An acoustical study of vocal pitch matching in congenital amusia

Sean Hutchins[a)]
International Laboratory for Brain, Music, and Sound Research (BRAMS), 1430 Boulevard Mont-Royal, Montréal, Quebec H2V 4P3, Canada and Department of Psychology, Université de Montréal, 1430 Boulevard Mont-Royal, Montréal, Quebec H2V 4P3, Canada

Jean Mary Zarate and Robert J. Zatorre
International Laboratory for Brain, Music, and Sound Research (BRAMS), 1430 Boulevard Mont-Royal, Montréal, Quebec H2V 4P3, Canada and Cognitive Neuroscience Unit, Montreal Neurological Institute, McGill University, 3801 Rue University, Montréal, Quebec H3A 2B4, Canada

Isabelle Peretz
International Laboratory for Brain, Music, and Sound Research (BRAMS), 1430 Boulevard Mont-Royal, Montréal, Quebec H2V 4P3, Canada and Department of Psychology, Université de Montréal, 1430 Boulevard Mont-Royal, Montréal, Quebec H2V 4P3, Canada

Vocal pitch matching is a foundational skill for singing and is an interesting place to study the relationship between pitch perception and production. To better understand this relationship, we assessed pitch-matching abilities in congenital amusics, who have documented disabilities in pitch perception, and in matched controls under normal, masked, and guided feedback conditions. Their vocal productions were analyzed for fundamental frequency and showed that amusics were significantly less accurate at pitch matching than the controls. However, five of the six amusics showed a significant correlation between their produced pitches and the target pitch. Feedback condition had no effect on pitch-matching accuracy. These results show impaired vocal pitch-matching abilities in amusics but also show a relationship between perceived and produced pitches. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3270391]

I. INTRODUCTION

Congenital amusia, commonly referred to as "tone-deafness," is characterized by the inability to consciously detect small pitch changes, recognize familiar tunes, or detect out-of-key notes in melodies (Ayotte *et al.*, 2002; Peretz, 2001; Peretz *et al.*, 2003). Prior studies have also linked amusia to worse-than-normal singing. Compared with normals, who are relatively proficient singers (Dalla Bella *et al.*, 2007; Pfordresher and Brown, 2007), congenital amusics are judged as having impaired singing abilities (Ayotte *et al.*, 2002). Acoustic analyses show that amusics are, on average, substantially worse at singing familiar melodies than normals (Dalla Bella *et al.*, 2009). These differences are amplified when the amusics are asked to sing using a neutral syllable (/la/) in place of lyrics, suggesting that most of the (relatively slight) proficiency the amusics do show in singing production may be due to long-term memory cues from pitches associated with lyrics.

However, this same study (Dalla Bella *et al.*, 2009) also provided evidence that auditory perception and action streams may be distinct in some ways. This study identified two congenital amusics who showed preserved singing abilities, despite their severe pitch perception deficits. In addition,

Loui *et al.* (2008) showed that amusics can vocally mimic the direction of intervals played to them. In their study, amusics could produce an interval in the same direction as a perceived interval, although their productions were at different absolute pitches and interval magnitudes; however, they were less accurate at naming the direction of the same interval (by saying "up" or "down"). This dissociation between conscious perceptual and production abilities is further supported by reports that quarter-tone differences in pitch can evoke electrophysiological responses without perceptual awareness in amusics (Peretz *et al.*, 2009). These reports suggest that sensory information about pitch is entering the system in amusics, and that some pitch discrimination abilities may be preserved (perhaps as an auditory analog to the visual perception phenomenon of blindsight, specifically the action-blindsight subtype, as categorized by Danckert and Rossetti (2005). These residual abilities may be too weak to support conscious perception but may be best expressed in production responses. Thus, although amusics are often reported to lack singing proficiency, this may be neither absolute nor universal. It is, therefore, important to more fully understand the pitch production abilities of amusics, both as a group and at the individual level.

Here, we tested amusics' ability to vocally match heard pitches. Pitch matching is a fundamental musical skill, considered to underlie many core musical abilities, and to be the most important factor in judging singing talent (Watts *et al.*,

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[a)]Author to whom correspondence should be addressed. Electronic mail: sean.michael.hutchins@umontreal.ca
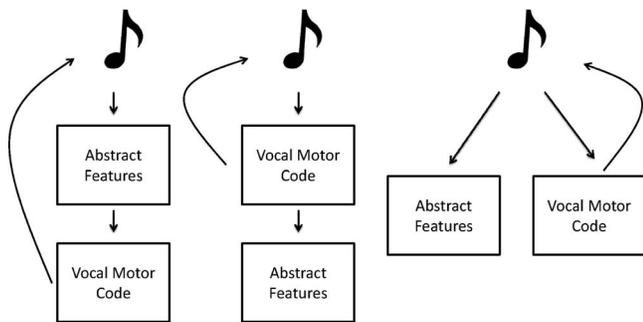
FIG. 1. Three possible models describing the relationship between perceived sounds, abstract feature categorization, the vocal-motor code, and auditory feedback.

2003). Despite the relative importance of this factor in singing (one of the most common means that people engage in music production), pitch matching is relatively unstudied as a phenomenon. The vast majority of the literature concerning pitch matching has been undertaken from a pedagogical standpoint and focuses on young children or adolescents. These studies have suggested several factors that may lead to poor pitch-matching abilities, including poor pitch discrimination (Pederson and Pederson, 1970), vocal control (Jones, 1979), and problems with normal developmental maturation (Goetze et al., 1990). In addition, pitch matching seems to be aided by use of a limited and appropriate range for the singer as well as by the timbral similarity of the model (Goetze et al., 1990). Pfordresher and Brown (2007) found that 87% of non-musicians could vocalize within one semitone of a target pitch, and that the instances of poor-pitch singing could not be attributed to poor perceptual abilities.

Pitch matching is an interesting place to study the relationship between perception and production because it represents the conceptually simplest interface between the two areas in the domain of pitch. Figure 1 shows three models outlining possible relationships between perceived notes in the environment, our brains' ability to abstract conceptual features of the heard note, and the motor codes underlying our ability to produce the pitch vocally. In each of the models, tones are present in the environment and are picked up by our sensory apparatuses. Two types of processes may subsequently ensue, based on the task demands. In the case of many standard perceptual tasks, the tone may need to be categorized, classified, and compared. This requires accessing abstract features of the tone, including a consciously accessible, symbolic representation of its (relative) pitch. A vocal pitch-matching task, however, does not necessarily require access to the abstract features of a tone but does require access to the vocal-motor code specific to that pitch. The leftmost diagram in Fig. 1 shows a traditional explanation of the relationship between these two types of processes. This model presumes that tones are first processed for their abstract features, which are then mapped to vocal-motor codes for production. Pitch matching in this model is mediated by the abstract representations of pitch. The middle diagram outlines a motor theory of pitch production, in which tones are first processed in terms of the motor codes necessary to produce the pitches, and then categorized into their abstract

features, including a symbolic representation of pitch (as in Liberman and Mattingly, 1985, for speech), but only if necessary for the task. Finally, the rightmost diagram in Fig. 1 shows a dual-route model, in which the vocal-motor code and abstract feature representation are accomplished by separate subsystems and need not be intrinsically related to each other. Each model can also receive auditory feedback from hearing one's own singing. To be clear, in all of these models, both abstract and motor codes include a representation of pitch. However, the abstract representation yields a categorical representation necessary for decision-making, and the motor code represents pitch solely in terms of motor activity. Furthermore, these models do not dispute that other motor code representations of pitch may be present, for example, in trained instrumentalists; however, the vocal-motor code should be present in all normal individuals.

The rightmost model shown in Fig. 1 bears a resemblance to other dual-route processing models, especially that of Hickok and Poeppel (2004). In their model, speech processing is handled by two separate subsystems, one of which maps speech sounds onto conceptual representations, while the other maps speech sounds onto motor representations. These two subsystems are neurally instantiated in two processing streams, i.e., the ventral and dorsal pathways, respectively. The ventral stream is used for conceptually oriented tasks, and the dorsal is used for production-oriented tasks. Other studies have also shown production and perception task dissociations. Goodale and Milner (1992) and Milner and Goodale (1995) proposed a similar division of labor within the visual system, with the ventral stream responsible for conceptual processing and the dorsal stream responsible for vision-for-action. Danckert and Rossetti (2005) described a dissociation between types of residual abilities found in patients with blindsight. Patients with residual ventral stream pathways show residual abilities in conceptual tasks, including discrimination and decision tasks, whereas patients with residual dorsal stream pathways show better performance in action tasks, such as grasping, pointing, or saccades.

In general audition, dual-pathway models have also been gaining some support. Some neuroscientists have suggested that ventral and dorsal pathways process auditory signals for information concerning "what" and "where," respectively (Rauschecker, 1998; Warren and Griffiths, 2003). However, others have proposed that the ventral and dorsal pathways may be better thought of as conceptual and action pathways, similar to the case of vision (Warren et al., 2005). Hickok and Poeppel's (2004) dual-route model of speech processing also falls under this organization schema of a ventral comprehension pathway and a dorsal production pathway. Indeed, recent findings on music processing also show evidence of a separable action stream (Griffiths, 2008). For example, Hafke (2008) showed vocal adjustments in trained singers to pitch-shifted feedback even when these shifts were not overtly perceivable. The work of Loui et al. (2008) also pointed toward separate streams of processing, as the amusic subjects were better able to process pitch information using sung responses than same-different judgments.

In theory, the pattern of errors we see in amusia for pitch-matching tasks can help us rule out particular models.

TABLE I. Amusic and control participant characteristics. Asterisks indicate amusic participants. MBEA global score refers to the average score across the six tests of the Montreal Battery of Evaluation of Amusia (Peretz et al., 2003). Pitch discrimination threshold refers to minimum pitch difference between tones needed for participants to be able to discriminate them 75% of the time (Hyde and Peretz, 2004). Trials completed refers to the number of vocal pitch-matching recordings obtained.

Subject	Age	Gender	Years of education	Years of music education	MBEA global score	Pitch discrimination threshold (in cents)	Trials completed
IC*	65	M	19	1	51.1	100	119
GC*	61	F	20	1	72.7	100	116
FA*	67	F	15	2	69.4	50	89
MB*	65	F	21	4	71.1	50	118
AS*	67	F	14	2	62.7	50	57
JL*	70	M	15	1	73.8	50	120
CL	57	F	16	3	90	25	107
GB	62	F	19	2	90.5	25	120
FB	57	F	13	2	91.6	25	119
RS	63	F	18	2	93.3	25	120

For example, if vocal pitch-matching is mediated by abstract pitch categorization of the perceived target note, performance on the former task should be as bad or worse than on decision tasks only requiring abstract pitch categorization. However, if amusics show better performance on pitch-matching tasks than on decision tasks, this points toward a motor model or dual-route model. Based on Loui et al.'s (2008) findings, we expect that amusics should be better at this pitch-matching task than their perceptual deficits would suggest, arguing against a vocal-motor code mediated by abstract categorization of pitch.

Another important way in which the relationship between perception and production has been studied is in terms of feedback. It is a well-known phenomenon that delayed auditory feedback can severely disrupt speech and music production (Finney, 1997; MacKay, 1987). In both speech and singing, shifting the pitch of the feedback a subject receives from her own voice can result in an automatic correction in the other direction (Burnett et al., 1998; Burnett and Larson, 2002; Natke et al., 2003). Altered feedback can also disrupt instrumental (piano) performance, regardless of skill level or experience (Pfordresher, 2005). Additionally, previous studies have shown that masking auditory feedback reduces pitch-matching accuracy (Anstis and Cavanagh, 1979; Elliott and Niemoeller, 1970; Mürbe et al., 2002; Ternström et al., 1988). These studies show that, under normal conditions, people are sensitive to the pitch, timing, and amplitude of the feedback they receive from their own voice or instrument. Pfordresher and Brown (2007) examined singing performance under three difference feedback conditions. They found that augmenting feedback (by playing the correct tones along with the sung responses) could help intervallic precision somewhat but had a small negative effect on pitch-matching abilities of poor singers. Masking the feedback had little effect on vocal performance. Wise and Sloboda (2008), on the other hand, found that accompaniment could aid pitch matching in a singing task. Manipulating the feedback to amusics during a pitch-matching task will help us understand how they use perceptual information to guide their productions. If amusics rely on feedback to guide their production, this would show evidence for a link between perception and production.

We hypothesized that performance would be affected by manipulations of the acoustic feedback. Compared with no feedback manipulations, we hypothesized that amusics and controls should match pitches more accurately when the target was re-presented as the participants began to sing (similar to Wise and Sloboda, 2008). In contrast, eliminating most of their auditory feedback through masking with noise should cause a decrease in pitch-matching accuracy (Anstis and Cavanagh, 1979; Elliott and Niemoeller, 1970; Mürbe et al., 2002; Ternström et al., 1988). This would indicate that amusics are sensitive to their own feedback and could point toward a way to improve amusics' vocal performance. We also expect to find a range of vocal pitch-matching abilities among amusics, who should be less accurate than controls. Because any inaccurate production can reasonably be attributed to perceptual difficulties, their average error should be related to the degree of perceptual deficit.

II. METHODS

A. Participants

Participants included six amusics (four female) and four non-amusic controls (all female). Amusics were determined by the scores on the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003). This battery assesses the components of music processing with a total of six sub-tests concerning melody, rhythm, meter, and memory. Amusics obtained a global score over two standard deviations below controls (amusic mean score=67.6% and control mean score=91.4%) but had normal hearing. Controls were matched for age (amusic mean age=65.6 and control mean age=59.8). Table I shows individual participant information for controls and amusics, including ages, education levels, MBEA global scores (the average score on all subtests of the MBEA, Peretz et al., 2003), and pitch discrimination thresholds (the minimum pitch difference between two tones needed for participants to be able to discriminate them over 75% of the time).
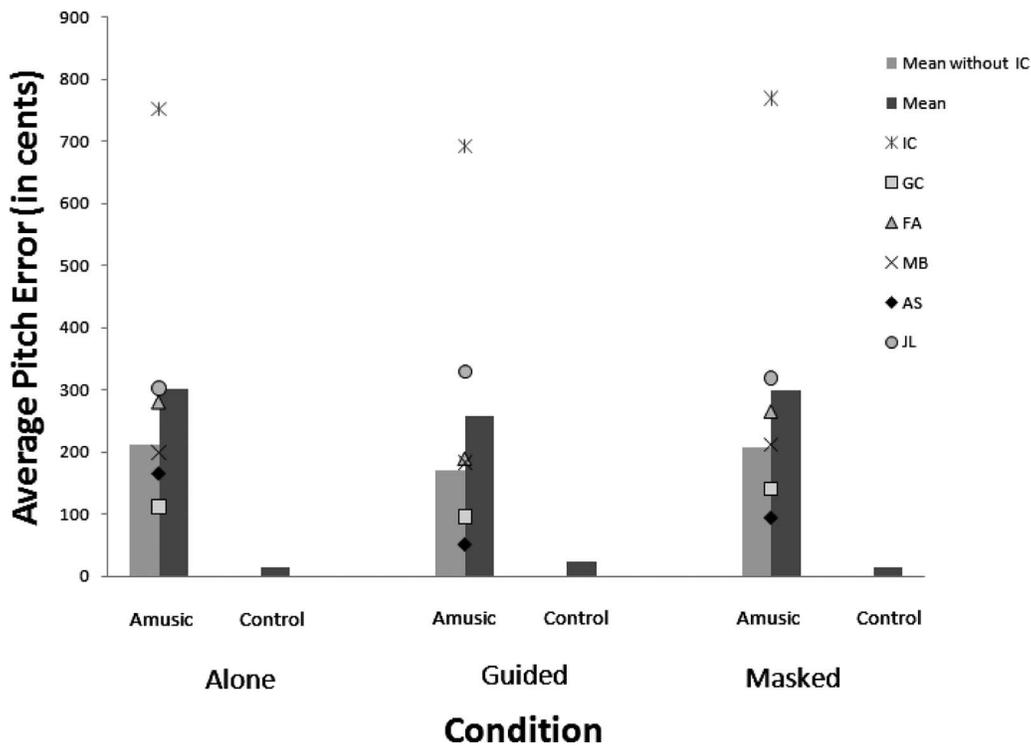
FIG. 2. Average absolute pitch errors of each amusic and control across feedback conditions. Mean for amusics is shown, both including and excluding IC.

B. Stimuli and equipment

Stimuli consisted of vocal tones with a duration of 2000 ms presented over Beyerdynamic DT770 pro headphones (Beyerdynamic GmbH & Co. KG, Heilbronn, Germany). Tones were presented at five pitches for each participant; males heard tones at D#3 (156 Hz), F3 (175 Hz), G#3 (208 Hz), B3 (247 Hz), and C#4 (277 Hz) in a male voice, and females heard female vocal tones 1 octave above those presented to males. Participants were visually cued on a computer screen to sing back the note for 4 s. All vocalizations were captured using a Shure 565D microphone (Shure Inc., Niles, IL) and recorded onto a Marantz PMD-670 digital recorder (Marantz Professional, Itasca, IL). The vocal signal was routed through a VoiceOne digital signal processor (TC Helicon Vocal Technologies, Westlake Village, CA) before it was presented to the participant as auditory feedback; for one particular task, the digital signal processor was programed to turn off the auditory feedback (see Sec. II C). We also presented pink noise to ensure that the main source of auditory feedback would stem from the digital signal processor. All auditory stimuli, including the participant's own vocal feedback, were delivered to the headphones through a mixer, where all volume levels were adjusted to comfortable levels for each participant. Pink noise was delivered at an average of 73.3 dB sound pressure level (SPL) A, and the vocal tones were presented an average of 9.7 dB above the pink noise. The experiment was run using MEDIA CONTROL FUNCTIONS (MCF) software (DigiVox, Montreal, Canada).

C. Procedure and design

Three response conditions were presented to each participant: alone, guided, and masked. In the alone conditions, participants heard the stimulus tone and attempted to vocally match it after the target tone finished sounding. In the guided condition, participants heard the stimulus tone and attempted to match it while the tone was presented again for 4 s. The masked condition had participants match the target tone while not receiving any vocal feedback; pink noise was the only auditory stimulus delivered to the headphones as participants sang. The experiment was composed of 120 trials; however, due to fatigue, some participants completed fewer than this (see Table I).

III. ANALYSIS AND RESULTS

A. Pitch analysis

Pitch analyses were conducted using YIN, a pitch analysis program available in MATLAB, which outputs fundamental frequency, aperiodicity, and signal power every 32 samples or a rate of 1378 Hz (de Cheveigné and Kawahara, 2002). These fundamental frequency outputs were converted into cents, using the originally presented vocal tones as the target frequencies, in order to allow for meaningful comparisons between trials on different pitches. For each sung tone, we analyzed the mean pitch, excluding the first and last 100 ms of each vocalization. The absolute errors were used in analyses concerning pitch errors to avoid sharp and flat errors canceling each other out, but pure pitch heights were used for comparisons between mean produced pitch heights and targets.

B. Data analysis

Figure 2 shows mean pitch errors for each amusic and control across alone, guided, and masked conditions. Results were computed with the Greenhouse–Geisser corrections when the assumptions of sphericity were violated. A 3×5

TABLE II. Correlation for each amusic and controls between target and produced pitches (as measured in cents), as well as average standard error for each subject at each target pitch. Asterisks denote that the correlation is significant. The numbers in parentheses next to the note names represent the relative distance in cents from C3 in males and C4 in females.

| | Correlation | Std. error | | | | |
		D# (300)	F (500)	G# (800)	B (1100)	C# (1300)
IC	0.13	15.54	13.12	17.86	17.64	13.62
GC	0.92*	23.57	25.95	19.58	22.50	21.33
FA	0.81*	103.10	118.91	137.19	75.58	101.18
MB	0.82*	55.17	67.06	39.79	37.37	29.48
AS	0.89*	20.01	43.29	54.71	44.74	14.46
JL	0.85*	24.71	37.12	48.78	49.80	25.50
Controls	0.99*	11.45	7.89	6.57	9.33	6.91

$\times 2$ mixed design analysis of variance (ANOVA) on the mean pitch errors, comparing the three feedback conditions (alone, guided, and masked), five pitch heights, and two participant groups (amusic and control) revealed the main effect of participant group to be approaching significance ($F(1,8) = 4.99$, $p = 0.056$). A non-parametric Mann–Whitney U test was subsequently run comparing amusics and controls, due to the small sample size, which showed a significant difference of participant group [$U(4,6) = 0$, $p = 0.01$]. Amusics had significantly larger errors in pitch matching than did controls. No other main effects or interactions reached significance. Further inspection of the data revealed that one amusic participant (IC) did not substantially change the pitch of his vocalizations across the different target pitches. An ANOVA comparing the pitches of each of IC's vocalizations (in fixed terms rather than relative to the target pitch) showed no differences between the productions for each target pitch $F(4,114) = 0.53$, n.s. Notably, this participant also showed the lowest global MBEA score, by a wide margin (see Table I). When IC was removed from the analysis, the pattern of results remained the same as presented above, with the main effect of participant group rising just above significance in the parametric test [$F(1,7) = 6.07$, $p = 0.043$].

We also examined correlations between the pitch height of the sung tones and of the targets. Using each of the six amusics' average pitch heights (in fixed terms relative to C3 in males and C4 in females) for each of the five target pitches, this correlation was $r(29) = 0.72$, $p < 0.01$. When IC was removed from the analysis, this correlation rose to $r(24) = 0.94$, $p < 0.01$. The correlations for each amusic and control participants are presented in Table II, as well as the standard errors for each participant, as a measure of precision. Figure 3 shows the individual pitch-matching performances for each target note collapsed across feedback conditions, as well as regression and R^2 values. With the exception of IC, amusics reliably produced higher pitches in response to higher targets. Amusics produced responses to target pitches with standard errors less than half a semitone, which is small enough to make their responses distinguishable from responses to other target pitches, and shows that there was not much overlap between their attempted pitch matches to different target pitches. These relationships between target and produced pitches did not differ between feedback conditions.

IV. DISCUSSION

These data demonstrate that amusics are indeed significantly worse than controls at matching pitches vocally. Although there was considerable variation between the amusics' performances, the most accurate amusic singer (GC) was still much less accurate than any matched control subject. The perceptual deficits shown by amusics thus seem to be accompanied by production deficits. However, despite their inaccurate performance, five of the six amusics showed a very clear relationship between the target pitch and their produced pitch, with R^2 values ranging from 0.66 to 0.85. For each target pitch, these amusics typically had a constant degree of pitch error, with average pitch responses ranging from very close to the target pitch, as in the case of GC, to averaging nearly three semitones flat, in the case of JL. The amusics typically had standard error measurements averaging around 50 cents. This shows a good deal of vocal precision and provides evidence that they are producing a different response to each of the five pitch heights; however, none reached the level of precision attained by the controls. The vocal precision shown by these five amusic subjects is surprising, given their lack of ability to perform perceptual decision tasks, such as detecting an anomalous note in a melody. It should be noted that the five target pitches presented spanned a range of ten semitones, covering a large vocal range. Because each target tone differed from its nearest neighbors by 200 or 300 cents, the targets were above the discrimination threshold of the amusics. Their ability to discriminate between the different target tones may explain the pattern of results. However, this is unlikely to be the sole reason for their ability to produce different responses to each tone, given that, in other experimental paradigms, amusics have shown the ability to produce vocal responses, which discriminate between targets differing by less than a semitone (Loui *et al.*, 2008).

The different response range for each target pitch and high correlation between targets and produced pitches indicates a fairly well-preserved pitch production ability. This shows evidence that the link between the input and vocal output is not completely severed. However, even among the
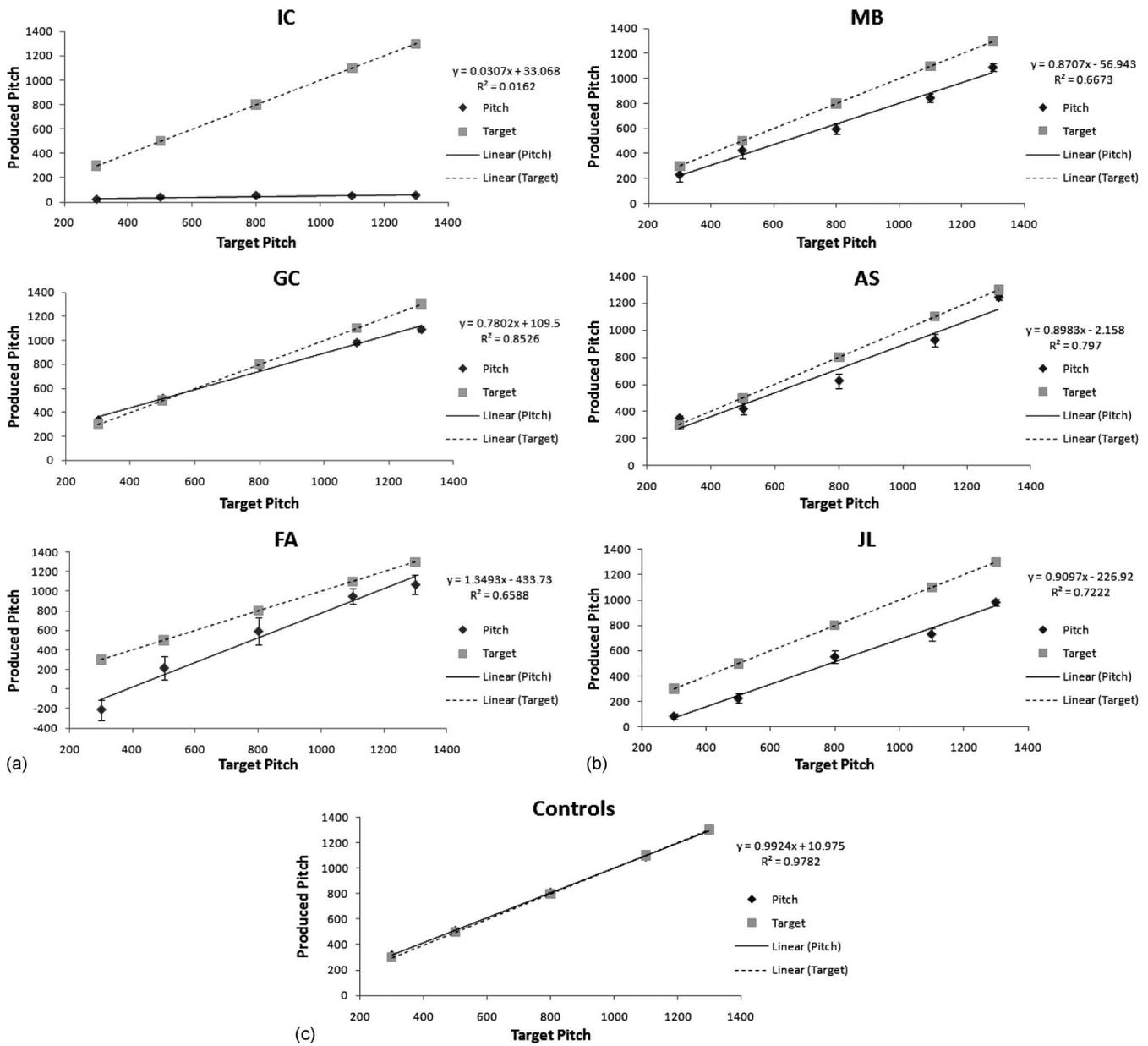
FIG. 3. The mean pitch (in cents) produced by each amusic and all controls for each of the five pitch heights with standard error bars and regressions comparing their performance to the targets and R^2 values. The data are collapsed across octaves between genders. 0 cents here refers to C3 for males and C4 for females.

five amusics who showed this pattern, there was a fairly constant downward shift from target pitches to produced pitches. Each amusic had a different degree of shift present in their responses, but all shifts were more or less constant across target pitches (with a slight tendency for greater downward shifts at higher target pitches). It is unlikely that this shift is a result of vocal range limitations, as it occurs nearly equally at all target pitches. Such a shift may be systematic, meaning that these amusics have distinct representations of vocal-motor codes for each pitch, which are linearly related to the auditory input. In this case, a constant shift may arise from their perceptual deficiencies, perhaps from an inadequate comparison between the vocal output and the target, which would be consistent with the lack of effect found for feedback condition in this experiment as well.

An alternative account for this shift is that each pitch may be mapped onto vocal productions in a manner that is based on the target range and is non-linear, but still preserving order. In this account, target pitches are categorized relative to the range of targets in a manner similar to Braida and Durlach's (1988) and Durlach and Braida's (1969) context coding mode in intensity perception. However, this account relies on positing that target pitches are constantly being compared to each other in memory, which is not necessary for a straight pitch-matching task. However, both of these accounts hold that the unique mapping between targets and vocal productions is no coincidence. Most amusics can perceive these pitch differences and possess the vocal control to produce different responses to each pitch.

In contrast to these patterns, IC showed no relationship between target pitches and his productions. This subject is

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one of the most severe cases of amusia and showed no indication of distinguishing between different pitch heights. This trend provides a sharp contrast to that of the other five amusics, who did show different responses to each pitch. Other studies with IC have indicated that he is able to produce pitches at different heights (Dalla Bella *et al.*, 2009), demonstrating that this pattern of results is not due to total vocal monotonicity. IC may represent a subpopulation of amusics who have severely impaired vocal production abilities in addition to their impaired perceptual abilities. A task for future research will be to determine how many different subtypes of amusia may exist, and what their relative prevalence may be.

The considerable degree of pitch-matching ability showed by most amusics demonstrates a partially preserved, but consciously inaccessible, perception ability. The fact that some perceptual abilities can be shown among amusics in this and other production-based experiments (Dalla Bella *et al.*, 2009; Loui *et al.*, 2008) provides evidence that vocal production does not necessarily require a conscious perceptual representation. Amusics' relatively high level of precision in the vocal pitch-matching task (less than half a semitone standard error) suggests that a motoric representation may exist apart from conscious perception. This study highlights an association between pitch input and vocal production output as well as a dissociation between vocal production and discrimination judgments as output measurements. A model that assumes first a coding of pitch based on its perceptual attributes, which is subsequently translated into a motor representation for production, would have a difficult time explaining this pattern. While we do not wish to oversell the vocal abilities of amusics, which are still considerably worse than controls, the fact that motoric types of responses tend to display better underlying knowledge of pitch than perceptual types of responses in amusics argues against this viewpoint, and for a direct link between perception and a motor representation of pitch. Although this pattern of results cannot directly discriminate between a motor theory and a dual-route theory, the fact that other individuals whose pitch discrimination and categorization abilities outstrip their singing abilities exist (see, for example, Pfordresher and Brown, 2007; Dalla Bella *et al.*, 2007) suggests a dual-route theory.

A dual-route model is also supported by neuroscience evidence. Specifically, several authors have suggested that auditory-motor integration, in general, likely involves interactions between posterior-dorsal auditory cortex and premotor regions (Hickok *et al.*, 2003; Zatorre *et al.*, 2007). In the case of auditory-vocal control for singing, a network has been identified that includes the auditory cortex, insula, supplementary motor area, and anterior cingulate (Brown *et al.*, 2004; Kleber *et al.*, 2007; Perry *et al.*, 1999; Özdemir *et al.*, 2006), together with parietal and premotor cortical regions (Zarate and Zatorre, 2008; Zarate *et al.*, 2009), which are specifically important for auditory-vocal integration. These cortical regions are primarily found within the dorsal stream of auditory processing, implying that it is this system that is responsible for transforming auditory representations of pitch information into vocal production of pitch, as is the case for speech, but with more of a right-hemisphere bias for pitch. Critically, recent studies of anatomical anomalies in amusia have identified anteroventral frontal regions (Brodmann area 47) and anteroventral temporal auditory cortices (BA 22) as sites of likely dysfunction (Hyde *et al.*, 2006; Hyde *et al.*, 2007; Mandell *et al.*, 2007). Putting together these anatomical studies which suggest that the ventral pathway is compromised, with the functional studies in normal singing showing that the dorsal pathway is recruited for pitch production, leads to the conclusion that the relatively spared singing capacity of amusics uncovered in the present study may well be the result of a partly functional dorsal pathway, whereas the major impairment in conscious pitch perception may be due to disconnection in a ventral route. Recent diffusion tractography data (Loui *et al.*, 2009) showed reduced connectivity in the dorsal pathway of amusics, however. This finding may be related to the fact that pitch matching is still impaired in amusics, even if it is relatively more preserved than pitch discrimination or may reflect differences in the populations studied. Nonetheless, such data will have to be reconciled with models proposing that auditory-motor interactions in speech take place primarily via a dorsal pathway (Hickok and Poeppel, 2004; Rauschecker and Scott, 2009), as they also do in vision (Milner and Goodale, 2008); this type of model would be in keeping with the proposal of a relative sparing of this system in amusia to the extent that the present data, and the data of Loui *et al.* (2008), demonstrate a greater degree of spared pitch production than perception.

The fact that the amusics' performance was not affected by feedback condition may indicate that they are behaving similarly to musically normal participants in this respect. The matched controls were neither aided nor hindered by providing more target pitch information (guided condition) or by masking the feedback through noise (masked condition), compared with the unaltered feedback condition (alone condition). This is similar to the effect found by Pfordresher and Brown (2007) for the monotonic (no pitch change) sequences. Their study used similar feedback conditions as the ones used here and found no effect of masking on singing performance. However, their guided condition led to different results for different skill groups. Among the accurate-singing non-musicians, guiding aided the production of the more complex stimuli (with multiple pitch changes). However, guiding tended to engender even less accurate singing among the 13% of participants who were poor-pitch singers. This inaccurate singing could not be attributed to perceptual difficulties. Our current data show a similar lack of feedback effect in all groups, although we do not see a hindrance from the guided condition. The lack of effect of feedback on performance may indicate that perception does not influence production control of single sung tones, and that perception and production constitute separable streams. However, this non-effect of feedback may have different root causes in amusics and normals. Whereas controls may not need to rely on external feedback to control their voices, amusics' perceptual difficulties may render them unable to recognize potentially useful sources of pitch feedback.

It also should be noted that all congenital amusics in this study were a great deal worse at the music perception tasks than non-amusics (by definition). Although there were not enough data to provide reliable correlations, there was gen-

erally better performance on the production task among amusics who scored higher on the MBEA. The performance of individual amusics also seems to be consistent between this pitch-matching task and the melodic singing data reported by Dalla Bella *et al.* (2009), which included the data of five of our six amusic participants. IC, who was categorized as particularly error-prone in that study, had a very high mean error in this study as well, and GC, who Dalla Bella *et al.* (2009) classified as a particularly good amusic singer, was also good, although still impaired, in the present pitch-matching study. This suggests consistency between pitch-matching and melodic singing tasks.

In conclusion, these data confirm that amusics do show impaired pitch-matching abilities compared to controls, across different pitch heights and feedback conditions. However, among amusics, there is a range of production abilities. The deficit in pitch matching can be attributed to their core deficit in pitch perception, and constitutes one of the most noticeable effects of amusia in daily life. As more research becomes available on the pitch-matching abilities of neurologically normal adults, finer comparisons between amusics and non-amusics on this subject will be possible.

ACKNOWLEDGMENTS

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