Singing in congenital amusia

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Congenital amusia is a musical disorder characterized by impaired pitch perception. To examine to what extent this perceptual pitch deficit may compromise singing, 11 amusic individuals and 11 matched controls were asked to sing a familiar tune with lyrics and on the syllable /la/. Acoustical analysis of sung renditions yielded measures of pitch accuracy (e.g., number of pitch errors) and time accuracy (e.g., number of time errors). The results revealed that 9 out of 11 amusics were poor singers, mostly on the pitch dimension. Poor singers made an anomalously high number of pitch interval and contour errors, produced pitch intervals largely deviating from the score, and lacked pitch stability; however, more than half of the amusics sang in-time. Amusics' variability in singing proficiency was related to their residual pitch perceptual ability. Thus, their singing deficiency might be a consequence of their perceptual deficit. Nevertheless, there were notable exceptions. Two amusic individuals, despite their impoverished perception, sang proficiently. The latter findings are consistent with the existence of separate neural pathways for auditory perception and action.
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I. INTRODUCTION

Singing is widespread in the general population. In spite of the general belief that most people are inept at singing, there is increasing evidence that the majority can carry a tune. Nonmusicians' sung performance is consistent both within (Bergeson and Trehub, 2002; Halpern, 1989) and across subjects (Levitin, 1994; Levitin and Cook, 1996) in terms of starting pitch and tempo. In addition, occasional singers can proficiently sing a well-known song provided that they perform it at a slow tempo (Dalla Bella *et al.*, 2007).

However, a significant proportion of the population have notorious difficulties with singing in-tune. 10%–15% of the population was classified as poor-pitch singers when singing a familiar song (Dalla Bella *et al.*, 2007) and when imitating unfamiliar pitch patterns (Pfordresher and Brown, 2007). Many factors (e.g., poor perception, poor motor planning and execution, and poor sensory-motor integration) can cause inadequate singing (see Pfordresher and Brown, 2007). One obvious cause of poor-pitch production is a faulty pitch perceptual system. Accurate singing requires fine perceptual monitoring of the vocal output, especially when learning melodies and when singing along with others. Through feedback analysis, singers can correct and adjust vocal performance. A poor-pitch perceptual system is likely to affect this feedback mechanism, hence leading to poor-pitch singing. This deficient perceptual monitoring of vocal performance is likely to be found in tone deafness. Self-defined "tone-deaf" or "unmusical" individuals consider poor singing as a hallmark of their musical deficiencies (see Sloboda *et al.*, 2005, for a discussion). Yet evidence is scant about singing proficiency in these individuals. This condition, more recently referred to as "congenital amusia," has been mostly studied and defined in terms of poor perceptual abilities (Ayotte *et al.*, 2002; Foxton *et al.*, 2004; Peretz, 2001; Peretz *et al.*, 2002, 2007; Peretz and Hyde, 2003).

Congenital amusia can be traced to degraded pitch perception abilities (Foxton *et al.*, 2004; Hyde and Peretz, 2004). Amusic individuals exhibit lower accuracy than matched controls in detecting pitch changes that are smaller than one semitone[1] and ones that are out-of-key whereas they are normal at detecting time changes in the same sequences (Hyde and Peretz, 2004; Peretz *et al.*, 2007). To the extent that singing reflects perceptual abilities, we predict poor performance for small pitch intervals and little sensitivity to key distance in singing in amusia.

In one prior study (Ayotte *et al.*, 2002), amusics' singing was judged by peers as impaired with regard to normal performance. The deficit mostly concerned, but was not limited to, the pitch dimension. This supports the notion that amusics' poor singing may result from an impoverished perceptual system (Ayotte *et al.*, 2002). Nonetheless, one congenital amusic was judged to sing accurately. This case raised the intriguing possibility that perceptual disorders may not completely account for singing impairments. This possibility finds some support in the recent discovery that congenital amusic individuals are able to reproduce the pitch direction of two successive single tones despite being unable to judge pitch direction (Loui *et al.*, 2008). It is noteworthy that spared production was confined to pitch direction; amusics' reproduction of pitch interval size was inaccurate. The reverse dissociation (i.e., impaired performance with spared

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TABLE I. Congenital amusics' characteristics, individual scores on the MBEA (percents of correct responses), and on a pitch change detection task (from Hyde and Peretz, 2004). For the pitch change detection task, average percents of Hits-F.A. across 25-, 50-, and 100-cent pitch changes are reported.

	AG	AM	AS	EL	FA	GC	IC	MB	PT	SR	TC	Controls (SD)
Gender	F	M	F	F	F	F	M	F	F	F	M	9F 2M
Age (years)	49	66	63	54	64	59	61	55	63	53	35	56 (6)
Education	17	16	15	19	16	19	19	17	16	18	15	15.8 (2)
Handedness	R	R	R	R	R	R	R	R	R	R	R	R
I.Q	N/A	116	117	110	N/A	128	107	120	108	N/A	N/A	N/A
M.Q.	N/A	135	134	114	N/A	137	112	130	114	N/A	N/A	N/A
						MBEA						
Scale	53.3[a]	60[a]	63.3[a]	53.3[a]	66.7[a]	56.7[a]	50[a]	46.7[a]	53.3[a]	53.3[a]	66.7[a]	92.1 (6)
Contour	70[a]	60[a]	63.3[a]	53.3[a]	70[a]	56.7[a]	50[a]	46.7[a]	53.3[a]	56.7[a]	66.7[a]	87 (8)
Interval	50[a]	56.7[a]	60[a]	53.3[a]	70	73.3	50[a]	73.3	53.3[a]	73.3	70	88.2 (9)
Rhythm	76.7	73.3[a]	76.7	63.3[a]	66.7[a]	96.7	50[a]	93.3	63.3[a]	76.7	90	90 (7)
Metric	70	66.7	60[a]	73.3	66.7	70	56.7[a]	70	66.7	50[a]	76.7	87.6 (9)
Memory	76.7	53.3[a]	73.3	66.7[a]	76.7	73.3	50[a]	76.7	50[a]	43.3[a]	76.7	85.5 (9)
Composite score	66.1[a]	61.7[a]	66.1[a]	60.5[a]	69.5[a]	71.1[a]	51.1[a]	67.8[a]	56.7[a]	58.9[a]	74.5[a]	89 (6)
Pitch change detection (Hyde and Peretz, 2004)	N/A	35.8	71.2	64.2	66	59.9	50.8	70	81.2	N/A	N/A	N/A

F=female, *M*=male, and N/A=not available.

[a] Below cut-off score (as indicated in Peretz *et al.*, 2003).

perception) is more common. Poor-pitch singing can occur in cases of normal perception (Bradshaw and McHenry, 2005; Dalla Bella *et al.*, 2007; Pfordresher and Brown, 2007; Wise and Sloboda, 2008). Similarly, brain damage (e.g., lesion of the right fronto-temporal regions) can selectively impair sung performance without affecting perception (Schön *et al.*, 2003, 2004). In sum, these findings point to the possibility of two separate streams for auditory perception and action (Griffiths, 2008), thus extending to the auditory modality the idea of independent perceptual and action systems previously observed in vision (i.e., the dorsal and ventral neural pathways, Goodale *et al.*, 1991).

In the study of Ayotte *et al.* (2002), singing proficiency was assessed by peer judgments. Such judgments are common in studies on singing (e.g., Alcock *et al.*, 2000a, 2000b; Hébert *et al.*, 2003; Racette *et al.*, 2006; Schön *et al.*, 2004). However, discrepancies among subjective ratings of impaired singing are frequent (e.g., Kinsella *et al.*, 1988; Prior *et al.*, 1990). This problem is likely the effect of music notation and perceptual constraints, which may impinge on judgments. For example, experts tend to integrate pitch and time information when embedded in a musical context (Jones and Pfordresher, 1997; Peretz and Kolinsky, 1993). In other words, judges cannot provide fine estimates of accuracy in terms of pitch and time, while keeping these two dimensions separate. Acoustical methods represent a powerful alternative to perceptual judgments (Dalla Bella *et al.*, 2007; Murayama *et al.*, 2004; Terao *et al.*, 2006). Based on acoustical features such as tone onset and pitch height, objective and reliable measures of singing proficiency on pitch and time dimensions can be obtained. With this method, we showed that occasional singers can sing proficiently a well-known melody from memory, provided that they sing at a slow tempo (Dalla Bella *et al.*, 2007). Nevertheless, a minority of individuals cannot sing proficiently: Their difficulty is confined to poor-pitch production with no evidence of a concomitant perceptual deficit, as assessed by a task that required the detection of pitch and time incongruities in unfamiliar melodies (Peretz *et al.*, 2008).

In the present study, the singing abilities of 11 adults with congenital amusia were examined with an acoustically-based method. Congenital amusics were asked to sing a well-known song in Quebec (*Gens du pays*, by Gilles Vigneault) with lyrics and on the syllable "ta" or "la."[2] Measures of pitch and time accuracy were yielded by an acoustical analysis of sung performance (as in Dalla Bella *et al.*, 2007). Since amusics' perceptual deficit affects mostly the pitch dimension (Hyde and Peretz, 2004; Peretz *et al.*, 2007), we predicted that amusics would sing out of tune while being able to sing in-time. Furthermore, we expected poor singing to be related to the severity of the music perceptual difficulties (as assessed by the Montreal Battery of Evaluation of Amusia; Peretz *et al.*, 2003), and to the degree of impairment in detecting pitch changes (as assessed in Hyde and Peretz, 2004). Nonetheless, in line with previous suggestions, we also expected to find some amusic individuals who would be able to sing accurately without awareness. Finally, in keeping with the findings by Loui *et al.* (2008), we predicted that amusics, despite impaired production of pitch interval sizes, would be able to produce the correct pitch contour.

II. METHOD

A. Participants

Eleven congenital amusics aged between 35 and 66 ($M=57$ years) participated in the study (see Table I). Amusics had no neurological or psychiatric history. Eight participants were assessed in previous studies (Ayotte *et al.*, 2002;
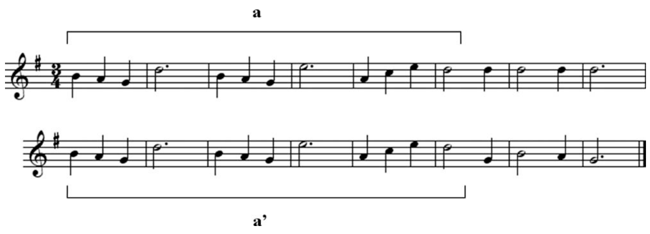
FIG. 1. Score of the chorus of *Gens du Pays*.

Hyde and Peretz., 2004). Amusics obtained a composite score between 55.1 and 74.5 on the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz *et al.*, 2003), hence below the cut-off score for amusia (77.6; Peretz *et al.*, 2003).

As can be seen in Table I, congenital amusics exhibited impaired music perception mostly affecting the melodic dimension (i.e., the scale, contour, and interval tests of the MBEA). A deficit in perceiving acoustical pitch was confirmed in each of the eight amusics tested on a pitch change detection task (Hyde and Peretz, 2004). In this task, participants had to detect a pitch change in five-tone standard and comparison sequences. In standard sequences (no change), all the tones had the same pitch level (1047 Hz). In comparison sequences (with change), the fourth tone was displaced at one of five pitch distances (from 25 to 300 cents) upward or downward from the pitch of the other tones. The results in the pitch change detection task are reported in Table I. At pitch distances smaller than one semitone, the amusics obtained a lower score than controls, whose performance was above 92% correct.

A control group ($n=11$) matched to amusics for age, gender, education, and musical training but with no musical difficulties participated in the study. Participants were remunerated for participating in the experiment.

B. Material and procedure

Participants were asked to sing the chorus of the song *Gens du pays* (Vigneault and Rochon, 1976), well-known in Quebec and typically sung to celebrate birthdays. The same tune was studied in our prior work on singing proficiency in the general population (Dalla Bella *et al.*, 2007). As can be seen in Fig. 1, the chorus of *Gens du pays* comprises 32 notes with a vocal range of less than an octave and a stable tonal center. Each note is associated with a syllable. The segment a' is a repetition of a; this characteristic of the melody served to assess pitch stability within the same performance (see below).

Participants sang the chorus of *Gens du pays* twice (*singing with lyrics* condition): at the beginning of the experiment (test 1) and immediately afterwards (test 2). Then, after a short break, participants were asked to sing the same melody twice on the syllable /ta/ or /la/ (*singing on /la/* condition). Participants did not receive cues (e.g., first notes of the melody) or indications about the beginning pitch of the melody. Performances were recorded in a laboratory setting with a Shure 565SD microphone (sampling frequency =44.1 kHz) directly onto an IBM-compatible computer using COOLEDIT software.

C. Acoustical analysis of sung performance

Only complete performances (i.e., with 32 notes, as indicated in the score) were analyzed. Acoustical analyses of sung renditions were performed on the vowel groups (e.g., /i/ in "mi"), determined by visual inspection of the waveform and of the spectrogram. Vowel groups are the best targets for acoustical analysis, given that vowels carry the maximum of voicing (e.g., Murayama *et al.*, 2004). Moreover, the initiation of the vowel group is well-suited to indicate the onset of musical tones, because vowel onsets, rather than consonant onsets, are typically synchronized with the beat in singing (Sundberg and Bauer-Huppmann, 2007). The onset of vowel groups was considered as the *note onset time*. The median of the fundamental frequencies within the vowel group served to measure *pitch height*. Note onset times and pitch heights were used to compute various measures of pitch and time accuracy.

1. Pitch dimension variables

Initial pitch is the pitch of the first note used to assess absolute pitch level.

Pitch stability is the difference between the produced pitch in the melody segment a and in the repetition a'. The absolute difference in semitones between the 12 corresponding notes (e.g., note 1 in segments a and a', note 2 in segments a and a', and so forth) was computed. Pitch stability is the mean of these absolute differences. The larger this mean difference, the more instable the pitch.

Number of contour errors refers to the number of produced intervals that deviated in direction from their respective notated intervals. Pitch direction was counted as ascending or descending if the sung interval between two notes was higher or lower by more than one semitone. If pitch direction was different to that noted in the musical score, it was counted as an error.

Number of pitch interval errors indicates the number of produced intervals that deviated in magnitude from their respective notated intervals. An error was scored when the sung interval was larger or smaller by one semitone than the interval prescribed by the notation. It is noteworthy that pitch interval errors were coded irrespectively of pitch direction (e.g., if a singer produced a one-tone ascending interval instead of a one-tone descending interval, this was not scored as a pitch interval error).

Interval deviation measures the size of the pitch deviations, by averaging the absolute difference in semitones between the produced intervals and the intervals prescribed by musical notation. Small deviation reflects high accuracy in relative pitch.

2. Time dimension variables

Tempo is the mean inter-onset-interval (IOI) of the quarter note.

Number of time errors indicates duration deviations from the score. When the duration of the sung note was 25% longer or shorter than its predicted duration based on the preceding note, as prescribed by the musical notation, this

TABLE II. Mean values for pitch and time variables obtained in the singing with lyrics and singing on /la/ conditions for congenital amusics and their controls.

	Singing with lyrics		Singing on /la/	
Variable	Amusics M (SE)	Controls M (range)	Amusics M (SE)	Controls M (range)
		Pitch dimension		
Initial pitch (Hz)				
Males	122.0 (8.1)	123.7 (117.5–129.8)	115.8 (−)[a]	132.1 (128.0–136.3)
Females	214.1 (13.3)	218.9 (175.2–273.9)	226.8 (24.8)	216.6 (168.2–294.5)
Pitch stability (semitones)	1.3 (0.2)[b]	0.5 (0.3–0.7)	1.3 (0.2)[c]	0.5 (0.2–1.0)
No. of contour errors	6.1 (2.0)[c]	1.0 (0–3.5)	3.4 (2.0)	0.8 (0.0–2.5)
No. of pitch interval errors	13.0 (1.9)[b]	3.6 (0–8.0)	11.0 (2.7)[b]	3.4 (0.5–8.5)
Interval deviation (semitones)	1.3 (0.2)[b]	0.5 (0.3–0.8)	1.1 (0.2)[d]	0.5 (0.3–0.8)
		Time dimension		
Tempo (mean IOI, ms)	314.4 (10.9)	299.0 (257.8–343.0)	334.5 (19.1)[c]	291.6 (254.2–332.7)
No. of time errors	3.2 (0.5)	2.4 (0–5)	2.2 (1.4)	1.2 (0.0–3.5)
Temporal variability (CV IOIs)	0.18 (0.02)[c]	0.12 (0.08–0.16)	0.17 (0.05)	0.10 (0.06–0.17)
Rubato	0.6 (0.08)	0.7 (0.4–0.9)	0.6 (0.1)	0.7 (0.1–0.9)

[a] Only one participant.

[b] $p<0.01$.

[c] $p<0.05$.

[d] Marginally significant ($p=0.07$).

was considered as a time error. The first and last notes were not used to compute time errors.

Temporal variability is the coefficient of variation (CV) of the quarter-note IOIs, calculated by dividing the standard deviation of the IOIs by the mean IOI.

Rubato consistency is an additional measure referring to variations in the timing of onsets of subsequent musical notes as compared with the musical notation. An example of rubato is observed when musicians speed up at the beginning of a musical phrase and slow down toward the end of it (e.g., Todd, 1985). Rubato consistency was obtained from the correlation of the quarter-note IOIs for the segment a with the IOIs for corresponding notes in segment a' (a similar measure was proposed by Timmers *et al.* (2000) in piano performance). High correlation reflects high consistency in the rubato pattern. Throughout the paper, for simplicity, the term *rubato* will refer to rubato consistency.

III. RESULTS AND COMMENTS

A. Singing with lyrics: Group results

All amusics and controls were able to produce complete renditions (i.e., 32 notes) with lyrics. Means and variability of pitch and time variables in the singing with lyrics condition for amusics and their controls are reported in Table II. The reported values are averaged across repetitions (i.e., test 1 and test 2). The measures of pitch and time accuracy were highly correlated across repetitions in both amusics and controls (with Spearman rho values between 0.60 and 0.98, average $p<0.01$)[3] with the exception of rubato (for amusics, Spearman rho$=0.41$, $p=$n.s.; for controls, rho$=0.29$, $p=$n.s.), pitch interval deviation, and pitch interval errors for controls (with rhos$=0.49$ and 0.50, respectively, ps$=$n.s.).

Amusics were impaired on the pitch dimension showing a large number of pitch interval errors, contour errors, lower pitch stability, and average pitch interval deviation larger than 1.2 semitones. However, amusics' difficulties were not confined to the pitch dimension. Amusics exhibited larger temporal variability (i.e., CV of the IOIs) than controls. It is noteworthy that amusics did not sing at a faster tempo than controls. Thus, it is unlikely that amusics' poor singing is due to tempo differences. Nevertheless, the amusics who performed at a slower tempo were more accurate than those singing at fast tempi, as revealed by the significant negative correlations between tempo (mean IOI) and pitch interval deviation (rho$=-0.62$, $p<0.05$), number of pitch interval errors (rho$=-0.61$, $p<0.05$), temporal variability (rho$=-0.64$, $p<0.05$). In controls, only a positive correlation between tempo (mean IOI) and temporal variability reached significance (rho$=0.64$, $p<0.05$), thus suggesting rather an increase in temporal variability at slower tempi. These discrepancies are probably due to the fact that the range of tempi in controls was much smaller (85 ms) than in amusics (134 ms). Yet, in general, these results are in keeping with the speed-accuracy trade-off previously found in occasional singers (Dalla Bella *et al.*, 2007).

Further analyses were conducted on pitch and time errors made by amusics and controls. In amusics, the number of pitch interval errors increased with the number of time errors (rho$=0.62$, $p<0.05$). This correlation did not reach significance in controls (rho$=-0.25$, $p=$n.s.). However, only 10% of pitch interval errors made by the amusics co-occurred with time errors (4% of errors in controls). Thus, errors on the pitch and time dimensions were relatively independent. To examine whether pitch interval errors led to produce notes in-key or out-of-key, the tonality of the sung melody was inferred based on the starting pitch; the notes in- and out-of-key were detected by approximating the produced pitches to the closest notes in the chromatic scale. Amusics produced on average 7.3 pitch errors that were in-key (i.e., 55.9% of total number of errors), and 5.7 notes that were out-of-key (44.1%). These productions did not differ from chance performance (as revealed by binomial tests; note that chance level differs for in-key—6 out of the 11 chromatic pitches in the octave, or 55% of the possible tones—and for out-of-key—5 out of 11 possible pitches, or 45%). Pitch interval errors occurred more often on strong beats ($M=7.4$ errors, 58.6% of the total number of errors) than on weak beats ($M=5.5$ errors, 41.4%) ($t(10)=4.48$, $p<0.01$) in amusics. This difference is significantly above chance (=50% for errors on strong beats, and 50% for errors on weak beats), as attested by a binomial test ($p<0.05$). Thus, even if about half the pitch errors were in-key, these are likely to be noticed because strong beats are the most salient events in melodies (Jones *et al.*, 2002). This effect was not observed in controls. Time errors always occurred on weak beats in both amusics and controls.[4]

In order to examine whether amusics are more impaired on small than large pitch intervals, we examined pitch interval deviations for each of the 31 pitch intervals from the chorus (spanning from the unison to nine semitones; see Fig. 1 for the musical notation of the correct intervals and Fig. 2 for the data, with panel (a) referring to amusics and panel (b) to controls). Positive and negative deviations indicate interval expansion and compression, respectively. The produced intervals were analyzed in 2 groups (amusics vs controls) by 5 interval sizes (2, 3, 4, 7, and 9 semitones)[5] by 2 deviation types (compression vs expansion) repeated-measures Analysis of Variance (ANOVA), taking intervals as the random factor.[6] Group and deviation types were considered as the within-item factors, and interval size as the between-item factor. As can be observed in Fig. 2, the effect of interval size was different in each group, as revealed by a significant group × interval size × deviation type triple interaction ($F(4,22)=15.33$, $p<0.001$). Separate interval sizes by deviation type ANOVAs were run for amusics and controls. Amusics exhibited a monotonic dependency of interval deviation on interval size, with a tendency to compress large intervals ($F(4,22)=40.88$, $p<0.001$). In controls, interval deviation did not significantly vary as a function of interval size. Thus, contrary to expectations, amusics' large pitch deviations from target intervals are not limited to small intervals (e.g., zero and two semitones). Amusic singing cannot be explained by a fine-grained perceptual pitch deficit alone. This finding will be examined in more detail in the discussion.

B. Singing with lyrics: Individual results

The individual data for pitch and time accuracy are presented in Figs. 3 and 4, respectively. As can be seen, individual amusics were more deviant from controls on the pitch than on the time dimension. Nonetheless, not all amusics exhibited impaired performance. For example, the amusic PT performed within the range of controls on all variables, and GC's performance fell outside the range of controls in terms of pitch stability only. To assess more thoroughly amusics' individual performance, we examined cases in which performance departed from the average obtained from the control group by more than 2 standard deviations (SD) (mildly impaired) or 3 SD (very impaired) on each variable (see Table III). The most common deficits observed in amusics, with the exception of PT, affected the pitch dimension (i.e., impaired pitch stability, increased number of pitch interval errors and contour errors, and larger pitch interval deviation from the score). In four cases (AM, EL, FA, and IC), poor-pitch singing was associated with large time variability. In no cases, however, did deficits of the time dimension occur in isolation. When ranked in terms of singing proficiency, AM and IC appear as the most impaired, and PT and GC as the least impaired (for examples of productions see Dalla Bella *et al.*, 2009).[7] AM and IC made numerous pitch interval errors (22.5 and 20, respectively) and contour errors (20 and 16); their renditions were characterized by large pitch interval deviations from the target (by 2.6 and 2.1 semitones on average; see also Fig. 2), low pitch stability (1.2 and 2.9 semitones), and high temporal variability (CVs of the IOIs =0.33 and 0.30, respectively). In contrast, PT and GC sang

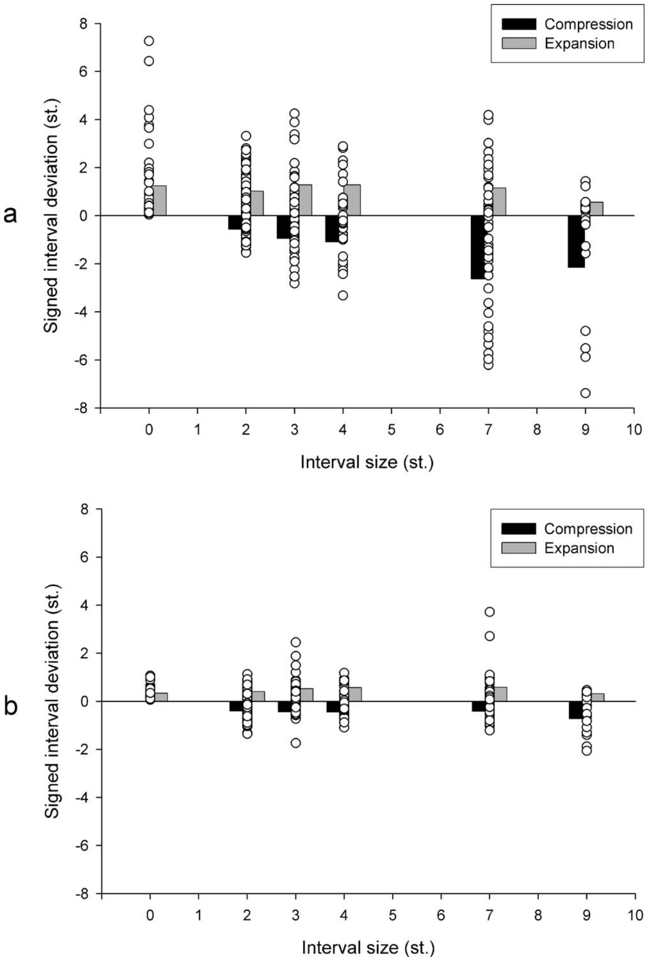

FIG. 2. Average pitch interval deviations in terms of compression and expansion for each interval of the chorus of Gens du pays (from unison to nine semitones) produced by amusics (a) and controls (b). A positive deviation indicates an extension of the target interval and negative deviation, a compression of the interval. The dots indicate individual performances.

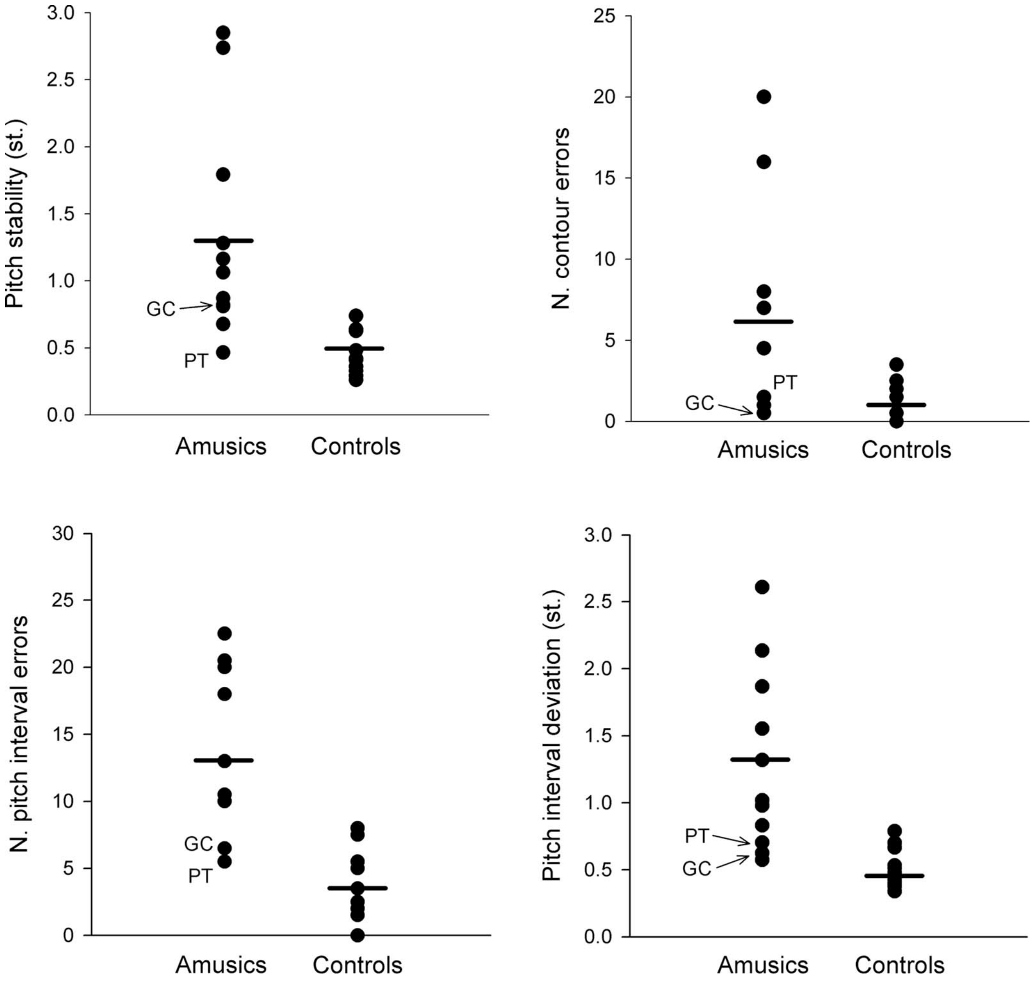

FIG. 3. Amusics' and controls' individual results for pitch stability, number of contour errors, number of pitch interval errors, and pitch interval deviation in the singing with lyrics condition. Horizontal lines indicate group averages.

quite proficiently. Five other amusics (AG, AS, EL, GC, and PT) did not make more pitch contour errors than controls (with less than two contour errors). These five amusics were impaired in perceiving melodic contour, as attested by the MBEA (see Table I). Hence, they were able to produce the correct pitch direction while being unable to perceive it, in line with the results of Loui *et al.* (2008) with single intervals. However, there are important differences between the results reported by Loui *et al.* (2008) and those obtained here. First, at least three amusics (AG, GC, and PT) were not impaired in producing interval sizes. Second and more important, six amusics were inaccurate in producing both pitch direction and pitch interval size. In sum, production in interval imitation tasks (Loui *et al.*, 2008) does not seem to predict performance in musical tasks.

C. Singing on /la/

Singing on /la/ turned out to be an extremely difficult task for amusics. Only 5 amusics out of 11 were able to produce complete performances (i.e., including 32 notes) when asked to sing on /la/ while all controls succeeded in producing complete performances. The other six amusics could only produce a few notes when asked to sing on /la/. The amusics who produced complete performances (i.e., AS, AG, GC, MB, and TC) were among the least severely impaired on the MBEA (mean composite score=69.1), as can be seen in Table I. In addition, the five amusics who produced complete performances had memory scores that lied in the low but normal range on the MBEA (see Table I). However, PT, who was able to sing proficiently with lyrics, failed to sing on /la/. It is noteworthy that the observed difficulty in amusics to sing on /la/ as compared to singing with lyrics was not found in controls. Pitch accuracy was comparable in the two conditions in controls; in addition, controls were more accurate on the time dimension when singing on /la/ than when singing with lyrics ($t(10)=2.41$, $p<0.05$).

Means and variability of pitch and time variables in the singing on /la/ condition for the minority of amusics who performed the complete song on /la/ and their controls are reported in Table II. The reported values are averaged across repetitions (i.e., test 1 and test 2). As can be seen, amusics' impairment was limited to the pitch dimension, as shown by their reduced pitch stability and larger number of pitch interval errors than controls. In addition, amusics sang slower than controls. To examine amusics' individual performance, we indicated in Table IV cases in which performance departed from the average obtained from the control group by more than 2 SD (mildly impaired) or 3 SD (very impaired) on each variable. As can be observed, two of the five amusics

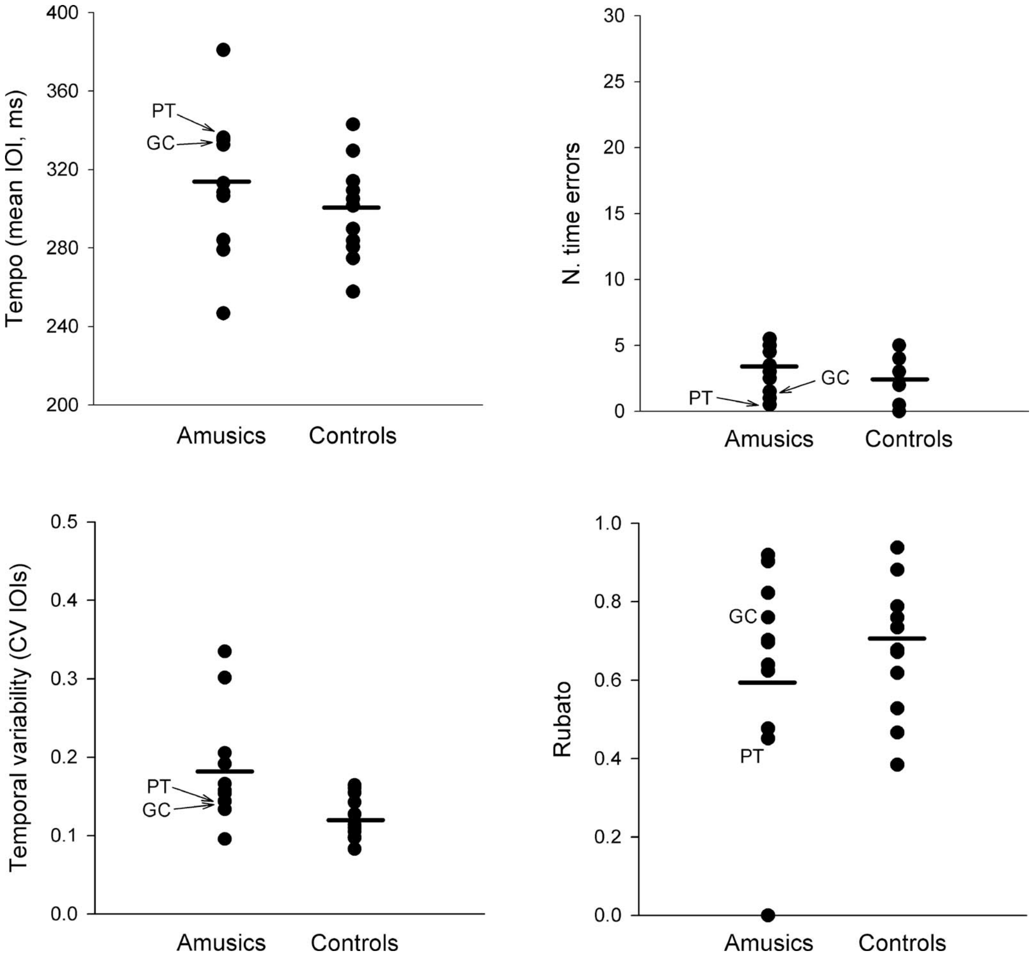

FIG. 4. Amusics' and controls' individual results for tempo, number of time errors, temporal variability, and rubato in the singing with lyrics condition. Horizontal lines indicate group averages.

(AS and MB) who were able to sing on /la/ were impaired on both the pitch and time dimensions. Deficits on the time dimension were always associated with poor-pitch singing (excluding the case of GC, for whom a difference in tempo cannot be considered as a real deficit). In addition, in keeping with what was found in the singing with lyrics condition, AS and MB were among the most impaired. Finally, we compared the performance of amusics who were able to sing on /la/ ($n=5$) in the two conditions (singing with lyrics and on /la/) using non-parametric tests (Wilcoxon). No significant differences were found.

D. Amusics' perceptual abilities

As noted above, the two amusics who were the most impaired on the MBEA were also the ones who sang most

TABLE III. Amusics' individual performance for pitch and time accuracy measures in the singing with lyrics condition ($n=11$).

Variable	AG	AM	AS	EL	FA	GC	IC	MB	PT	SR	TC
					Pitch dimension						
Pitch stability	--	--	--	−	--	−	--	−	+	--	+
No. of contour errors	+	--	+	+	−	+	--	--	+	--	--
No. of pitch interval errors	+	--	−	−	−	+	--	--	+	--	--
Interval deviation	+	--	--	−	--	+	--	--	+	--	--
					Time dimension						
Tempo	--	+	+	+	+	+	+	+	+	+	+
No. of time errors	+	+	+	+	+	+	+	+	+	+	+
Temporal variability	+	--	+	−	−	+	--	+	+	+	+
Rubato	--	+	+	+	+	+	+	+	+	+	+

+=normal, −=mildly impaired (>2 SD from controls), and −−=severely impaired (>3 SD).

TABLE IV. Amusics' individual performance for pitch and time accuracy measures in the singing on /la/ condition ($n=5$).

Variable	AG	AS	GC	MB	TC
Pitch dimension					
Pitch stability	--	--	+	+	--
No. of contour errors	+	+	+	--	−
No. of pitch interval errors	+	−	+	--	--
Interval deviation	+	--	+	--	--
Time dimension					
Tempo	--	+	−	+	+
No. of time errors	+	--	+	--	+
Temporal variability	+	--	+	+	+
Rubato	+	+	+	+	−

+=normal, −=mildly impaired (>2 SD from controls), and −−=severely impaired (>3 SD).

poorly (i.e., AM and IC). Similarly, amusics with mild perceptual deficits (i.e., with MBEA scores closest to cut-off) exhibited little impairment in sung performance (e.g., GC). However, there are notable exceptions. TC, the least impaired of the amusics (composite score=74.5), was very poor at singing (i.e., with 13 pitch interval errors, interval deviation=1.32 semitones on average, and 7 contour errors when singing with lyrics). Conversely, PT is one of the most severe cases of amusia (composite score=56.7), and yet sang as proficiently as controls. The observation that a severe amusic can sing proficiently, both in terms of pitch interval size and pitch direction, is very intriguing and is reported here for the first time. Indeed, the amusic individuals described by Loui *et al.* (2008) could correctly reproduce pitch direction of isolated intervals. Yet these same amusics were inaccurate in imitating pitch interval sizes and hence cannot be considered as proficient singers.

The puzzling case of PT may, in fact, be best explained by relatively spared pitch perception. PT obtained the best score on the pitch change detection task (81.2%, see Table I; this score is significantly lower than controls but clearly above chance). The pitch change detection task is a perceptual task that does not engage short-term memory whereas the MBEA is highly loaded in working memory demands. Most MBEA tests require the subject to hold a melody in memory in order to compare it to the same melody or to a slightly modified one. The fact that PT suffers from severe amusia (as indicated by her MBEA scores) may be due to poor short-term memory. In sum, her spared abilities to perceive small pitch changes may be sufficient to support feedback analysis, and ultimately, to support proficient singing. This possibility deserves further enquiry.

We also examined whether the singing results obtained in the other seven congenital amusics (i.e., AM, AS, EL, FA, GC, IC, and MB) who completed the pitch detection task could be related to their performance in pitch perception. Correlations were computed between accuracy in detecting pitch changes and pitch stability, number of contour errors, number of pitch interval errors, and interval deviation, as obtained in the singing with lyrics condition. Parametric correlation tests revealed that lower pitch change detection scores were associated with larger pitch instability ($r=-0.87$, $p<0.01$), more contour errors ($r=-0.83$, $p<0.05$), larger interval deviation ($r=-0.74$, $p<0.05$), and more pitch interval errors ($r=-0.67$, $p=0.07$, marginally significant). Thus, amusics' difficulties in pitch production were tied to their impairment in detecting pitch changes in an acoustical context. However, there was one exception. GC, one of the most proficient amusic singers performed quite poorly (<60% of Hits-F.A.) when asked to detect a pitch change. Thus, it seems possible to find cases who are able to sing in-tune despite the presence of a severe perceptual pitch disorder.

E. Analyses of melodic complexity

The musical material used in the production task (Chorus of "Gens du pays") might be easier than the musical selections presented in the MBEA. These differences in stimulus complexity may account for the pitch perception-performance mismatch observed here in some of the amusics. For example, cases such as PT (who exhibit poor scores on the MBEA but good singing abilities) might be due to differences in the musical material presented in the two testing situations. This possibility was examined by computing melodic complexity, based on both pitch and rhythm-related factors, for stimuli used in the three melodic tests from the MBEA (scale, contour, and interval tests), and for the chorus of Gens du pays, using the expectancy-based model of melodic complexity (Eerola and North, 2000). Complexity, as obtained with MATLAB MIDI toolbox (Eerola and Toiviainen, 2004), is a value that is based on the Essen collection (with mean=5 and SD=1). High values indicate large complexity. Gens du pays has a complexity of 4.54. Likewise, the average complexity of the melodies used in the MBEA is 4.53 (range=2.58–6.11). A further test was conducted by selecting ten melodies from the MBEA, which have complexity values in the vicinity of Gens du pays (i.e., the first five melodies above, and the first five below the complexity value 4.54). With this subset of melodies of average complexity, amusics are still performing below the cut-off score (<72.2%; see Peretz *et al.*, 2003), with the exception of GC (77%). The observed differences between perception and performance do not seem to result from differences in stimulus complexity.

IV. DISCUSSION

The results of the present study show that congenital amusia is characterized by poor singing. Amusic individuals could not maintain a stable pitch throughout singing and were inaccurate at producing pitch intervals; however, many succeeded in singing in-time. This singing pattern is consistent with the amusics' perceptual profile, which is characterized by impaired melodic pitch perception. As predicted, amusics' variability in singing proficiency was related to their ability to detect pitch changes (Hyde and Peretz, 2004). Amusics with markedly impaired ability to detect pitch changes were the most unstable in pitch production, made numerous pitch interval and contour errors, and exhibited significant pitch interval deviation from the score. However, amusics' impairment was not confined to pitch intervals of one semitone, as one would expect from their deficient detection of such pitch changes; the implications of this finding will be discussed below. Poor singers' deficits were very consistent across repetitions, thus indicating stable impairment. However, there were a few notable exceptions. PT, despite severely impaired melodic pitch discrimination on the MBEA, was able to sing quite proficiently with lyrics. In addition, GC, one of the best amusic singers, had severely impaired pitch perception. Thus, it seems possible to find cases who are able to sing relatively in-tune despite the presence of a severe perceptual pitch disorder. We will return to this paradoxical dissociation below.

When singing the same song without lyrics but on /la/, more than half of the amusics failed to sing more than a few notes. None of the controls experienced this difficulty. On the contrary, normal singers tend to sing more in-time when singing without words. This striking finding fuels the long-held debate as to whether lyrics and melody in songs are represented in a separate or integrated fashion. Lyrics and melody in songs have been previously treated as parts of an integrated representation (e.g., Serafine *et al.*, 1984, 1986); yet, neuropsychological evidence points toward separate codes in perception, memory, and performance (e.g., Besson *et al.*, 1998; Hébert *et al.*, 2003; Peretz, 1996; Samson and Zatorre, 1991).

This dissociation between singing with and without lyrics can be explained by weak memory traces of the musical component of songs. This hypothesis is consistent with the observation that five out of the six amusics who could not sing on /la/ were also impaired on the incidental memory test of the MBEA. Severe amusics might be able to produce complete performances with lyrics due to the benefit of the strong association between melody and text in memory or by relying on an integrated representation of melody and lyrics. When the task requires the association of a well-known melody to new speech segments, such as the repeated syllable /la/, retrieval of melodic information from memory alone may become impossible. Faulty memory for musical information may encourage amusics to rely on a melody-lyrics compound code. This faulty memory representation of melodies cannot be explained by melody complexity since complexity was comparable in the singing and memory tasks. Further work is needed to understand the origins of this poor memory for melodies.

Most congenital amusics sang out of tune but a few sang in-time. This finding mirrors neuropsychological dissociations between pitch and time previously uncovered in the perceptual domain with patients suffering from acquired and developmental music disorders (e.g., Peretz, 1990; Peretz and Kolinsky, 1993; Peretz *et al.*, 1994). This dissociation supports the notion that pitch and time processing may be governed by separable mechanisms both in perception and in performance.

Another intriguing observation relates to the apparent separability between perception and production. In the present study, as mentioned above, low pitch accuracy in singing is associated with poor-pitch discrimination, highlighting the close coupling between perception and action. Yet, amusics were inaccurate at producing pitch intervals far above one semitone, whereas such large pitch intervals lie well above the anomalously high threshold for detection of pitch changes in amusics (see Hyde and Peretz, 2004). Therefore, deficient low-level pitch perception cannot be the sole cause of amusics' poor-pitch singing. Indeed, amusics are also deficient in the melodic tests of the MBEA, which require comparing pitch intervals in a melodic context, which, with a few exceptions, differ by more than a semitone (see also Foxton *et al.*, 2004, for a similar finding). Thus, a more general musical pitch perception deficit is likely to be responsible for amusics' poor-pitch singing. This possibility is confirmed by the observation that the least proficient amusic singers were also the most severe amusics, as indicated by the MBEA. In sum, these findings are in keeping with the perceptual account of poor-pitch singing in congenital amusics but the origins must lie at a higher level than acoustical processing. One likely source of the difficulty experienced by amusics in musical pitch tasks is related to their difficulty in mapping pitch onto musical scales (Peretz, 2008).

However, there are notable exceptions. In a few amusics, perception and performance seem to dissociate. For example, PT, who suffers from a severe pitch perceptual defect, sang with lyrics as proficiently as controls. Conversely, TC, who had only mild problems on the pitch dimension in perception, was a very poor singer. In addition, we found support for dissociations between perception and performance at the level of the melodic contour. All amusics were impaired in perceiving contour changes in melodies, as assessed by the MBEA. However, five of them (AG, AS, EL, GC, and PT) were able to produce the correct contour when singing with lyrics. These findings are consistent with recent evidence of patients with impaired perception but spared production of pitch direction (Loui *et al.*, 2008). Together with previous evidence of poor-pitch singing in presence of unimpaired pitch perception (Bradshaw and McHenry, 2005; Dalla Bella *et al.*, 2007; Pfordresher and Brown, 2007; Wise and Sloboda, 2008) and of selectively impaired sung performance following brain damage without perceptual disorders (Schön *et al.*, 2003, 2004), these results point toward a double dissociation between pitch perception and production mechanisms (for a discussion, see Griffiths, 2008). These findings seem to question the more dominant view that perception and action share a common representational basis (e.g., Hommel *et al.*, 2001; Prinz, 2005, for a review). The latter model is supported by neurophysiological studies showing that neurons in the prefrontal cortex of the macaque monkey (i.e., mirror neurons) respond both during action execution (e.g., picking a nut) and during action observation (see Rizzolatti, 2005, for a review). The dissociations reported here between perception and performance rather argue for independence. However, task differences (i.e., production of well-known songs from memory vs novel melody discrimination) may account for the dissociation. Further studies with highly comparable perception/production tasks (see Loui *et al.*, 2008, for an example) are in order to clarify the degree of independence between the two musical pitch systems.

The surprising finding that two amusic cases were able to sing in-tune despite severely impaired pitch perception deserves particular attention. This dissociation is reminiscent of action-blindsight in vision (e.g., Danckert and Rossetti, 2005, for a review) where the lack of awareness for visual stimuli does not preclude implicit treatment of information by the visual system (e.g., sufficient for spatial localization by pointing or saccading toward the stimuli). Similarly, amusics are generally impaired on tasks (e.g., pitch change detection) requiring explicit analysis of pitch differences. This pitch perception deficit is associated with brain anomalies within right front-temporal cortical regions (Hyde *et al.*, 2006, 2007). Yet, in the two aforementioned amusic cases, an implicit pitch-tracking mechanism may still be functional. Such mechanism would allow the analysis of fine-grained pitch differences without conscious awareness, thus providing sufficient feedback information for proficient singing. Note that this implicit pitch-tracking mechanism cannot be studied by simply asking amusics to judge their own singing proficiency. Amusics are notoriously unaware of how they sing. Yet, implicit pitch-tracking may be uncovered by recording brain responses to pitch differences that amusics are not aware of (such as quarter-tone pitch differences; see Peretz *et al.*, in press, for supporting evidence).

In summary, the present study indicates that components of the general ability to sing fractionate as a result of a developmental anomaly. For example, the ability to produce pitch intervals can be selectively disrupted without disrupting time, thus confirming what we previously observed in normal participants (Dalla Bella *et al.*, 2007). Hence the detailed study of singing provides a rich source of information not only on the multiple processing components involved in music cognition but also on how spared knowledge can drive behavior in a more natural setting than perceptual experiments.

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[1] Note that the discrimination of one-semitone differences in repeating tone sequences is impaired in amusic individuals as compared to matched controls, but not abolished. This poor but residual ability to discriminate semitones in an impoverished tone context may not support reliable pitch encoding in a rich musical context where pitch intervals mostly vary between zero and three semitones (Vos and Troost, 1989; Peretz and Hyde, 2003).

[2] For simplicity, the condition in which participants sang *Gens du pays* on a syllable will be referred to as "singing on /la/" regardless of the fact that some of the patients sang the melody either on /la/ or on /ta/.

[3] Due to the small samples, non-parametric correlation coefficients (i.e., Spearman's rho) were reported instead of standard Pearson r coefficients.

[4] Analyses considering items (i.e., intervals) instead of participants as the random factor yielded the same results.

[5] Because compression is impossible in the case of the unison, data for this interval were not considered in this analysis.

[6] The same ANOVA considering subjects instead of intervals as the random factor yielded a main effect of interval size ($F(4,80)=3.30$, $p<0.05$). Group × interval size, and group × interval size × deviation type interactions did not reach significance. This might be due to the small sample sizes in each group.

[7] As can be heard from the examples, PT and GC may appear less confident than controls in sustaining pitch, although they sing quite proficiently. This potential difference between amusics and controls was not captured by the aforementioned measures of pitch accuracy. However, further analyses indicated that amusics did not significantly differ from controls in sustaining pitch within a vowel group.

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