The effect of superior auditory skills on vocal accuracy

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The relationship between auditory perception and vocal production has been typically investigated by evaluating the effect of either *altered* or *degraded* auditory feedback on speech production in either normal hearing or hearing-impaired individuals. Our goal in the present study was to examine this relationship in individuals with *superior* auditory abilities. Thirteen professional musicians and thirteen nonmusicians, with no vocal or singing training, participated in this study. For vocal production accuracy, subjects were presented with three tones. They were asked to reproduce the pitch using the vowel /a/. This procedure was repeated three times. The fundamental frequency of each production was measured using an autocorrelation pitch detection algorithm designed for this study. The musicians' superior auditory abilities (compared to the nonmusicians) were established in a frequency discrimination task reported elsewhere. Results indicate that (a) musicians had better vocal production accuracy than nonmusicians (production errors of 1/2 a semitone compared to 1.3 semitones, respectively); (b) frequency discrimination thresholds explain 43% of the variance of the production data, and (c) all subjects with superior frequency discrimination thresholds showed accurate vocal production; the reverse relationship, however, does not hold true. In this study we provide empirical evidence to the importance of auditory feedback on vocal production in listeners with superior auditory skills. [DOI: 10.1121/1.1536632]

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I. INTRODUCTION

Auditory feedback influences speech and vocal production in a complex manner. Typically, this relation has been studied extensively by examining the effect of either *altered* or *degraded* auditory feedback on speech production in either normal hearing or hearing-impaired population. Few studies, however, have examined this relation in populations with *superior* auditory abilities such as musicians. Our goal in the present study was to evaluate whether musicians, who demonstrate superior auditory skills, would also have higher vocal production accuracy.

Studies with normal-hearing individuals showed immediate voice changes when auditory feedback was altered: vocal intensity increased when individuals were subjected to background noise (also known as the Lombard effect),[1] the speech rate decreased when auditory feedback was artificially delayed,[2] and fundamental frequency changed when auditory feedback frequencies have been altered.[3] A more recent study reported changes in vowel production to compensate for feedback alterations in the first three formants of the vowel; changes that were large enough to influence the vowel's perceived phonetic identity.[4] These data support the hypothesis that auditory information is used in a closed-loop system, which provides moment-to-moment feedback for the control of vocal production.

Studies with the hearing impaired showed differences in the role of auditory feedback on speech production between those deafened after speech and language acquisition had been completed (postlingual) and those deafened before the age of two (prelingual). In *post-lingually* deafened adults, hearing loss had a minimal effect on speech *intelligibility* but a slow and gradual effect on certain speech and *vocal parameters*.[5–14] The data support the hypothesis of a predominantly open-loop speech motor control system once the speaker establishes the relationship between motor commands and resulting sound output (as occurs in individuals with the late onset of deafness). It is in those cases that the speaker uses their knowledge to compute the motor sequence for desired speech/vocal production in the absence of auditory feedback.[15]

In *prelingual* hearing-impaired children, the absence or partial auditory information prior to and during speech acquisition has a deleterious effect on speech production and its intelligibility.[16–18] These children develop abnormal phonemic-motor patterns because of their need to rely on visual, tactile and proprioceptive feedback.[19–21] The fact that the partial restoration of hearing after many years of auditory deprivation does not result in good speech production skills supports the nonlinear relationship between perception and production and the involvement of additional factors such as the plasticity of the speech production mechanism to accept changes.

While the hearing impaired represent one end of the auditory abilities spectrum, musicians are typically viewed as representing the other end of this spectrum. As discussed above, the deleterious effect of absent or degraded auditory abilities on speech and vocal production have been widely demonstrated. Yet, it is not clear whether individuals with exceptional auditory abilities (e.g., musicians) would also demonstrate better-than-normal vocal abilities.

The superior auditory performance of musicians has

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been established on tests that reflect specific facets of music and on basic psychoacoustic tasks. Musicians demonstrated superior processing of timbre and rhythm,[22] the identification of mistuned harmonics,[23] the labeling of musical intervals (frequency ratio),[24–26] musical memory,[27] and a smaller difference limen for frequency (DLF).[28–30]

Physiological data suggest that the differences in behavioral tests between musicians and nonmusicians stem from neurological and/or functional differences in the auditory system. Micheyl,[31] for example, found that musicians demonstrated a significant reduction in cochlear emission in response to contralateral stimuli, suggesting different auditory-nerve efferent activity in musicians compared to nonmusicians. Functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) showed a pronounced hemispheral asymmetry in the planum temporal among musicians, which is assumed to be related to their superior auditory abilities.[32] Studies of Evoked Related Potentials (ERPs) reported musicians to exhibit a larger P_3 in response to music stimuli compared to nonmusicians.[33] Musicians also showed increased neural activity (using magneto encephalography) in response to musical tones compared to pure tones.[34]

The question of whether individuals with exceptional auditory abilities, such as musicians also demonstrate better-than-normal vocal production has been investigated directly in only two published studies. The first was conducted by Seashore in 1919.[35] In this pioneer study, Seashore asked a group of singing teachers to evaluate their students' singing accuracy. He then tested these students' DLF and concluded that there is "a slight tendency toward relationship" (p. 58). Nevertheless, this study should be examined with caution due to several methodological issues. The validity of the variables used in this study is difficult to evaluate. Singing accuracy was not evaluated directly. Instead, the participants' vocal "brightness" was rated, subjectively, by the teachers, with no reported reliability. Pitch discrimination, on the other hand, was evaluated as accurately as possible for that time (using a series of tuning forks). Moreover, Seashore himself raised doubts regarding the young participants' ability to comprehend the task requirements and present their actual musical capacity.

The second study to have addressed this question was conducted by Ternstrom, Sundberg, and Collden.[36] They asked a group of trained singers to sustain their pitch while producing different vowels. This task was performed both with normal auditory feedback and with masked auditory feedback. No control group was included in the study. They reported that the singers were less accurate in maintaining their pitch in the presence of background noise than with normal feedback.

Given the methodological concerns in these two studies: the absence of control groups and the fact that both studies examined the performances of trained singers and not musicians with no vocal training, it appears that the question of whether better *auditory abilities* result in improved vocal production has yet to be addressed. One can only speculate why this issue has not been investigated in depth. One possible explanation is that studies that focused on the relation between auditory perception and vocal production were interested primarily in pathological speech. This led to testing the theories in clinical populations, such the hearing impaired. Another possibility is that speech/voice production was viewed as inherently limited by the constraints of the articulatory system. Furthermore, any mispronunciations or inaccuracies can be resolved by the speaker's knowledge of the language. Thus, it might seem logical to assume that musicians would not produce voice more accurately that nonmusicians due to the objective mechanical constraints of the vocal production system. Finally, it is possible that the methodological challenges of measuring minute changes in vocal production and compare them with subtle perceptual parameters posed technological obstacles that made such a study more difficult to perform.

It is our belief, however, that investigating the relationship between exceptional auditory abilities and vocal production is of interest and may complement the existing data on the role of auditory feedback on vocal production. It will also shed light on the question of whether the importance of auditory feedback is unique to speech or can be extended to nonverbal stimuli.

Our purpose in this study, therefore, is to test whether musicians who have significantly better auditory frequency discrimination than nonmusicians, will exhibit better-than-normal performance on vocal production accuracy task. Prior to the present study, the DLF of 16 musicians and 14 nonmusicians were examined for reference tones 250, 1000, and 1500 Hz in a three-interval, three-alternative forced-choice adaptive procedure.[28] The musicians showed significantly better DLF than nonmusicians for all frequencies. Once the superior auditory performance of musicians has been established, we proceeded to test 26 of these subjects (13 musicians and 13 nonmusicians) in an accuracy imitative vocal production task. It is our purpose in this paper to report on the results of the production task and on the comparison between perception and production performance in musicians and nonmusicians.

II. METHOD

A. Subjects

Twenty-six male subjects participated in the study: 13 were professional musicians and 13 nonmusicians, approximately matched in age and education. The musicians were 20–33 years of age (average 25 years old), playing at least one musical instrument for 7–24 years (an average of 13 years). All of them were members of a formal musical group (an orchestra or a band).

The nonmusicians were 23–34 years of age (average 27 years old). These subjects had no previous musical training (less than 1 year) or experience in psychoacoustic testing. All subjects had no previous vocal and singing training or experience. All subjects had pure-tone air-conduction thresholds less than 15 dB HL bilaterally at octave frequencies from 250–4000 Hz.[37] Thresholds for relative DLF were established for each participant prior to the collection of the production data, as reported extensively in Kishon-Rabin *et al.*[28] These data are summarized in Table I for each subject and

TABLE I. Individual participants' relative DLF (*rel*DLF%) for the three tones tested, based on the data presented in Kishon *et al.* (2001).

Group	Subject	*rel*DLF% 250 Hz	1000 Hz	1500 Hz
Musicians	1	0.95	0.26	0.34
	2	0.37	0.29	0.26
	3	0.60	0.36	0.27
	4	1.40	0.44	0.80
	5	1.65	0.56	0.48
	6	1.70	1.14	1.05
	7	1.80	0.70	0.73
	8	0.85	0.45	0.59
	9	1.30	0.61	0.62
	10	0.47	0.10	0.33
	11	0.92	0.26	0.67
	12	0.87	0.23	0.31
	13	0.57	0.45	0.34
Nonmusicians	1	2.30	1.09	1.19
	2	2.97	1.68	1.12
	3	1.05	0.61	0.31
	4	3.77	1.96	1.32
	5	2.05	1.00	1.02
	6	2.20	0.34	0.45
	7	1.77	1.05	1.11
	8	3.42	1.58	1.23
	9	2.02	0.69	1.04
	10	2.27	0.90	1.18
	11	2.30	0.63	1.30
	12	1.67	0.58	1.03
	13	3.32	1.83	1.25

frequency. Note that the values are expressed in percentage relative DLF ($rel\mathrm{DLF}\% = \Delta f / f * 100$).

B. Stimuli

Three reference tones at frequencies 131, 165, 196 Hz (C3, E3, G3, respectively) were selected as representing the mid-range frequencies of the average untrained male voice register.[8] The sine waves were generated digitally using the Sound Forge 4.5 computer program (version 4.5 g, Sonic Foundry, Inc.) at a sampling rate of 22 050 Hz, 16 bits/sample, with a duration of 2 s, and were stored on a hard disk of a personal computer.

C. Procedure

The subjects stood in a quiet room 15 cm from a dynamic Sony microphone (F-170). Signals were presented to the subjects binaurally, through headphones (MDR-CD270) directly from the computer at 80–85 dB SPL.[37]

Each tone was presented three times, totaling nine target stimuli. These were then presented in random order. The subjects were instructed to listen to each stimulus until it ended and then reproduce it, using the vowel /a/ at the same pitch as accurately as possible. The subjects' productions were recorded directly into a computer using a sampling rate of 22 050 Hz. Each production lasted approximately 2 s. The subjects were also asked to produce a vocal sweep of frequencies in order to ensure that the stimuli were within their dynamic vocal range.

D. Vocal analysis

1. Pitch detection algorithm

Pitch detection was performed by computing the autocorrelation over successive windows of 30 ms, with an overlap of 20 ms. The location of the largest local maximum in the autocorrelation curve was taken to be the fundamental period at that window. We remark that when this method is applied to the pitch detection of normal speech, it is prone to false detection under certain circumstances, such as the presence of strong high harmonics and a weak fundamental frequency. Nevertheless, in the present study such conditions did not occur.

The resolution of this method is limited by the sampling rate, giving a different *relative* error for each detected frequency. Specifically to this study, the fundamental periods for frequencies 131, 165, and 196 Hz are 168.32, 133.64, and 112.5 samples. Since the maximum error in detecting the peak of the autocorrelation function can be half a sample, adding 0.5 to each of these periods and translating back to frequencies gives 131.25, 164.55, and 195.13 Hz. The maximum relative errors are thus 0.3%, 0.37%, and 0.44%, respectively. These percentages give an upper bound on errors due to the limited frequency resolution in the vicinities of frequencies used here. In order to improve the resolution, the autocorrelation curve was interpolated by a factor of 4, using FIR interpolation. This reduced the upper bounds on relative resolution errors to 0.07%, 0.09%, and 0.11%, respectively. Thus, the resolution errors are far below the production errors themselves, as shown in the next section, and are further reduced by averaging over the utterances.

2. Applying the pitch detection routine

An analysis was performed by presenting the experimenter with a graphic window containing the recorded production. The experimenter selected the middle 50% of each file. The fundamental frequency was computed over this segment, and averaged. If the chosen section presented exceptional instability (>4%) in frequency or intensity, a similar section from another part of the recording was analyzed. In recordings with no stable section at the initially required length, a shorter section was used, subject to the condition that it would not be shorter than 0.5 s. In addition, a randomly chosen set of 20% of the responses was remeasured, by the same judge and by a second judge, to evaluate interjudge and intrajudge reliability of the fundamental frequency measurements. Correlations between original and repeated measurements were $\mathbf{r} = 0.99$, $p < 0.001$ for interjudge reliability and $\mathbf{r} = 1$, $\mathbf{p} < 0.001$ for intrajudge reliability.

III. RESULTS

As described above, each participant produced the target tones (131, 165, and 196 Hz) three times. The three fundamental frequency measurements were averaged for each target frequency and participant. The mean individual production data for the three frequencies are presented in Table II.

The distribution of the production values for each target tone within the two groups are illustrated in Fig. 1. In this box plot graph, the box represents the interquartile range,

TABLE II. Fundamental frequencies (in Hz) of the productions performed by each musician and nonmusician for each of the three target tones (values reported represent means of three repetitions of each production).

Group	Subject	Target tone 131 Hz	165 Hz	196 Hz
Musicians	1	132.86	172.88	195.44
	2	129.02	165.45	196.49
	3	125.73	159.92	188.68
	4	123.25	158.12	190.58
	5	124.18	153.44	157.57
	6	131.45	157.15	183.02
	7	133.54	165.43	195.88
	8	127.07	167.84	195.22
	9	127.93	163.56	196.79
	10	127.43	157.31	197.71
	11	131.68	163.59	192.84
	12	123.20	162.59	187.93
	13	129.02	166.75	195.75
Nonmusicians	1	106.61	184.40	232.75
	2	118.29	148.23	173.09
	3	134.96	167.82	192.95
	4	129.52	162.40	180.78
	5	128.05	163.38	194.33
	6	131.03	158.61	196.95
	7	126.91	157.07	185.03
	8	182.60	279.84	327.75
	9	128.12	142.22	165.32
	10	126.41	142.73	148.29
	11	113.26	168.38	197.49
	12	128.80	161.63	186.02
	13	88.92	88.18	161.90

which contains 50% of the values. The line within the box marks the median, the whiskers above and below the box extend to the 90th and 10th percentiles, and the outlying data are graphed as filled circles. Clearly, the nonmusicians group had a wider range of values than the musicians group. Standard deviations for the nonmusicians group were markedly larger than for the musicians group (21.03 vs 3.51, 41.71 vs 5.30 and 44.80 vs 10.75 for frequencies 131, 165, and 196 Hz, respectively). Tests for the equality of variance revealed

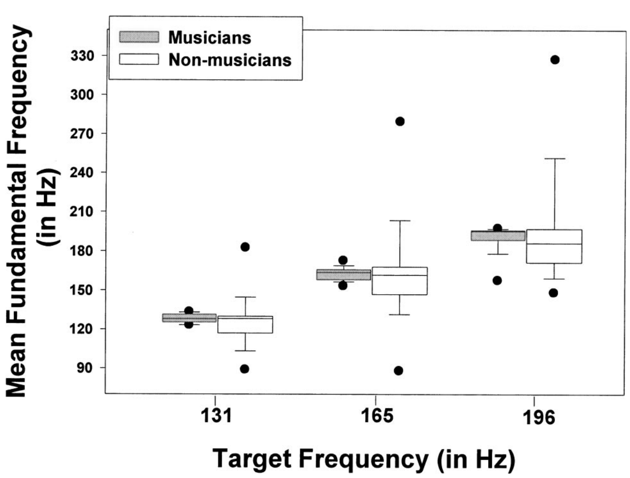

FIG. 1. Distribution of the fundamental frequencies produced by musicians and nonmusicians for each target tone. The box represents the interquartile range, which contains 50% of values. The line within the box marks the median, the whiskers above and below the box extend to the 90th and 10th percentiles, and the outlying data are graphed as filled circles.

that these group differences were statistically significant for all frequencies ($\mathbf{p}<0.0005$). In addition, to evaluate the intrasubject reproducibility between the three tones produced by each subject for each frequency, an intraclass correlation was employed, yielding a Cronbach's alpha of 0.92 for the musicians group and 0.63 for the nonmusicians group. Note that the majority of the vocal productions (approximately 72%) were produced at frequencies *lower* than the expected frequencies.

The accuracy of the vocal production was calculated as the absolute difference between the observed fundamental frequency and the reference frequency relative to the reference frequency in percent. This measure, which we termed *relative accuracy* (*rel*Accuracy%), is assumed to reflect the accuracy of production. This value decreases as the difference between the observed frequency of vocalization and the target frequency decreases. For example, for a reference tone of 131 Hz and a measured production of 144 Hz, the *rel*Accuracy% is 9.92% ($100^*|131-144|/131$). Means of the *rel*Accuracy% for both groups are presented in Table III. Data are presented separately for the three tones as well as a calculated mean value for each participant. In addition, the mean frequency discrimination threshold (in *rel*DLF%), adopted from Kishon-Rabin *et al.*[28] is reported for each participant. Note that in approximately 3% of the measurements shown in Table II, production was closer to one octave above or below the target frequency. In these cases, the reference frequency was adjusted accordingly and presented in Table III. For example, subject 13 of the nonmusicians produced 88.92 Hz when the target was 131 Hz. In this case, the reference frequency was considered 65.5 Hz (131/2) and the *rel*Accuracy% computed as 35.57% (Table III).

The *rel*Accuracy% grand mean (combining all three tones) was 2.88% (SD=2.67) for the musicians group, and 8.94% (SD=7.53) for the nonmusicians group. Thus, the musicians group produced the tones approximately three times more accurately than the nonmusician group. Using an analysis of variance with repeated measures (MANOVA) with Group as a fixed factor and Frequency as the repeated factor, these group differences were found to be statistically significant [$\mathbf{F}(1.24)=4.48$, $\mathbf{p}<0.05$]. However, no significant differences were found among the three frequencies ($\mathbf{p}=0.95$), as well as no Frequency X Group interaction ($\mathbf{p}=0.80$). Also, an Equality-of-Variance Two-Sample T-Test revealed a significantly larger distribution of the *rel*Accuracy% values in the nonmusicians group, in comparison to the musicians group ($\mathbf{p}<0.0005$).

A. Relation between frequency discrimination and accuracy of production

A Pearson correlation was performed between frequency discrimination and production using the *rel*DLF% and the *rel*Accuracy% averaged each across the tested frequencies for each subject. This correlation, for the two groups combined, is illustrated in Fig. 2. A significant correlation was found between the two measures ($\mathbf{r}=0.67$, $\mathbf{p}<0.001$). This analysis suggests that approximately 43% of the variance of the production data can be explained by auditory perception. Figure 2 also demonstrates the relatively small between-

TABLE III. Individual production data (in *rel*Accuracy%) and perceptual data (in *rel*DLF%) (Ref. 28) of the participants in the musicians (M) and the nonmusicians (NM) groups.

Group	Participant	*rel*Accuracy 131 Hz	165 Hz	196 Hz	Mean value	*Rel*DLF% Mean value
M	1	1.42	4.77	0.29	2.16	0.52
	2	1.51	0.27	0.25	0.68	0.31
	3	4.03	3.08	3.74	3.61	0.41
	4	5.92	4.17	2.77	4.28	0.88
	5	5.21	7.01	19.61	10.61	0.90
	6	0.34	4.76	6.62	3.91	1.30
	7	1.94	0.26	0.06	0.75	1.07
	8	3.00	1.72	1.69	1.71	0.63
	9	2.34	0.87	0.40	1.21	0.84
	10	2.73	4.66	0.40	2.75	0.30
	11	0.52	0.85	0.87	1.00	0.62
	12	5.95	1.46	4.12	3.84	0.47
	13	1.51	1.06	0.52	0.90	0.46
Mean		2.80	2.69	3.14	2.88	
(SD)		(1.92)	(2.18)	(5.34)	(2.67)	
NM	1	18.62	11.76	18.75	16.38	1.53
	2	9.70	10.16	11.69	10.52	1.92
	3	3.02	1.71	1.56	2.10	0.66
	4	1.13	1.58	7.77	3.49	2.35
	5	2.25	0.98	0.85	1.36	1.36
	6	0.02	3.87	0.48	1.46	1.00
	7	3.12	4.81	5.60	4.51	1.31
	8	39.39	15.20	16.40	23.66	2.08
	9	2.20	13.81	15.65	10.55	1.25
	10	3.50	13.50	24.34	13.78	1.45
	11	13.54	2.05	0.76	5.45	1.41
	12	1.68	2.04	5.09	2.94	1.09
	13	35.75	6.88	17.40	20.01	2.13
Mean		10.30	6.80	9.72	8.94	
(SD)		(13.29)	(5.36)	(8.12)	(7.53)	

subject variability for both perception and production in the musicians group compared to the nonmusicians group.

The data in Fig. 2 shows that *rel*DLF% of 12 of the 13 musicians is under 1.1 and the same proportion of the production accuracy of musicians is less than 4.3%. Furthermore, 85% (11/13) of the musicians have auditory perception *and* vocal production accuracy of less 1.1 and 4.3, respectively. These musicians are within the performance range indicated by the horizontal and vertical arrows in Fig. 2. In contrast, only three nonmusicians fall within this range of performance. It can also be seen that all subjects but one (regardless of musical experience) showed good production accuracy for *rel*DLF% smaller than 1.1. For perception thresholds greater than 1.1, the production data demonstrate greater variability: four of the nonmusicians have *rel*Accuracy% of less than 6, whereas the other six remaining subjects in this group have values of 10 to 24.

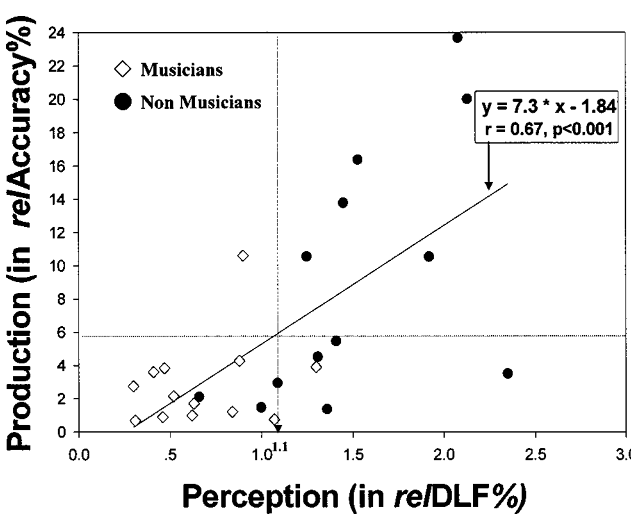

FIG. 2. Individual production data (*rel*Accuracy%) as a function of individual perception data (*rel*DLF%) (Ref. 28) for musicians (open symbols) and nonmusicians (filled symbols). The solid line represents the best fitting linear function for *all* data. The arrows represent the boundary range of performance of 12 of the 13 musicians for perception (vertical arrow) and production (horizontal arrow).

IV. DISCUSSION

In this paper we investigated the role of auditory perception on vocal production in a population with exceptional auditory abilities. If such individuals, who had no previous experience in voice training, show better-than-normal vocal production accuracy, it could have important implications on the importance of auditory feedback for vocal production that may be not specific to speech. Such information complements existing investigations on the perception–production relationship, which used primarily degraded or altered auditory feedback and verbal stimuli.

The current results indicate that, as a group, musicians who showed exceptional frequency discrimination ability also showed greater vocal production accuracy. This finding is highlighted by the fact that these musicians had no formal vocal experience. Thus, it is possible that listeners use immediate auditory feedback for vocal production. The interesting question remains *how* do musicians use the auditory information to vocalize accurately. It is possible that they are tuned to acoustic parameters in vocal production that are otherwise ignored by nonmusicians. Another hypothesis is that musicians are able to transfer the underlying assumptions of the ''motor theory'' for speech[38] to the perception of auditory stimuli produced by musical instruments. The motor theory suggests that the relationship between perception and production of speech stems from the listeners ability to translate acoustic patterns to articulatory gestures and *vice versa*. It is possible that musicians develop mental representations of sounds as they are produced by musical instruments and then translate it, when producing sounds via the human vocal system. Furthermore, musicians may have had many years of fine auditory perception to motoric-production training. This hypothesis is supported by the finding of reduced intersubject variability (in both perception and production) in the musicians' group, which is commonly observed in studies where learning has occurred. Clearly, many of these issues need to be substantiated empirically in future studies.

An additional interpretation of our results is derived when converting the data to semitones. The musicians group had average production errors that were no greater than half of a semitone for each frequency. In contrast, the nonmusicians had mean errors of approximately 1.3 semitones. Keeping in mind the fact that the musical scale is based on notes that are defined in semitones units, inaccuracies that are greater than one semitone are perceived as a melody change. Thus, plus or minus one-half semitone may be viewed by musicians as a musical boundary (analogous to categorical boundary), where ''crossing'' this boundary creates a musical meaningful difference. Alternatively, inaccuracies less than one semitone could create the subjective feeling of a ''mistune,'' but would not create a meaningful difference. It should be noted that the nonmusicians in the present study demonstrated larger vocal inaccuracies compared to those reported in Weiner *et al.*[39] It is difficult, however, to discuss these differences due to the lack of background information regarding the musical training of the Weiner *et al.* subjects.

When looking at the individual relationship between perception and production data we found that perception explained approximately 43% of the variance of the production data. All listeners but one, regardless of musical experience, that had superior frequency discrimination (*rel*DLF% less than 1.1) demonstrated accurate pitch vocalization (*rel*Accuracy% between 0.27 and 4.5). However, listeners with poor frequency discrimination (*rel*DLF% greater than 1.1) were divided in terms of their vocal ability: six of them showed poor vocal pitch accuracy (*rel*Accuracy% greater than 10), whereas five subjects showed accurate production (*rel*Accuracy% less than 6). Although these findings emphasize the importance of auditory frequency discrimination for the accurate pitch production of non-verbal sounds, they also suggest that subjects may be able to use other musical skills and/or different mechanisms to vocalize accurately.

It should be noted that although the correlation analysis was based on the average of the tested frequencies for both perception and production, it might be more reasonable to correlate one frequency at a time. The underlying assumption would be that accuracy in production frequency is related to frequency discrimination at that frequency range. A reanalysis of the data correlating auditory frequency discrimination only at 250 Hz, to vocal accuracy at 131–196 Hz resulted in r^2 of 0.31, a value smaller than that observed for the mean frequencies. Thus, our data did not support the assumption that perception and production accuracy should be tested with the same frequency. We assumed that averaging the tested frequencies for a single measure for both auditory frequency discrimination and vocal accuracy is valid because no statistical differences were found between the tested frequencies and by doing so, the intrasubject variability is reduced. Nonetheless, we recommend that future studies explore the importance of using the same tested frequency in both auditory perception and production accuracy and the carryover to other frequencies.

In summary, in the present study we provide empirical evidence of the important role that auditory feedback has in vocal production when superior though nonvocal musical skills are involved. Specifically, individuals with superior frequency discrimination abilities were able to vocally imitate pure tones with great accuracy. Frequency discrimination thresholds, however, could not be predicted from production accuracy. It appears that while all individuals with small *rel*DLF% exhibited accurate vocalization, some subjects exhibited accurate pitch vocalization, despite poor frequency discrimination. These individuals may be using other auditory abilities that were not included in the present study but may be linked to the vocal task evaluated here. Future studies examining the relationship between perception and production should include several auditory perceptual and production tasks. The present data also shed light on the importance of auditory experience on improved vocalizations. This may have implications on vocal training of singers. It would be of interest to investigate whether auditory training improves vocalization.

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