a main effect of tone type, $F(1, 24)=4.88$, $p=.037$, $\eta_p^2=.17$, suggesting that complex tones ($M=4.03$, $SE=.10$) were rated higher in pleasantness than sine-tones ($M=3.68$, $SE=.11$), but no significant interaction between group and tone type, $F(1, 24)=.01$, $p=.909$, $\eta_p^2=.001$. The interaction between tone type and type of dyad was significant, $F(6.15, 147.47)=6.19$, $p<.001$, $\eta_p^2=.21$. The three-way interaction between type of dyad, tone type and group was not significant, $F(6.15, 147.47)=1.43$, $p=.20$, $\eta_p^2=.056$. The main effect of group was not significant, $F(1, 24)=1.97$, $p=.173$, $\eta_p{}^2=.08$.

Supplementary Fig. A.1 shows the significant interaction between type of dyad and group. The range of pleasantness ratings of the 12 dyads is smaller in amusics (min.=2.97, max.=3.99) than in controls (min.=2.03, max.=4.80). Interestingly, amusics and controls generally did not differ in terms of their rank ordering of dyads regarding pleasantness ratings. In other words, in both groups, dyads traditionally regarded as dissonant, such as the major and minor seconds, were rated as unpleasant, whereas dyads traditionally regarded as consonant, such as the major third or major sixth, were rated as pleasant. This supports the view that amusic individuals were sensitive to differences in consonance and dissonance. The observed interaction between tone type and type of dyad regarding pleasantness ratings of dyads may be explained by the fact that the rank ordering of these ratings differed between the two tone types (sine-tone dyads: m2 < M2 < M7 < P8 < m7 < Tri < M6 < m6 < m3 < P5 < P4 < M3; complex-tone dyads: m2 < M2 < M7 < m7 < Tri < m6 < m3 < P4 < M3 < P5 < M6 < P8). In contrast to the complex-tone octave, the sine-tone octave was not rated as the most pleasant dyad. Instead, the major third and perfect fourth were rated as most pleasant among sine-tone dyads, which was not the case for complex-tone dyads. Another difference concerns the major sixth, which was rated as comparatively more pleasant in complex-tone dyads than in sine-tone dyads.

To make our results comparable to previously reported results on pleasantness ratings of sounds varying in consonance/dissonance in controls and amusic individuals (Cousineau et al., 2012; McDermott et al., 2010), we plotted profiles of pleasantness ratings

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[1] To compare with previous data (Cousineau et al., 2012), Kendall's coefficients of concordance (W), usually used for ranked data, are presented here. Sine-tone dyads: amusics ($W=.49$, $\chi^2=70.46$), controls ($W=.25$, $\chi^2=35.32$); complex-tone dyads: amusics ($W=.56$, $\chi^2=80.92$), controls ($W=.38$, $\chi^2=55.1$).

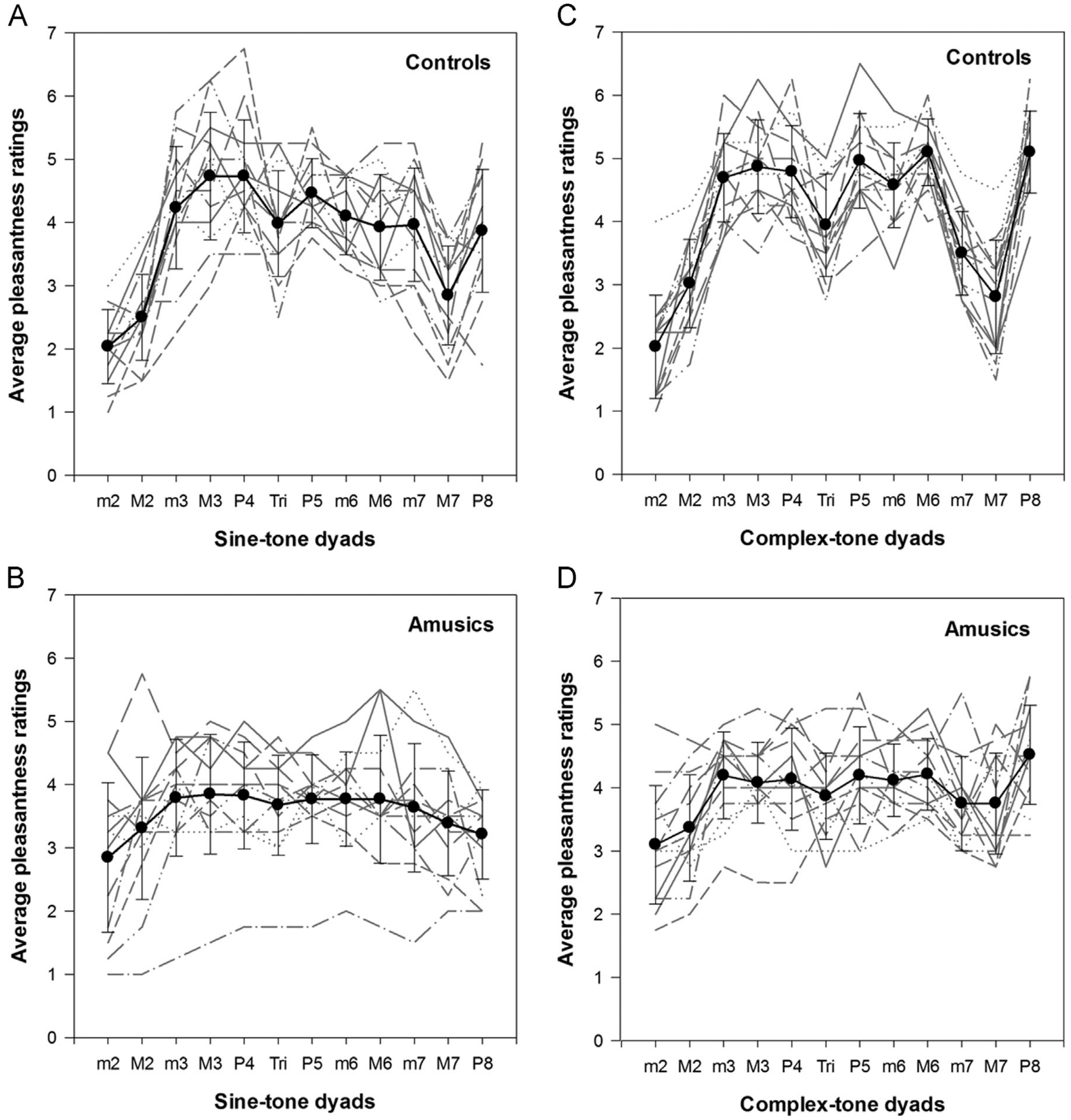

Fig. 1. Average (black) and individual (grey) pleasantness ratings of dyads by the control and amusic groups. Dyads contained two sine tones (A, B) or complex tones in piano timbre (C, D) separated by an integer number of semitones. Error bars denote one standard deviation.

of dyads, separately for each group and tone type (Fig. 1). For control participants, the profile of pleasantness ratings in response to sine-tone dyads follows the expected pattern of significantly lower pleasantness ratings for dissonant dyads (minor second, major second and major seventh) than the median rating and higher pleasantness ratings for consonant dyads, such as the minor and major thirds, as well as the perfect fourth and fifth, as shown in Fig. 1A. However, the data revealed that the octave, which was not rated higher than the median rating, was also not rated as higher in pleasantness than the minor third, the tritone, the minor and major sixths as well as the minor seventh. Interestingly, the tritone was not rated as particularly unpleasant (see McDermott et al. (2010) for a similar result) (see Table 4 for more details).

For amusic individuals, the profile of pleasantness ratings in response to sine-tone dyads varied to a much lesser degree, as shown in Fig. 1B and Table 4. Except for the minor second and the octave, which received significantly lower pleasantness ratings than the median, all other dyads were rated as neutral and similar in pleasantness. Fig. 1B further shows that one amusic individual perceived sine-tone dyads as very unpleasant compared to all other amusic individuals.

Turning to consider the profile of responses for complex-tone dyads, for controls the profile of pleasantness ratings for dyads in piano timbre (Fig. 1C) generally resembles the profile in response to sine-tone dyads (Fig. 1A) (see also McDermott et al., 2010). However, ratings for the minor and major sixths as well as for the minor sevenths, which were similar for sine-tone dyads, clearly differed from each other and the minor seventh received lower ratings in pleasantness compared to the major and minor sixths. Except for the tritone, all other types of dyads were rated significantly above or below the median rating (Table 4).

The profile of pleasantness ratings in response to complex-tone dyads for amusics generally resembled that of controls (with the

Table 4
Comparison of the mean pleasantness ratings for each sine-tone and complex-tone dyad with the median rating score by single sample *t*-tests.

Group		Sine tones				Complex tones			
		Mean pleasantness rating (*SD*)	*t*	*p*	Cohen's *d*	Mean pleasantness rating (*SD*)	*t*	*p*	Cohen's *d*
Amusic	**m2**	**2.85 (1.18)**	**−.351**	**.004***	**.97**	3.10 (.94)	−3.47	.005	.96
Control	**m2**	**2.04 (.58)**	**−12.09**	**<.001***	**3.38**	**2.02 (.82)**	**−8.72**	**<.001***	**2.41**
Amusic	M2	3.31 (1.12)	−2.22	.046	.62	3.37 (.84)	−2.73	.018	.75
Control	**M2**	**2.50 (.68)**	**−7.99**	**<.001***	**2.21**	**3.02 (.70)**	**−5.08**	**<.001***	**1.4**
Amusic	m3	3.79 (.92)	−.83	.425	.23	4.19 (.69)	1.01	.332	.28
Control	m3	4.23 (.97)	.86	.408	.24	**4.69 (.70)**	**−3.56**	**.004***	**.99**
Amusic	M3	3.85 (.94)	−.59	.568	.16	4.08 (.64)	.43	.673	.13
Control	M3	4.73 (1.00)	2.62	.023	.73	**4.87 (.74)**	**4.22**	**.001***	**1.18**
Amusic	P4	3.83 (.84)	−.74	.474	.20	4.13 (.81)	.60	.559	.16
Control	P4	4.73 (.89)	2.95	.012	.82	**4.79 (.73)**	**3.91**	**.002***	**1.08**
Amusic	Tri	3.67 (.79)	−1.49	.163	.42	3.87 (.68)	−.71	.490	.19
Control	Tri	3.98 (.84)	−.08	.935	.02	3.94 (.81)	−.26	.802	.07
Amusic	P5	3.77 (.70)	−1.18	.260	.33	4.19 (.76)	.91	.382	.25
Control	P5	4.46 (.55)	3.04	.010	.84	**4.96 (.75)**	**4.63**	**.001***	**1.28**
Amusic	m6	3.77 (.75)	−1.12	.287	.31	4.12 (.57)	.73	.482	.21
Control	m6	4.10 (.61)	.57	.579	.16	4.58 (.67)	**3.10**	**.009***	**.87**
Amusic	M6	3.77 (1.01)	−.82	.427	.23	4.21 (.57)	1.35	.203	.37
Control	M6	3.92 (.84)	−.33	.746	.10	**5.10 (.52)**	**7.52**	**<.001***	**2.12**
Amusic	m7	3.63 (1.01)	−1.30	.218	.37	3.75 (.74)	−1.21	.248	.34
Control	m7	3.96 (.89)	−.16	.879	.04	3.50 (.66)	**−2.73**	**.018***	**.76**
Amusic	M7	3.38 (.83)	−2.68	.020	.75	3.75 (.80)	−1.13	.280	.31
Control	**M7**	**2.85 (.78)**	**−5.33**	**<.001***	**1.47**	**2.81 (.90)**	**4.80**	**<.001***	**1.32**
Amusic	**P8**	**3.21 (.71)**	**−4.03**	**.002***	**1.11**	4.52 (.79)	2.38	.035	.66
Control	P8	3.87 (.97)	−.50	.626	.13	**5.10 (.65)**	**6.10**	**<.001***	**1.69**

Note. **p* significant at alpha = .05 after Bonferroni–Holm correction was applied. All *dfs* = 12. Values in bold indicate dyads with mean pleasantness ratings significantly lower or higher than the median (4 in all cases) computed on all trials per group and condition. Pleasantness ratings range from 1 (*very unpleasant*) to 7 (*very pleasant*). *SD* = standard deviation, *t* = test statistic of the one sample *t*-test, *p* = calculated probability, m2 = minor second, M2 = major second, m3 = minor third, M3 = major third, P4 = perfect fourth, Tri = tritone, P5 = perfect fifth, m6 = minor sixth, M6 = major sixth, m7 = minor seventh, M7 = major seventh, P8 = octave.

exception of lower ratings for the major and minor sevenths in controls) (Fig. 1D). The amusic group thus clearly showed sensitivity to differences between dissonance and consonance when complex-tone dyads were rated, but they distinguished less accurately between consonant and dissonant dyads. Similar to the sine-tone condition, amusic individuals rated the minor and major seconds as less pleasant than other dyads. Interestingly, the octave received the highest pleasantness ratings, which we interpret as evidence for sensitivity to high consonance (Table 4). Even though differences from the median were not always significant after applying the Bonferroni–Holm correction, effect sizes (Cohen's *d*) suggest large effects with respect to the minor and major seconds and a medium effect for the octave.

In a subsequent step, the twelve dyads were categorized into consonant and dissonant dyads, following Helmholtz (1863/1954) definition of consonant dyads as tones having one or more overtones (excluding the seventh or ninth overtones) in common. This analysis enabled a more global assessment of the perception of consonance and dissonance. Thus, consonant dyads comprised the minor third, the major third, the perfect fourth, the perfect fifth,

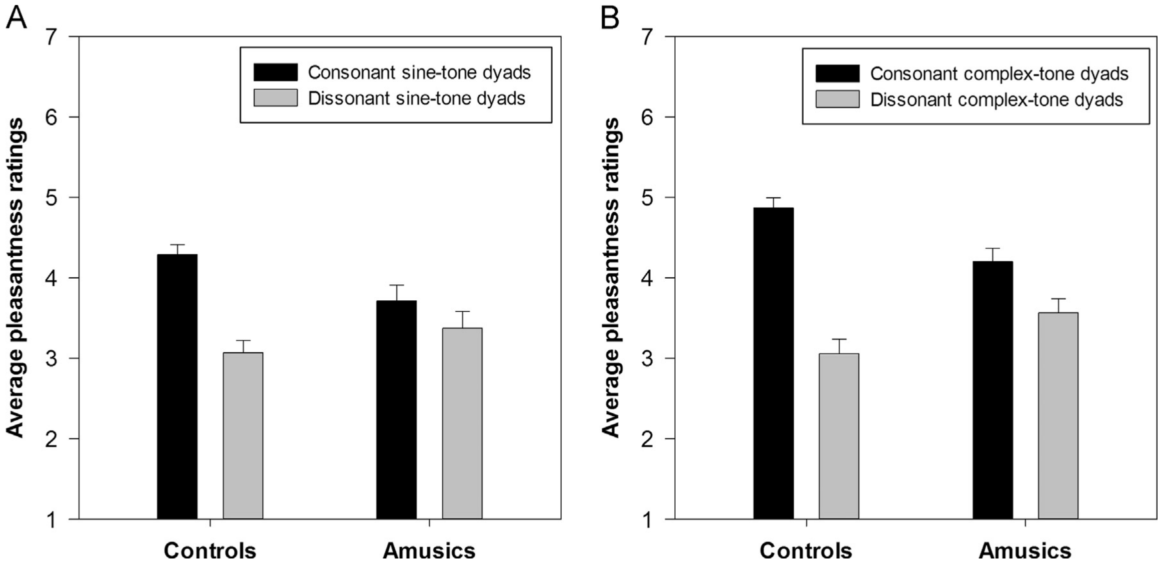

Fig. 2. Average pleasantness ratings of sine-tone (A) and complex-tone dyads (B), separately given for consonant and dissonant dyads. Error bars denote one standard error of the mean.

the minor sixth, the major sixth and the octave (m3, M3, P4, P5, m6, M6, and P8). All other dyads were defined as dissonant dyads (m2, M2, Tri, m7 and M7). For each category, mean ratings were calculated for sine- and complex-tone dyads, respectively.

A repeated-measures ANOVA with tone type (sine vs. complex) and degree of consonance/dissonance (consonant vs. dissonant) as within-subject factors and group (control vs. amusic) as between-subjects factor revealed a significant main effect of degree of consonance/dissonance (Fig. 2), $F(1, 24)=98.73$, $p<.001$, $\eta_p^2=.80$, and a significant interaction between group and degree of consonance/dissonance, $F(1, 24)=25.77$, $p<.001$, $\eta_p^2=.52$, as well as a significant interaction between tone type and degree of consonance/dissonance, $F(1, 24)=21.69$, $p<.001$, $\eta_{p^2}=.48$. There was a marginal effect of tone type, $F(1, 24)=3.84$, $p=.062$, $\eta_{p^2}=.14$. Neither the main effect of group, $F(1, 24)=.60$, $p=.448$, $\eta_p^2=.024$, nor the interaction between tone-type and group, $F(1, 24)=.04$, $p=.852$, $\eta_p^2=.001$, reached significance. The interaction between degree of consonance, tone type and group was not significant, $F(1, 24)=2.28$, $p=.144$, $\eta_p^2=.09$. This pattern of results was identical when the amusic individual who gave low pleasantness ratings in response to sine-tone dyads was removed from the analysis.

A closer inspection of the interaction between group and degree of consonance/dissonance revealed that controls ($M=4.58$, $SE=.11$) reported higher ratings of pleasantness in response to consonant dyads than amusics ($M=3.96$, $SE=.13$), $t(24)=-3.95$, $p=.002$ (corrected p-values according to Bonferroni–Holm), $r=.62$, but amusics ($M=3.47$, $SE=.13$) reported higher pleasantness in response to dissonant dyads than controls ($M=3.06$, $SE=.13$), $t(24)=2.18$, $p=.039$, $r=.41$. Amusics showed sensitivity to the difference between consonant and dissonant dyads in general, $t(12)=4.02$, $p=.002$, $r=.75$. Taken together, these findings provide support for the hypothesis that amusics are sensitive to the difference between consonance and dissonance in dyads of two tone types, but that amusics find consonant and dissonant dyads to differ less in terms of pleasantness than controls. This reduced differentiation in amusics is not only due to lower pleasantness ratings in response to consonant dyads, but also to higher pleasantness ratings in response to dissonant dyads.

The interaction between tone type and degree of consonance/dissonance was due to the fact that consonant complex-tone dyads ($M=4.54$, $SE=.10$) were rated as more pleasant than consonant sine-tone dyads ($M=4.00$, $SE=.12$), $t(25)=-3.46$, $p=.004$, $r=.57$, whereas the ratings of complex-tone ($M=3.31$, $SE=.13$) and sine-tone dyads ($M=3.22$, $SE=.13$) did not differ for dissonant dyads, $t(25)=-.54$, $p=.594$, $r=.11$.

In order to test whether changes in pitch height affected pleasantness ratings differently in the two groups, the dyads were grouped into four pitch categories (low, lower intermediate, higher intermediate and high). For each tone type, data for the 12 types of dyads were averaged according to their base pitch (G3, Bb3, C#4, E4) in order to keep variations of consonance/dissonance constant with respect to pitch height. A repeated-measures ANOVA with pitch height (low, lower intermediate, higher intermediate and high) as within-subject factor and group (control vs. amusic) as between-subjects factor was computed on the ratings of sine-tone and complex-tone dyads. For sine-tone dyads (Supplementary Fig. A.2A), there was no significant main effect of pitch height, $F(1.29, 20.93)=.91$, $p=.371$, $\eta_p^2=.04$, no significant interaction between group and pitch height, $F(1.29, 20.93)=.50$, $p=.531$, $\eta_p^2=.02$, and finally, no significant main effect of group, $F(1, 24)=.89$, $p=.356$, $\eta_p^2=.04$. For complex-tone dyads (Fig. A.2B), higher dyads were rated as more pleasant, $F(1.65, 39.28)=23.28$, $p<.001$, $\eta_p^2=.49$, but there was no interaction between group and pitch height, $F(1.65, 39.28)=1.44$, $p=.238$, $\eta_p^2=.06$, and no main effect of group, $F(1, 24)=.80$, $p=.379$, $\eta_p^2=.03$.

Table 5
Mean roughness (Vassilakis and Fitz, 2008) and harmonicity values (harmonicity index corresponding to the percentage of energy found in the periodic part of the signal) for sine-tone and complex-tone dyads and triads.

	Type	Sine tones		Complex tones	
		Mean roughness (*SD*)	Mean harmonicity [%] (*SD*)	Mean roughness (*SD*)	Mean harmonicity [%] (*SD*)
Dyad	m2	6.92 (.57)	98.62 (.30)	18.80 (3.50)	93.01 (1.35)
Dyad	M2	6.81 (.45)	97.98 (.90)	13.42 (4.89)	92.15 (1.30)
Dyad	m3	5.02 (.91)	98.56 (.22)	12.58 (4.96)	93.67 (2.09)
Dyad	M3	3.19 (1.04)	99.37 (.22)	9.93 (2.18)	96.83 (.70)
Dyad	P4	1.88 (.85)	99.97 (.03)	9.58 (2.91)	98.60 (.48)
Dyad	Tri	1.03 (.57)	98.28 (.53)	10.02 (2.39)	93.67 (2.25)
Dyad	P5	.54 (.36)	99.99 (.01)	7.91 (3.79)	99.08 (.44)
Dyad	m6	.27 (.21)	98.53 (.79)	10.76 (4.26)	94.17 (3.34)
Dyad	M6	.13 (.12)	99.37 (.28)	9.17 (3.58)	97.50 (.99)
Dyad	m7	.06 (.06)	97.77 (.61)	8.70 (4.00)	95.00 (3.53)
Dyad	M7	.03 (.03)	97.40 (.24)	8.11 (4.01)	95.12 (4.23)
Dyad	P8	.01 (.01)	99.99 (.02)	4.98 (2.86)	99.59 (.30)
Triad	Major triad	6.69 (1.95)	99.14 (.28)	15.81 (5.45)	96.73 (.67)
Triad	Minor triad	6.97 (1.85)	96.82 (1.34)	17.73 (6.86)	92.43 (.78)

Note. Descriptive statistics per type of dyad are based on four trials varying in pitch height, those for triads on twelve trials. *SD*=standard deviation. *SDs* are generally higher for complex tones due to register effects. m2=minor second, M2=major second, m3=minor third, M3=major third, P4=perfect fourth, Tri=tritone, P5=perfect fifth, m6=minor sixth, M6=major sixth, m7=minor seventh, M7=major seventh, P8=octave.

3.2. Relationship between acoustical parameters and pleasantness ratings of dyads

To assess how the acoustical parameters of roughness and harmonicity (see Table 5 for descriptive statistics and Supplementary Fig. A.4) were associated with pleasantness ratings of dyads, linear regression models (forced entry, i.e., both predictors were forced into the model simultaneously) were fitted to the data, based on the average ratings per dyad calculated for each group separately. First, correlations between subjective ratings and acoustical parameters are reported for sine-tone dyads, initially for controls and then for amusics, followed by linear regression models calculated for each group. Then, the same analysis is presented for complex-tone dyads.

Pleasantness ratings of sine-tone dyads showed a significant negative correlation with roughness in controls, $r(46)=-.47$, $p=.001$, and in amusics, $r(46)=-.37$, $p=.01$. On the other hand, pleasantness ratings were significantly positively correlated with harmonicity in controls, $r(46)=.47$, $p=.001$, but not significantly in amusics, $r(46)=.13$, $p=.37$. The sine-tone dyads' roughness and harmonicity values were not significantly associated with each other, $r(46)=-.15$, $p=.32$. For controls, roughness, $b=-.42$, $t(45)=-3.51$, $p=.001$, as well as harmonicity, $b=.41$, $t(45)=3.44$, $p=.001$, were significant predictors of pleasantness ratings and yielded a significant model, $F(2, 45)=14.13$, $p<.001$, adjusted $R^2=.36$. For amusics, only roughness, $b=-.36$, $t(45)=-2.54$, $p=.015$, but not harmonicity, $b=.08$, $t(45)=.57$, $p=.572$, was a significant predictor in the model, $F(2, 45)=3.68$, $p=.033$, adjusted $R^2=.10$.

The acoustical measures of roughness and harmonicity showed a significant negative correlation for complex-tone dyads, $r(46)=-.68$, $p<.001$. In controls, we found a significant negative

Table 6
Intraclass correlation coefficients (ICCs) for happiness/sadness ratings of two conditions of sine-tone and complex-tone triads varying in modality (major vs. minor).

Group	ICC(2,13) Sine tones average	ICC(2,1) Sine tones single	ICC(2,13) Complex tones average	ICC(2,1) Complex tones single
Amusic	$r = -3.38$ CI [−27.7, 1.0] (not reliable)	$r = -.06$ CI [−.08,.95] (not reliable)	$r = .83$ CI [−.10, 1.0]	$r = .28$ CI [−.006, 1.00]
Control	$r = .84$ CI [−.04, 1.0]	$r = .29$ CI [−.003, 1.0]	$r = .97$ CI [.82, 1.0]	$r = .73$ CI [.26, 1.0]

Note. ICC(2,k)=two-way random average measure, type consistency, ICC(2,1)= two-way random single measure, type consistency, CI=95% confidence interval.

association between pleasantness ratings and roughness $r(46) = -.60$, $p < .001$, and a significant positive association for harmonicity, $r(46) = .58$, $p < .001$. In amusics, the direction of the associations was similar, with a significant negative correlation for roughness, $r(46) = -.80$, $p < .001$, and a significant positive one for harmonicity, $r(46) = .64$, $p < .001$. Pleasantness ratings of controls were significantly predicted by roughness, $b = -.38$, $t(45) = -2.46$, $p = .018$, and harmonicity, $b = .32$, $t(45) = 2.08$, $p = .043$, which led to a significant model, $F(2, 45) = 15.90$, $p < .001$, adjusted $R^2 = .39$. In amusics, roughness was a significant predictor, $b = -.68$, $t(45) = -5.81$, $p < .001$, whereas harmonicity was not, $b = .18$, $t(45) = 1.57$, $p = .124$, yielding a significant regression model, $F(2, 45) = 44.60$, $p < .001$, adjusted $R^2 = .65$. In sum, these findings show that roughness and harmonicity were able to predict pleasantness ratings in response to sine- and complex-tone dyads in controls, but only roughness was a significant predictor in amusics.

3.3. *Happiness/sadness ratings of triads*

Inter-rater reliability and agreement were first assessed by calculating ICCs for the two conditions of chord quality (major vs. minor), separately for each type of triad (sine-tone vs. complex-tone). In the sine-tone condition, ICC results were not reliable for amusics (i.e., the analysis revealed negative ICC values). However, ICC values for the complex-tone condition were satisfactorily high in both groups. Overall, these analyses suggest that amusic individuals did not provide random ratings of perceived happiness or sadness in response to complex-tone triads (Table 6).[2]

A repeated-measures ANOVA with chord quality (major vs. minor) and tone type (sine-tone vs. complex-tone) as within-subject factors and group (control vs. amusic) as a between-subjects factor revealed a significant main effect of chord quality, $F(1, 24) = 23.89$, $p < .001$, $\eta_p^2 = .50$, indicating that major triads ($M = 4.09$, SE=.09) were rated as happier than minor triads ($M = 3.56$, SE=.08). There was also a significant interaction between chord quality and group, $F(1, 24) = 9.66$, $p = .005$, $\eta_p^2 = .29$, and a marginal effect of tone type (sine-tone vs. complex-tone), $F(1, 24) = 4.14$, $p = .053$, $\eta_p^2 = .15$. There was also a significant main effect of group, $F(1, 24) = 6.84$, $p = .015$, $\eta_p^2 = .22$, suggesting that controls ($M = 4.00$, SE=.08) gave higher ratings of happiness than amusics across all stimulus conditions ($M = 3.67$, SE=.08) (see Fig. 3). The interaction between chord quality and tone type was not significant, $F(1, 24) = 3.07$, $p = .09$, $\eta_p^2 = .11$. Neither the interaction between group and tone type, $F(1, 24) = 1.05$, $p = .317$, $\eta_p^2 = .04$, nor the interaction between chord quality, tone type and group, $F(1, 24) = .004$, $p = .952$, $\eta_p^2 = .00$, were significant.

The interaction between chord quality and group revealed that major triads were assigned significantly higher ratings of happiness by controls ($M = 4.41$, SE=.12) than by amusic individuals ($M = 3.76$, SE=.12), $t(24) = -3.78$, $p = .002$, $r = .61$, but that ratings of controls ($M = 3.53$, SE=.11) and amusics ($M = 3.57$, SE=.10) were similar for minor triads, $t(24) = .24$, $p = .815$, $r = .05$. Further within-group comparisons showed that controls rated major triads as significantly happier than minor triads ($M = 3.53$, SE=.11), $t(12) = 4.49$, $p = .002$, $r = .79$. In the group of amusics, the difference in happiness ratings for major and minor triads was marginally significant, $t(12) = 1.95$, $p = .075$, $r = .49$.

The current data may suggest some sensitivity to the association between major/minor chord quality and happiness in amusic individuals. For example, the effect size of the difference between ratings for major and minor triads in the group of amusics was moderate (close to the benchmark of a large effect) and nearly reached the level of significance. Considering complex and sine tone stimuli separately, it should be noted that results on the comparison of happiness/sadness ratings of major and minor complex-tone triads (Fig. 3B) also showed a large effect size in both groups (Bonferroni corrected; controls, $t(12) = 6.01$, $p = .001$, $r = .87$; amusics, $t(12) = 2.45$, $p = .060$, $r = .58$). In sine-tone triads, we observed a marginally significant effect in controls, $t(12) = 2.50$, $p = .056$, $r = .58$, but amusics' ratings for major and minor triads did not differ, $t(12) = .48$, $p > .638$, $r = .14$.

To examine whether possible effects of pitch height on happiness/sadness ratings differed between amusics and controls, the 12 lowest major and minor chords and the 12 highest major and minor chords of each tone type were grouped to form low-pitch and high-pitch groups of chords (Supplementary Fig. A.3). A repeated-measures ANOVA with pitch height (low vs. high), chord quality (major vs. minor) and tone type (sine vs. complex) as within-subject factors and group (amusic vs. control) as between-subjects factor showed a significant main effect of pitch height, $F(1, 24) = 69.37$, $p < .001$, $\eta_p^2 = .74$, suggesting that higher major and minor chords were rated as more pleasant. Importantly, the interaction between group and pitch height was not significant, $F(1, 24) = .01$, $p = .932$, $\eta_p^2 = .001$. Other significant effects of this analysis are not reported here because they are not relevant for demonstrating that effects of pitch height were similar in both groups.

3.4. *Relationship between acoustical parameters and happiness/sadness ratings of triads*

In order to test how roughness and harmonicity (see Table 5 and Supplementary Fig. A.4) were related to happiness/sadness ratings of triads, we computed average ratings per chord for each participant group and predicted them with the calculated roughness and harmonicity values in a linear regression model (forced entry). First, correlations between subjective ratings and acoustical parameters are reported for sine-tone triads, initially for controls and then for amusics, followed by linear regression models calculated for each group. Then, the same analysis is presented for complex-tone triads.

In controls, happiness/sadness ratings were not significantly correlated with harmonicity for sine-tone triads, $r(22) = -.14$, $p = .516$, but showed a significant negative correlation with roughness, $r(22) = -.94$, $p < .001$. In amusics, the correlation between affective ratings of sine-tone triads and harmonicity was negative and marginally significant, $r(22) = -.38$, $p = .067$, and also significantly negative for roughness, $r(22) = -.97$, $p < .001$. The correlation between harmonicity and roughness measures of sine-tone triads was marginally significant, $r(22) = .36$, $p = .082$. A linear regression model in controls revealed that both roughness, $b = -1.02$, $t(21) = -16.40$, $p < .001$, and harmonicity, $b = .23$, t

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[2] To compare with previous data (Cousineau et al., 2012), Kendall W values are presented here. Sine-tone triads: amusics ($W = .81$, $\chi^2 = 19.32$), controls ($W = .46$, $\chi^2 = 10.94$); complex-tone triads: amusics ($W = .79$, $\chi^2 = 18.98$), controls ($W = .80$, $\chi^2 = 19.09$).

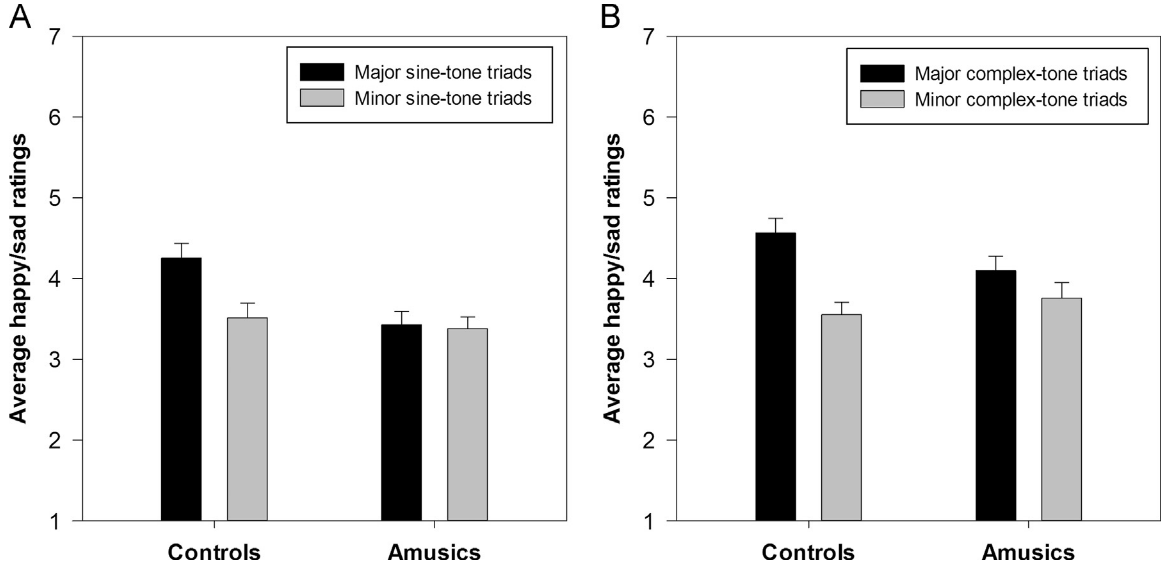

Fig. 3. Average happiness/sadness ratings of sine-tone (A) and complex-tone (B) triads, separately given for major and minor triads. Error bars denote one standard error of the mean.

(21)=3.71, p=.001, were significant predictors of happiness/sadness ratings in response to sine-tone triads, explaining a very high proportion of variance, adjusted R^2=.92, F(2, 21)=137.33, $p<.001$. Harmonicity of sine-tone triads was not a significant predictor in amusics, $b=-.03$, $t(21)=-.58$, p=.571, but roughness alone, $b=-.96$, $t(21)=-17.92$, $p<.001$, was able to predict a similar amount of variance, yielding an adjusted R^2=.94, F(2, 21)=189.43, $p<.001$.

Turning to complex-tone triads, harmonicity, r(22)=.59, p=.002, and roughness, $r(22)=-.73$, $p<.001$, were both significantly associated with affective responses in controls. In amusics, harmonicity, r(22)=.30, p=.148, was not significantly correlated with subjective ratings of complex-tone triads, however, the correlation was significant for roughness, $r(22)=-.92$, $p<.001$. Harmonicity and roughness measures of complex-tone triads were negatively, but not significantly, correlated, $r(22)=-.26$, p=.230. A linear regression model in controls revealed that both roughness, $b=-.62$, $t(21)=-5.07$, $p<.001$, and harmonicity, b=.43, t(21)=3.56, p=.002, were significant predictors and explained a high proportion of variance, adjusted R^2=.68, F(2, 21)=25.47, $p<.001$. In amusics, roughness was the only significant predictor, $b=-.90$, $t(21)=-10.51$, $p<.001$, explaining a high proportion of variance as well, adjusted R^2=.84, F(2, 21)=61.91, $p<.001$. In summary, our data provides evidence from two different tasks, namely pleasantness ratings of dyads and happiness/sadness ratings of triads, suggesting that both roughness and harmonicity are related to affective responses of controls, whereas amusics' ratings are mainly based on variations in roughness.

Table 7
Kendall's tau coefficients between differences in ratings for consonant/dissonant dyads and major/minor chords, pitch-related MBEA measures and sine-tone detection/direction thresholds.

Measure	Group	Sine-ple	Complex-ple	Sine-hap	Complex-hap
Pitch direction discrimination Threshold	Amusic	−.39	−.09	−.16	.09
	Control	−.48	−.27	−.58	−.34
	All	−.61*	−.49*	−.38*	−.36
Pitch change detection Threshold	Amusic	−.11	−.25	.16	.07
	Control	−.21	−.23	−.21	−.03
	All	−.16	−.28	−.06	−.03
MBEA Interval	Amusic	−.24	.14	−.04	.40
	Control	.51	.37	.48	.18
	All	.50*	.55*	.37	.47*
MBEA Pitch Composite	Amusic	−.23	.35	.21	.57
	Control	.43	.30	.53	−.03
	All	.48*	.59*	.43*	.46*

Note. *$p<.05$ after Bonferroni–Holm correction, df=11 for amusic and control groups; All=both participant groups, df=24 for All, sine-ple=difference between pleasantness ratings of consonant and dissonant sine-tone dyads, complex-ple=difference between pleasantness ratings of consonant and dissonant complex-tone dyads, sine-hap=difference between happiness ratings of major and minor sine-tone triads, complex-hap=difference between happiness ratings of major and minor complex-tone triads, MBEA=Montreal Battery for the Evaluation of Amusia, MBEA pitch=the pitch composite score is the mean score based on the scale, contour and interval subtests of the MBEA.

3.5. Relationships between affective sensitivity and pitch-related measures

To address the question of whether sensitivity to consonance/dissonance and the association between mode and affective judgment is related to the degree of pitch perception impairment, correlations were computed between the affective rating scores and (a) pitch threshold measures and (b) MBEA scores (Table 7). In controls, a (non-significant) negative association was present between the pitch threshold measures and differences in pleasantness ratings of sine tones. Specifically, controls with small (good) pitch thresholds showed larger differences in pleasantness ratings, with the strongest correlation for the pitch direction discrimination threshold. Furthermore, moderate (non-significant) positive correlations with the MBEA measures were observed for the group of controls. In amusics, a moderate (non-significant) negative relationship between the pitch direction discrimination threshold and the sensitivity to consonance and dissonance in sine tones was present.

In the case of complex-tone dyads, we generally noted small or no negative associations (non-significant) between the differences in pleasantness ratings of complex-tone dyads and pitch thresholds in both groups. The two MBEA measures correlated positively (though non-significantly) with difference ratings of complex-tone dyads in both groups, with the exception that the relationship with the MBEA interval subscale was not present in amusics.

Sensitivity to affective associations with major/minor sine-tone

Table 8
Kendall's tau coefficients between differences in ratings for consonant/dissonant dyads and variables derived from the timbre questionnaire used in Marin et al. (2012).

Group	Measure	General liking for music	Aversiveness of music	Music listening time	Musical timbre perception	Environmental timbre perception	Timbre categorisation task
Amusic	Sine-ple	−.31	−.14	.22	−.07	−.29	.31
Control		−.29	−.06	.18	−.20	.00	.09
All		−.31	−.15	.33	−.46*	−.10	.46*
Amusic	Com-ple	−.23	−.09	.34	−.31	−.32	.61*
Control		−.45	−.25	.16	.20	.19	−.09
All		−.39	−.22	.39	−.43*	−.07	.52*

Note. *$p < .05$ after Bonferroni–Holm correction, $df=11$ for amusic and control groups,All=both participant groups, $df=24$ for All, sine-ple=difference between pleasantness ratings of consonant and dissonant sine-tone dyads, com-ple=difference between pleasantness ratings of consonant and dissonant complex-tone dyads.

chords and its relation to pitch thresholds did not show a coherent pattern of results in amusics, but the results suggested a (non-significant) negative association in controls. Both MBEA measures were non-significantly positively correlated with affective sensitivity in controls but not to the same degree in amusics. For ratings of complex-tone triads, correlations with pitch thresholds were generally absent, but we observed moderate positive (non-significant) associations with the two MBEA measures in amusics but not in controls.

3.6. Relationships between affective sensitivity, self-reports and timbre categorisation ability

Marin et al. (2012) showed that amusics were impaired in their ability to categorize musical timbres. They also collected questionnaire data on self-reported liking for music, aversiveness of music, music listening time, musical timbre perception as well as environmental timbre perception. We were able to correlate the performance in the affective ratings tasks with the questionnaire data as well as with the performance in the timbre categorisation task because the same participants were tested in both studies. Table 8 shows that we observed a strong significant positive correlation between the sensitivity to consonance/dissonance in complex tones and the performance in the timbre categorisation task in amusics, $\tau(11)=.61$, and when both groups were considered together, $\tau(24)=.52$. For sine-tone dyads, this correlation was weaker and not significant, $\tau(11)=.31$, in amusics, but reached significance for data based on both groups, $\tau(24)=.46$. All other correlations were not significant, besides a significant negative association between self-reported musical timbre perception and sensitivity to consonance/dissonance in both tone-types when amusics and controls were grouped together. Table 9 shows the results for affective sensitivity to the happiness/sadness associations with major/minor triads. None of these correlations were significant, but self-reported musical timbre perception correlated positively (but not significantly) with affective sensitivity to major/minor triads of both tone types in amusics.

4. Discussion

We collected pleasantness ratings of simultaneous dyads as well as happiness/sadness ratings of triads in a group of amusic individuals enculturated to Western tonal music in order to characterize affective evaluations in this group, and to determine whether similar acoustic information contributed to these evaluations in amusics relative to controls. Amusic individuals' pleasantness ratings indicated sensitivity to dissonance and consonance for complex-tone (piano timbre) dyads and, to a lesser degree, for sine-tone dyads. The observed effects among amusics were significant but reduced compared to the group of matched controls. Furthermore, we found a tendency for amusic individuals to associate major triads with happiness and minor triads with sadness in the complex-tone condition. We also controlled for possible effects of pitch height on these affective responses and found similar trends in both participant groups.

Given this demonstrated affective sensitivity to tone combinations in amusics, along with recent findings by Gosselin et al. (2015) on the perception of musical emotion among amusics, it is important to consider how this can be explained in terms of what we know about the auditory and perceptual deficits of individuals with congenital amusia. We believe that this question can be addressed from two perspectives: first, in relation to the role of roughness and harmonicity, two frequently used acoustic parameters in the study of the affective perception of sound combinations (i.e., bottom-up processes), and second, in relation to effects of familiarity on these affective responses (i.e., top-down processes). In our regression models amusics' affective ratings were only associated with roughness, therefore our results are in line with the finding that sensitivity to roughness seems to be unimpaired in amusics (Cousineau et al., 2012). It is important to note that we used different timbres from those used by Cousineau et al., suggesting that this is a robust result. However, in contrast to Cousineau et al., we found that amusics reported reliable and consistent affective ratings across all tasks with response patterns similar to those observed in controls. This similarity was stronger in the complex-tone condition than in the sine-tone condition. Moreover, amusics even reported the highest pleasantness ratings

Table 9
Kendall's tau coefficients between differences in ratings for major/minor triads and variables derived from the timbre questionnaire used in Marin et al. (2012).

Group	Measure	General liking for music	Aversiveness of music	Music listening time	Musical timbre perception	Environmental timbre perception	Timbre categorisation task
Amusic	Sine-hap	.03	−.31	−.32	.21	−.21	−.23
Control		−.22	−.03	.23	−.12	.09	.09
All		−.12	−.23	.13	−.20	−.03	.15
Amusic	Com-hap	.29	.22	.03	.36	.19	.09
Control		.05	.10	−.20	−.45	−.08	.39
All		.05	.06	.10	−.34	.01	.41

Note. *$p < .05$ after Bonferroni–Holm correction, $df=11$ for amusic and control groups, All=both participant groups, $df=24$ for All,Sine-hap=difference between happiness ratings of major and minor sine-tone triads, Com-hap=difference between happiness ratings of major and minor complex-tone triads.

in response to the complex-tone octave, which suggests some sensitivity to harmonicity.

One other plausible explanation for the similarity in responses by amusics and controls is that amusic individuals possess implicit learning capacities for musical materials (Omigie and Stewart, 2011; Tillmann et al., 2012, but see also Peretz et al. (2012)), and these learning capacities are in line with long-term memory for musical pieces (Tillmann et al., 2014). In other words, through mere exposure to and familiarity with Western harmonic structures, varying in consonance and dissonance as well as in chord quality, amusic individuals may have implicitly formed long-term memory templates whose recognition may partly underlie the perception of consonance (McLachlan et al., 2013). In general, this theory resembles those describing mere-exposure effects (Zajonc, 1968) and fluency accounts of aesthetic processing (Reber et al., 2004).

Of course, it is reasonable to assume that the influence of music exposure on pleasantness and happiness/sadness ratings may be attenuated in amusic individuals compared to controls, given that amusic individuals may seek out music experiences to a lesser extent than controls (McDonald and Stewart, 2008; Omigie et al., 2012). Exposure effects may partly explain the reduced effects in the group of amusics in response to complex-tone dyads and triads. Moreover, familiarity may also explain the finding that the effects observed for the sine-tone conditions were either smaller than in the complex-tone conditions (consonance/dissonance task) or even absent (major/minor task). Weak (non-significant) positive correlations between music listening time and the sensitivity to consonance/dissonance in both participant groups support the view that exposure to music may have some impact on affective sensitivity. However, we did not observe positive correlations between music listening time and the performance in the major/minor task in amusics. Future research may thus collect familiarity ratings of stimuli in addition to information on music exposure to further investigate the role of familiarity in affective processing in congenital amusia.

We also assessed individual differences and performances across the four affective ratings tasks. In general, pitch-related measures used to characterize the severity of congenital amusia did not correlate strongly with affective sensitivity to simultaneous pitches, apart from a non-significant moderate correlation between the sensitivity to the major-happiness association and the MBEA interval and pitch composite scores, respectively. Moreover, we observed a significant correlation between the performance in a timbre categorisation task (Marin et al., 2012) and the sensitivity to consonance/dissonance in complex-tone dyads in amusics. These findings, together with the fact that amusics are generally sensitive to differences in consonance/dissonance, and to a lesser degree to chord quality of complex-tone combinations, may suggest two things. First, the pitch processing impairment of congenital amusia may only partly be related to simultaneous pitch processing but probably mostly to the processing of a series of pitches, i.e. sequences of tones (e.g., Gosselin et al. (2009), Jiang et al. (2013), Tillmann et al., 2009). Second, it may be possible to characterize a sub-group of amusic individuals who show an impairment of simultaneous pitch processing, as manifested by deficits in timbre categorisation and harmonicity processing of triads. This testable hypothesis is motivated by the fact that the MBEA test, currently widely used to diagnose congenital amusia, comprises only tasks involving melodies (Peretz et al., 2003), and thus is not designed to assess simultaneous pitch processing. This is also the case for the pitch threshold tests (Liu et al., 2010) that are often used alongside the MBEA in establishing a diagnosis of congenital amusia.

Our current study also sheds some light on theories of affective responses to dyads and triads in controls. Acoustical analyses revealed that controls' pleasantness ratings of dyads and happiness/sadness ratings of triads were predicted by both roughness and harmonicity, which stands in contrast to recent findings by McDermott et al. (2010), who identified preference for harmonicity as the sole correlate of difference ratings between pleasant and unpleasant tone combinations. We attribute the discrepancy between our findings in controls and those reported by McDermott et al. (2010) to the fact that our acoustical analyses were performed on the tone combinations that were actually rated by the participants, whereas McDermott et al. (2010) correlated differences in subjective ratings of three tasks to investigate the basis of consonance (i.e., pleasantness ratings of chords of four types of timbres varying in consonance and dissonance according to the rules of the Western musical system; acoustic preferences of beating and harmonicity in response to synthetic stimuli). Although the elegant design of McDermott et al. (2010) allowed for the differentiation between preference for acoustic parameters and their relation to pleasantness ratings of other types of tone-combinations, it cannot be ruled out that familiarity with the stimuli type differed across the three tasks and thus differentially affected the ratings. In general, effects of familiarity on preference ratings of musical excerpts have been frequently reported in empirical studies on musical aesthetics (e.g., Marin and Leder (2013), Parncutt and Marin (2006), Schubert (2007)), and in particular, familiarity has been mentioned as an important factor underlying affective responses to simultaneous pitches (Guernsey, 1928; McLachlan et al., 2013).

Instead of trying to base the perception of consonance and dissonance on either acoustical correlates of tone combinations (e.g., Helmholtz (1863/1954), McDermott et al. (2010), Stumpf (1890, 1898)) or on effects of familiarity and expertise (e.g., Guernsey (1928), McLachlan et al. (2013)), we argue that the present study may provide some evidence for a combination of both types of theories, thus integrating bottom-up and top-down processes. This line of argument gains support from models of aesthetic experiences that acknowledge stimulus-driven processes as well as those that are inherent to the perceiver (e.g., Brattico et al. (2013), Leder et al. (2004)). Moreover, models on cross-cultural emotion processing have also integrated these two aspects (Balkwill and Thompson, 1999; Thompson and Balkwill, 2006, 2010). Here, we demonstrated that in controls roughness and harmonicity were reliable correlates of affective ratings of simultaneous pitches, explaining between 36–92% of the variance depending on the type of stimulus. Interestingly, the amount of variance explained was lower in the models predicting ratings for dyads than in those predicting ratings for triads (which was also the case in amusics).

The current study also adds to our understanding of the underlying mechanisms in the formation of happiness and sadness associations with chords varying in chord quality (major vs. minor) in Western listeners. Is there an acoustical basis from which happiness/sadness ratings can be deduced, or are these associations merely the consequence of cultural learning? In controls and amusics, the proportion of explained variance (based on the same acoustical parameters as those used for the study of consonance and dissonance) was very high for ratings of sine- and complex-tone triads, ranging from 68–94%. This suggests that there is a strong acoustical basis for the differentiation between happy and sad chords, which corroborates research by Cook (2009) and Bakker and Martin (2015), who argued that the associations between happiness/sadness and modality could be explained without cultural factors. However, similar to current findings with regard to the perception of consonance and dissonance, it is likely that acoustical properties of chords as well as familiarity effects may interact in the formation of affective judgements.

Altogether, our findings on the pleasantness–consonance (or unpleasantness–dissonance) relationship as well as on the happiness-major and sadness-minor associations suggest testable predictions concerning the functional bases for these affective judgements in the amusic brain. In light of our current results and the findings that subcortical and cortical activity can be modulated by consonant and dissonant dyads (Bidelman and Krishnan, 2009) as well as by different types of triads common in Western tonal music (Bidelman and Krishnan, 2011), we would predict that amusics' subcortical response activity would be somewhat similar to that of controls when complex-tone combinations are considered.

The current research adds to the growing body of literature on affective responses to Western tonal music in congenital amusia (Ayotte et al., 2002; Cousineau et al., 2012; Gosselin et al., 2015) and call for future studies involving different types of tones (timbres) and chord qualities. Although amusic individuals are impaired in the processing of dynamic aspects of pitch (melodies), our results suggest that they are sensitive to affect communicated by simultaneous complex-tone pitches. However, previous research has also indicated that amusic individuals may have impairments regarding musical timbre processing (Marin et al., 2012), which may be related to deficits in the perception of harmonicity. Therefore, future studies may systematically investigate affective responses to isolated pitch combinations varying in timbre.

Finally, our results have implications for theories of the underlying neural deficits in congenital amusia, adding to other evidence on the nature of impairments at different levels of processing. This evidence suggests, for example, that initial stages of pitch processing may well be intact (Cousineau et al., 2015), whereas brainstem responses to auditory stimuli are possibly impaired (Lehmann et al., 2015; but see Liu et al. (2014) for conflicting evidence), and conscious central pitch processing is almost certainly impaired (Albouy et al., 2013; Moreau et al., 2013; Omigie et al., 2013). Further efforts to develop a neurological model of the nature of congenital amusia may thus profit from the study of the neural processing of simultaneous pitch combinations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2015.10.004.

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