# Long-Term Horizontal Vocal Directivity of Opera Singers: Effects of Singing Projection and Acoustic Environment

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**Summary:** Vocal directivity refers to how directional the sound is that comes from a singer's mouth, that is, whether the sound is focused into a narrow stream of sound projecting in front of the singers or whether it is spread out all around the singer. This study investigates the long-term vocal directivity and acoustic power of professional opera singers and how these vary among subjects, among singing projections, and among vastly different acoustic environments. The vocal sound of eight professional opera singers (six females and two males) was measured in anechoic and reverberant rooms and in a recital hall. Subjects sang in four different ways: (1) paying great attention to intonation; (2) singing as in performance, with all the emotional connection intended by the composer; (3) imagining a large auditorium; and (4) imagining a small theatre. The same song was sung by all singers in all conditions. A head and torso simulator (HATS), radiating sound from its mouth, was used for comparison in all situations. Results show that individual singers have quite consistent long-term average directivity, even across conditions. Directivity varies substantially among singers. Singers are more directional than the standard HATS (which is a physical model of a talking person). The singer's formant region of the spectrum exhibits greater directivity than the lower-frequency range, and results indicate that singers control directivity (at least, incidentally) for different singing conditions as they adjust the spectral emphasis of their voices through their formants.

**Key Words:** Singing–Voice directivity.

## INTRODUCTION

Unamplified, an opera soloist can fill an auditorium with the sound of their voice, remaining clearly audible even in the presence of orchestral accompaniment. Characteristics of the singing voice that make this extraordinary feat possible have been the subject of many studies in the singing acoustics literature, concentrating on the way in which large amounts of acoustic power can be generated and their optimal spectral distribution. One area that has received little attention is the role that vocal directivity could play in vocal projection. In reverberant rooms, directivity is one way of achieving clarity, a fact widely exploited in sound reinforcement system design. If a singer can achieve greater vocal directivity, the increase in clarity may be slightly advantageous in performance. Increased directivity could occur through the physical features of the singer, for example, through a larger mouth opening, a larger or flatter face, and a larger torso. Conceivably, it could be manipulated in unconventional ways, for example, by cupping the hands around the mouth or by wearing an acoustically reflective costume. The concentration of vocal energy into a frequency range that is highly directional could also be used to increase overall vdirectivity, and this is a practical means by which a singer might control his or her vocal directivity.

The frequency range of 2–4 kHz has been identified as being of prime importance for vocal projection in opera soloists, through their formants.[1,2] Operatic soloists, especially males, create a formant in this region that coincides with the frequency range of maximum sensitivity in the ear, thereby optimizing the audibility of their voices. The formant is present in female operatic solo voices but is not so critical for audibility with the higher fundamental frequencies and may be poorly defined when the fundamental frequencies are in the high range (eg, sopranos).[3,4]

If a singer's voice is directional, it means that sound is predominantly projected in a particular direction, presumably to the front of the singer. One effect of greater directivity is to make the voice louder for an audience in front of the singer. The voice is, then, quieter behind the singer, and, because the back-radiated sound contributes only to the reverberant sound energy in an auditorium, the result is reduced reverberation (ie, *quieter* reverberation, although the technical reverberation time value of the auditorium remains the same). The combination of louder direct sound and quieter reverberation leads to greater clarity—sung words are more easily discerned, and the sound is less "muddy." In auditorium acoustics, this concept of acoustic clarity is formalized through the definition of "clarity index," which is the ratio of early-arriving sound energy (including the direct sound and some early reflections) to late-arriving sound energy (ie, reverberation), measured from the stage to the audience area and expressed in decibels.

Most previous studies of vocal directivity have been concerned with speech.[5–11] These show that, in general terms, vocal directivity increases with frequency, as would be expected for a small sound source in a solid head. The most

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detailed published results are those of Chu and Warnock,[8] which are given for 40 subjects (20 males and 20 females) for conversational speech.

Physical models have been constructed to emulate the long-term directivity patterns of the human voice. Flanagan,[12] Olsen,[13] Kob and Jers,[14] Bozzoli et al.,[15] and Stewart and Cabrera[16] constructed models of the head and torso, with sound radiating from the mouth. Mathematical models of vocal directivity have also been developed and compared with physical models by Flanagan,[12] Huopaniemi,[17] and Kob.[18] For the purposes of telephonometry, the International Telecommunication Union has standardized a head and torso simulator (HATS), with a loudspeaker within a mouth orifice.[19] Some studies of speech directivity have compared measurements of human subjects to the HATS, finding some differences. Chu and Warnock[8] and Halkosaari et al.[11] find that the HATS is a little more directional than the average for human subjects in the high-frequency range. Halkosaari et al[11] show that the directivity of a speech simulator is controlled by the mouth aperture size, and Stewart and Cabrera[16] tested a larger range of mouth apertures on a HATS, yielding substantial changes in directivity. Bozzoli and Farina[9] and Bozzoli et al[10,15] also find significant differences among the directivities of human subjects and the HATS (and differences with a physical model built in their laboratory), especially at the back of the head. They suggest that this is because of the material differences between artificial and real heads. The physical model of Kob and Jers[14] was designed to emulate a singer, and it has a larger and rounder mouth area than the standard HATS. They compare this with a vocal directivity measurement of one female singer, finding reasonable agreement.

Marshall and Meyer[20] studied the vocal directivity of three professional choral singers (baritone, alto, and soprano, each singing alone). Measurements were made for three test syllables (representing three vowels) over one octave range of notes. Two vocal projections were used—*forte* and *piano*—and a small reduction in the relative side-radiated sound level was observed for *piano*. The differences between male and female singers were mainly in the median vertical plane measurements. Results also show that the vowel influences directivity in the octave bands centered on 1 kHz and above (greatest differences were in the 2-kHz octave band). At the time of writing, there is little other published data on singer directivity—Kob and Jers,[14] Kob,[18] and Katz[21] present limited data for their human singer measurements.

In simple physical terms, voice directivity can be understood as being the result of a combination of physiological features, including the mouth, head, and body. Most of the sound is radiated by the mouth,[5] and the size of the mouth opening will influence directivity: a very small aperture is least directional, being smaller than the wavelengths of vocal sound.[16] If we consider vocal sound to be mainly within the frequency range of 125 Hz – 8 kHz, this corresponds to wavelengths from 3.44 m (at 125 Hz) to 0.043 m (at 8 kHz). Once the aperture becomes comparable to vocal sound wavelengths, the inherent directivity of the mouth becomes greater. For example, if the diameter of a circular acoustic radiator is half a wavelength, then sound will not be radiated well to the side, because the sound at one side of the circle is out of phase with that of the other by the time sound travels from one side to the other (in other words, side radiation is partially canceled out acoustically). On the other hand, sound is in phase across the whole circle with respect to forward radiation, and hence, sound radiation in the forward direction is reinforced. For a real mouth, this effect is likely to mainly affect the high-frequency range, as low-frequency sound wavelengths are too long compared with conceivable mouth apertures—certainly, there is likely to be little effect below 2 kHz, where the wavelength is 0.172 m. A second physical consideration is the size of the head. The head can be thought of as producing an acoustic shadow behind it (ie, blocking rearward sound radiation) and also reinforcing forward radiation by reflecting sound forward, which would otherwise have been radiated rearward. Again, this effect depends on wavelength and will be most prominent at high frequencies (where wavelengths are shorter than the head diameter).[17,18] The torso, then, provides further reflecting and shadowing effects to augment the head effect, with the larger size of the torso extending this to a lower-frequency range.

In this study, we investigate the long-term average vocal directivities of eight professional opera soloists, to determine their general directivity patterns, whether there are differences among individuals, and whether the vocal projection yields differences in vocal directivity.

## METHOD

Measurements were made in three test rooms: an anechoic room, a reverberation room, and a recital hall.

### Anechoic room conditions

An anechoic room is a room with negligible acoustic reflections (including negligible reflections from the floor), and this allows the directivity of a singer to be measured directly without the complication of room acoustics. The anechoic room for our measurement was relatively small (about 5 × 4-m floor plan), with an anechoic low-frequency limit (when empty) of 250 Hz. Free-field Brüel & Kjær 1/2-inch microphones (types 4190 and 4165) (Brüel & Kjær Sound & Vibration Measurement, Nærum, Denmark) were positioned around the room at a height of 1.5 m, so as to be at angles of 0°, 15° right, 30° left, 45° right, 60° left, 90° right, 120° left, 150° right, and 180°, with respect to the direction that the singer faced. The assumption here is that a singer's directivity pattern will have approximate left-right symmetry—but that small deviations from symmetry can be ameliorated by alternating microphones between left and right. These microphones were at an average distance of 2.1 m from the singer's mouth position (ranging from 1.7 to 2.6 m). In the measurements reported in this article, distances have been effectively normalized to 1 m, by applying the inverse-square relationship between free-field sound intensity and point source-receiver distance. For this purpose, distances were measured acoustically using an upward-facing compression driver at the singer mouth position and measuring the impulse response (and hence the acoustic delay) between this point and each of the microphones.

A "T" was marked in tape on a piece of carpet, which was on the absorptive floor of the room. This mark gave the singer a position to stand in, such that his or her toes were against the top of the T, with the central line between their feet. The subjects faced a lightweight black cotton curtain, featureless, except for a yellow paper dot at head height, which gave them a point to look at when singing.

A head-mounted microphone was worn by each subject. This was a B&K 4939 1/4-inch microphone (Brüel & Kjær Sound & Vibration Measurement, Nærum, Denmark). The microphone was carefully positioned for each subject, with the position relative to the corner of his or her mouth noted. The microphone position necessarily varied among subjects because of their different head and mouth shapes.

### Reverberant room conditions

A reverberant room is a room with predominantly hard surfaces, which has a long reverberation time for its size. The concept is that the room's reverberation is so strong that only a few measurements are required to adequately assess the total sound radiated from a source in all directions. The reverberation room used is rectangular, with dimensions of $6.35 \times 5.10 \times 4.00$ m (height). Thirty-two rectangular perspex reflectors, each $0.92 \times 1.25$ m, were suspended throughout the room in a random configuration so as to increase the diffusion of the sound field. Seven microphones were positioned in the reverberation room, although technical difficulties limited the analysis to five of these. These was a variety of free-field 1/2-inch microphones, some mounted on sound level meters (Brüel & Kjær 2215 and 2260). The microphones were between 1.9 and 3.9 m from the singer, and in most cases, the direct sound was blocked by the suspended perspex sheets. Even assuming no obstructions, the diffuse field was at least 12 dB greater than the direct field for such distances up to and including the 4-kHz octave band, allowing for a less than 0.5-dB error in local diffuse field measurement, notwithstanding other effects. Microphones were positioned more than 1.2 m from reflective surfaces to avoid broadband phase coincidences with reflections for the frequency range under consideration. Microphones were more than 2 m apart for statistical independence for the frequency range under consideration.

The purpose of the reverberation room measurements was to obtain spatially integrated values for the sound radiated by a singer in all directions, at least in broad frequency bands. In contrast, the anechoic measurements were restricted to the horizontal plane. The head-mounted microphone was also used in the reverberation room to provide a reference for matching results with the anechoic room and recital hall.

The absorption of the reverberation room was measured (from reverberation time and room volume) with a person standing at the singer position. These values, shown in Table 1 (with standard deviations of less than 0.25 $m^2$), allow the sound power of the singer to be estimated using Sabine's room acoustics theory,[22] and hence, the free field spatially integrated pressure at specified distances can be inferred. A "T" symbol was marked on the floor to define the singer position, and a mark on the wall was used as a visual cue to help maintain head orientation.

**TABLE 1.**
**Measured Acoustic Absorption of the Reverberant Room With a Person in the Singer's Position**

| Octave Band Center Frequency (Hz) | Absorption ($m^2$) |
|---|---|
| 250 | 5.8 |
| 500 | 6.2 |
| 1000 | 6.5 |
| 2000 | 7.2 |
| 4000 | 8.7 |

### Recital hall conditions

The recital hall had a volume of 8000 $m^3$ and a stage area occupying 40% of the main floor. Its reverberation times, measured from the HATS to the microphones in the audience area, were approximately 1.5 seconds in the octave bands from 250 to 4 kHz. Being a small-volume auditorium, the reverberant sound field is relatively strong in this hall.

Sennheiser MKH816P48 shotgun microphones (Sennheiser Electronic, Wennebostel, Germany) were positioned at 0°, 15°, 30°, 60°, 90°, 120°, 150°, and 180° with respect to the direction that the singer faced (only on their right side) at a nominal distance of 1.8 m from the singer. Microphones were only on one side so that there was no risk of the subject coming into contact with a microphone stand as they moved to and from the singing position from the left. Microphone distance was measured precisely for analysis using impulse responses taken from an upward-facing compression driver at the singer's mouth position, so that corrections could be applied to create a virtual microphone distance of 1 m.

As in the other rooms, a "T" was marked on the stage for singer positioning. The headset microphone was used, with the distance between mouth corner and microphone preserved. An additional eight omnidirectional measurement microphones were situated in the audience area, in two arcs of four microphones, 10 and 15 m from the singing position. These were the same microphones as had previously been used in the anechoic room. The microphone installation is illustrated in Figure 1. The voices of only seven of the eight subjects were recorded in the recital hall because of their availability.

### Recording setup

In all situations, the subject was recorded using an Alesis HD-24 hard disc recorder (24-bit, 48-kHz sampling rate) (Alesis, Cumberland, RI). This recorder provides up to 24 channels of audio recording. Recordings were carried out in the anechoic and reverberant rooms in quick succession for each subject, and so the 10 microphones of the anechoic room and eight microphones of the reverberant room were connected to different channels of the hard disc recorder (these numbers include the head-mounted microphone channels).

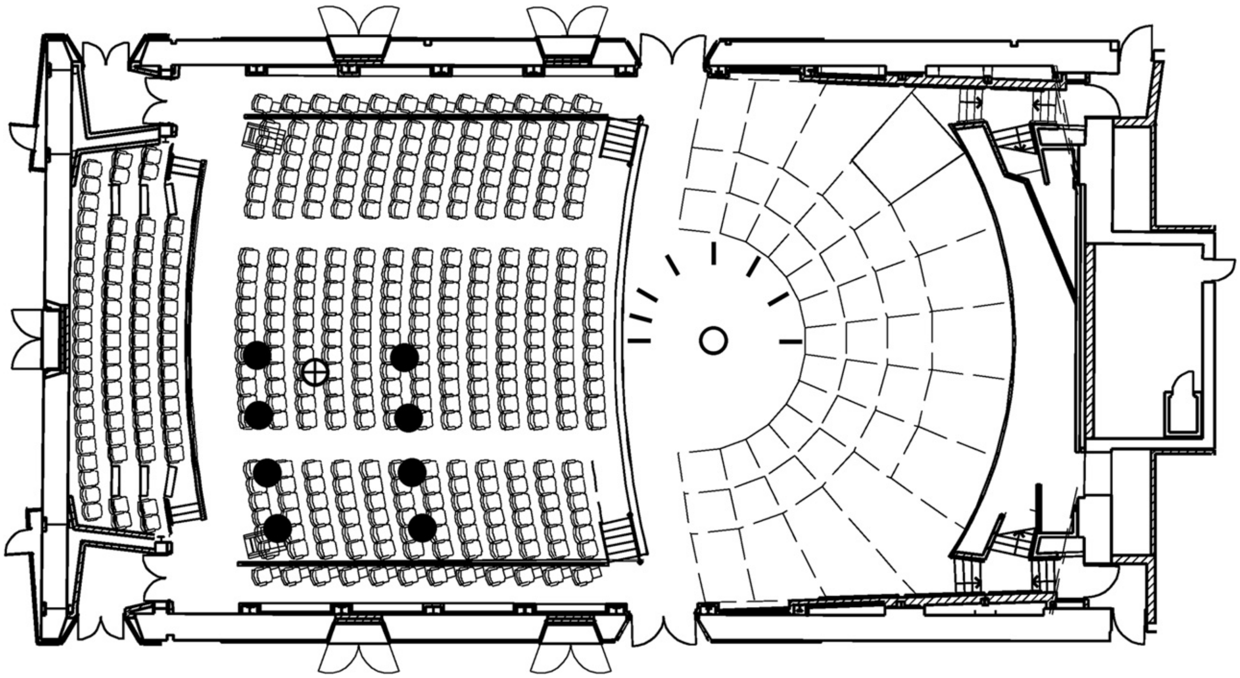

**FIGURE 1.** Plan of the recital hall, showing the singer position as an *open circle*, the shotgun microphones as *black lines* around the singer position, the 10- and 15-m microphone positions as *filled circles*, and the visual target for small auditorium singing as a *crossed circle*.

Various microphones were powered by Brüel & Kjær power supplies, the sound level meters on which they were mounted, or by a Nagra V recorder (in the case of the head-mounted microphone) (Nagra, Cheseaux, Switzerland). Where separate preamplification was required, Sound Devices MP1 preamplifiers (Sound Devices, LLC, Reedsburg, WI) were used, providing a balanced connection to the HD-24. An exception to the aforementioned condition occurred with the shotgun microphones (in the recital hall), which were powered and preamplified and converted to digital by a PreSonus Digimax LT (PreSonus Audio Electronics, Inc., Baton Rouge, LA).

Calibration tones (1 kHz, 94 dB) were recorded from a microphone calibrator on all channels before and after recording sessions. However, in the case of the shotgun microphones, the microphones could not be fitted with a calibrator; hence, only the remainder of the recording chain was calibrated (by substituting another microphone for each shotgun microphone).

In all three rooms, impulse responses were recorded from a Brüel and Kjær 4128C HATS (Brüel & Kjær Sound & Vibration Measurement, Nærum, Denmark) in the singer's position to the measurement microphones (including the head-mounted microphone at various positions). These impulse responses were recorded using a 16th-order maximum length sequence signal system with a 32-kHz sampling rate. In the anechoic room and recital hall, these HATS measurements provide a means of qualifying the measurement system by comparison with the detailed anechoic HATS directivity measurements of Chu and Warnock[8] (where the HATS may have been in a chair). The average signed and unsigned deviations among corresponding microphone angles, relative to the 0° microphone, are shown in Table 2. This is presented in octave bands (three

**TABLE 2.**
**Deviations Between HATS Directivity Measurements Made in this Study and Those of Chu and Warnock (2002)[8] for Corresponding Microphone Angles in the Horizontal Plane**

| | Octave Band Center Frequency | | | | |
|---|---|---|---|---|---|
| Comparison | 250 Hz (dB) | 500 Hz (dB) | 1 kHz (dB) | 2 kHz (dB) | 4 kHz (dB) |
| Mean signed deviation—anechoic | −4.7 | −1.3 | 0.0 | −1.4 | −1.3 |
| Mean absolute deviation—anechoic | 4.8 | 1.5 | 1.5 | 1.8 | 2.2 |
| Mean signed deviation—recital hall | 1.3 | 1.2 | −0.7 | 1.0 | 0.8 |
| Mean absolute deviation—recital hall | 1.6 | 1.6 | 1.0 | 1.5 | 2.2 |

The comparison is made relative to the 0° degree microphone angle in the anechoic room and the 15° angle in the recital hall. A negative number (for a signed deviation) indicates that the remaining microphones of Chu and Warnock received relatively greater sound levels than those of the present study. In the recital hall, the 0° microphone was excluded because of a measurement error (Figure 3).

one-third octave bands combined), because the relevant analysis in this article is in octave bands. For the anechoic room, these measurements give a mean error of 1.4 dB or less for the 500- to 4-kHz octave bands, taken from the signed deviations, and an unsigned error of 2.2 dB or less for these four octave bands. However, the 250-Hz octave band exhibits a more substantial deviation, which can probably be attributed to the anechoic cutoff frequency of the test room. Fortunately, the sound power level of the singers proved to be relatively weak below the 500-Hz octave band, and hence, this limitation does not affect the analysis presented. Unfortunately, there was a measurement error for the 0° microphone in the recital hall (which appears to have only affected the HATS measurements); hence, this microphone was excluded in the comparison with Chu and Warnock's[8] data. Instead, the 15° microphone was used as the reference in the comparison. Results indicate similar accuracy to the anechoic room array (except that they generally have positive rather than negative deviations). Greatest accuracy for both measurement systems is in the 1-kHz octave band, which, for female singers in this study, is usually the band with the highest sound power level.

### Singers, song, and performance style

The sound of subjects singing the final 16 bars of *Torna a Surriento* by Ernesto Di Curtis, an Italian song in *bel canto* style, were recorded, spanning one-and-a-half octaves. This song was chosen, because it was familiar to all likely participants and for consistency with other scientific studies by the second author and colleagues.

The singing modes were (1) paying great attention to intonation; (2) singing as in performance, with all the emotional connection intended by the composer; (3) imagining singing in a large auditorium; and (4) imagining singing in a small theatre. The first of these modes was a way of having the singers perform with an emphasis on technical precision, which contrasted with the second mode. In the recital hall, mode D was varied by asking the singer to "sing to" a HATS, which was positioned in the audience area 12 m from the singer (Figure 1). Because of concern about the high sound pressure levels in the reverberant room, singers wore earmuffs (Bilsom Viking Sperian Protection Australia Pty Ltd., Victoria, Australia) for hearing protection in that room. For consistency, earmuffs were also worn in the anechoic room. However, singing mode C was performed in the anechoic room both with and without earmuffs. In the recital hall, singing was done without earmuffs, except that singing mode C was also performed with earmuffs. Subjects sang the given song at their own pace, with song renditions varying between 40 and 60 seconds in duration.

The eight singers are classified with the help of Bunch and Chapman's taxonomy.[23] Each subject was a professional opera singer as defined by this taxonomy but, nonetheless, encompassed a broad range from International and National Opera Principal to Chorus/National/Big City and Minor Principal/Regional/Touring. The primary mode of singing for subjects 1, 3, 5, and 6, is as part of an ensemble and, for subject 4, when not in chorus, is singing minor roles in small acoustics. It should be noted that subject 2 unlike subjects 1, 3, 4, 5, and 6, has had considerable experience singing solo in large acoustics for major competitions. This could be seen to align subject 2 more with subject 7 in terms of solo singing in a large acoustic and less with subjects 1, 3, 4, 5, and 6. It should also be noted that subject 8 has had a long international career as a soloist, far greater in terms of experience than the other participants. Subject 7 is much younger than subject 8 and, as such, could be seen as less experienced in terms of the number of hours of solo singing on stage. Similarly, subject 2 is also younger than subject 7 and, similarly, is without the many years of solo experience accrued by subject 8. Characteristics of these subjects are summarized in Table 3.

## RESULTS

### Treatment of data for analysis

Recordings of the singers were initially analyzed using 16 384-point fast Fourier transforms (Hann window), with results of multiple windows power averaged over the entire duration of each song rendition. Coarser spectral representation was derived from these, namely, 1/3-octave band and octave band spectra, as well as the sound levels from 0 to 2 kHz and from 2 to 4 kHz. The analysis in this article mainly presents the results for the low-frequency range (0–2 kHz) and singers' formant frequency range (2–4 kHz) and some octave band results from the reverberation room (because reverberation time was measured in octave bands).

Microphone calibration tone recordings, and distance measurements where appropriate, were taken into account in adjusting these spectra to sound pressure levels (or merely relative levels in the case of the shotgun microphones used in the recital hall).

### Effect of situation

The recording situations used in this study were vastly different. The anechoic environment is strange, unsupportive, tiring, and disturbing for a singer. The reverberation room is almost as strange, because it gives too much acoustic support (except that the subjects were wearing earmuffs there). The auditorium was a comfortable, familiar, and even pleasurable environment

**TABLE 3.**
**Classification of Subjects Based on Bunch and Chapman (2000)[23]**

| Subject | Sex | Category |
|---|---|---|
| 1 | Female | 3.1c Opera Chorus |
| 2 | Male | 3.1c Opera Chorus + 3.1b Minor Principal |
| 3 | Female | 3.1c Opera Chorus |
| 4 | Female | 3.1c Opera Chorus + 4.1b Regional/ Touring Minor Principal |
| 5 | Female | 3.1c Opera Chorus |
| 6 | Female | 3.1c Opera Chorus + 3.1b Minor Principal |
| 7 | Female | 3.1a Major Principal |
| 8 | Male | 2.1a International Opera Principal |

for singing. An obvious question is whether these contrasts affect the measurements, both in terms of singer performance and measurement artifact.

**Effect of earmuffs.** The use of earmuffs could conceivably change the directivity of a singer because of the change in head shape when earmuffs are included. It could be hypothesized that earmuffs would increase vocal directivity by making the head larger and, hence, reducing diffraction around it. Earmuffs could also have an effect on the singer's control of his or her voice, by reducing airborne acoustic feedback to almost certainly negligible levels (in contrast with bone-conducted sound). Hence, to the extent that a singer could control his or her own directivity, there could be some effect.

Nevertheless, measurements (Figure 2) show, in some cases, no change among the horizontal radiation patterns with and without earmuffs. Subjects 1, 3, 5, and 7 have very close matches among measurements with and without earmuffs, both in anechoic and auditorium conditions. For the other subjects, there are changes, but these changes are not consistent among subjects and, hence, do not give a general directivity effect of wearing earmuffs. The changes can be characterized more as overall-level or spectral-balance changes rather than directivity changes. Of these subjects showing changes, subject 4, nevertheless, has well-matched measurements in the recital hall, and subject 6 has well-matched measurements in the anechoic room.

There is a minor directivity effect noticeable in most cases with the 180° angle (ie, directly behind the singer). Wearing earmuffs usually sees a greater reduction in sound level directly behind the subject than not wearing earmuffs for the 2- to 4-kHz frequency band.

**Effect of room.** There was a consistent change in the measured horizontal directivity of singers when comparing anechoic with auditorium conditions. Most subjects see a reduction in back-radiated sound in the anechoic condition in both frequency ranges, as seen in Figure 3. Measurements with the HATS show a similar reduction in back-radiated sound at high frequencies but not at lower frequencies. Because HATS measurements were only available in standard 1/3-octave bands and the HATS energy spectrum is arbitrary, Figure 3 shows HATS measurements for octave bands centered on 1.25 and 3.15 kHz, as these frequency ranges tend to dominate the voice spectrum energy. At least in the high-frequency range, the apparently greater amount of back-radiated sound in the recital hall may be an artifact of the environment, with some contribution from reflected or reverberated sound in the microphones. As the HATS does not show this tendency at lower frequencies, it is not clear that the increased back radiation at low frequencies is an environment artifact. The 3-dB reduction in sound pressure between the 15° and the 0° microphones for the HATS in the hall is difficult to explain except as a result of measurement error.

Measurements made with the head-mounted microphone allow the effect of the room on the singer's sound power to be assessed. Although the microphone was placed at different positions for each subject, its position was carefully maintained

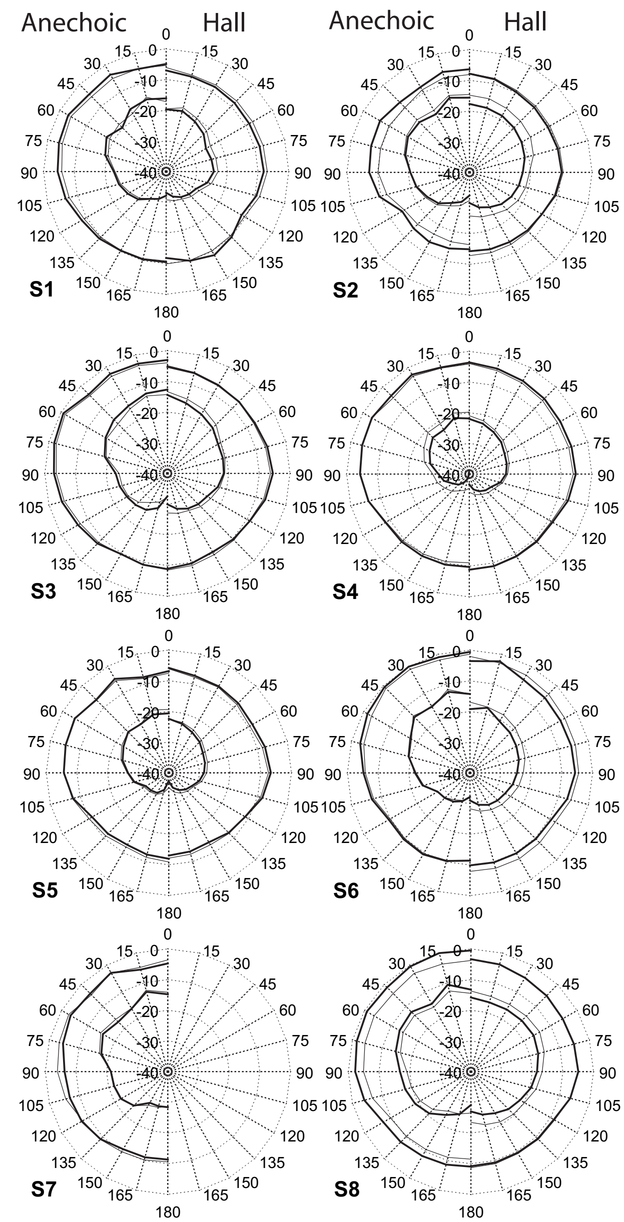


**FIGURE 2.** Horizontal directivities for each subject (large-hall projection) in the anechoic room (*left semicircle*) and recital hall (*right semicircle*) for the subjects with and without earmuffs (thick and thin lines, respectively). The outer pair of lines are the 0- to 2-kHz levels, and the inner pair of lines are the 2- to 4-kHz levels. For the anechoic room, values are sound pressure levels minus 100 dB at 1 m. For the recital hall, the levels have a constant relative value, which has an unknown offset from sound pressure level. Angles are in degrees, with 0° representing the front of the singer, and 180° is behind the singer.

for each subject in the three rooms. On average, the anechoic room recordings are quite close in sound pressure level to those of the reverberation room for a given subject at a given projection (the reverberation recordings are, on average, 0.5 dB greater), and the recital hall had the highest sound pressure level at this microphone (0.7 dB greater than that of the anechoic room for the low-frequency band, 1.7 dB greater for the 2- to

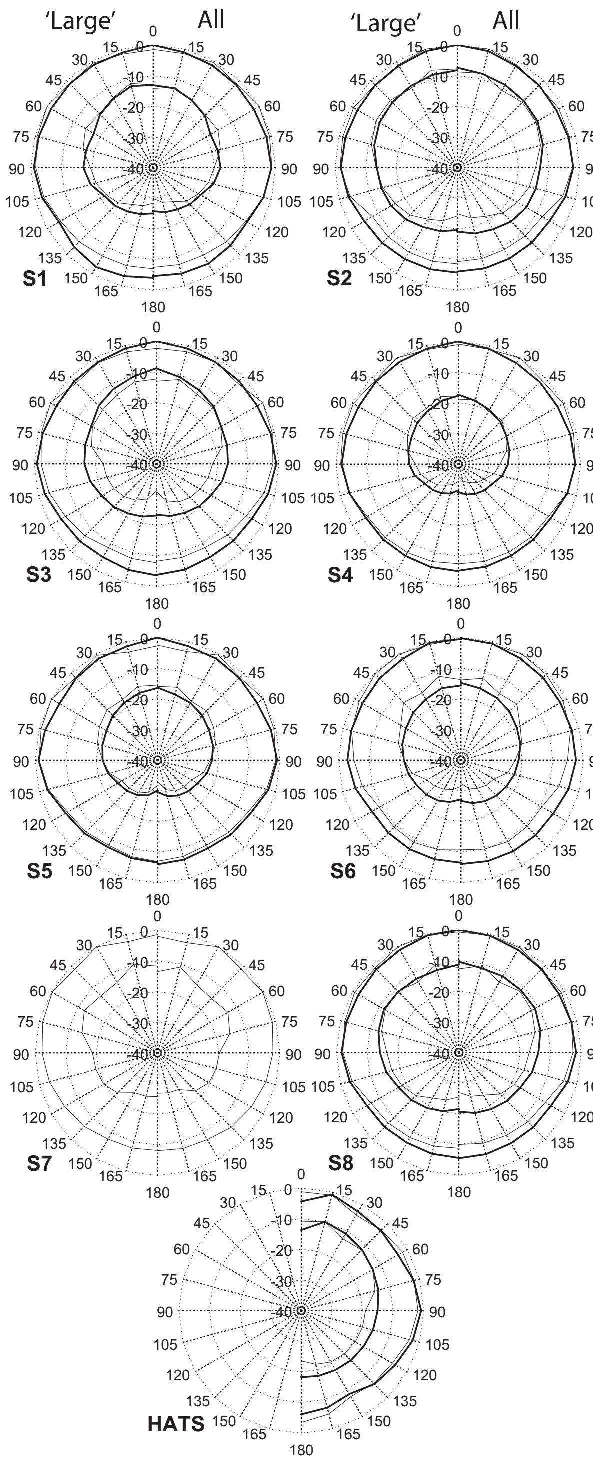


**FIGURE 3.** Horizontal directivities for each subject in the anechoic room (*thin line*) and recital hall (*thick line*) for the "large hall" singing condition (*left semicircle*) and all singing styles combined (*right semicircle*). The outer pair of lines are the 0- to 2-kHz levels, and the inner pair of lines are the 2- to 4-kHz levels. Values for each singing condition are normalized (so that maximum is 0 dB) before averaging. Angles are in degrees, with 0° representing the front of the singer. Directivity measurements for the head and torso simulator are shown for the 1.25- and 3.15-kHz octave bands (−10 dB) for comparison (based on 1/3-octave band normalized patterns). Note that S7 was not measured in the recital hall.

4-kHz band). Almost all of the reverberation room and recital hall measurements are within 3 dB of the anechoic room measurements, showing a degree of consistency among the rooms. Impulse response measurements made with the HATS in the reverberant room and recital hall show that the energy contribution of the room reverberation is less than the apparent average increase in sound pressure level. The ratio of the two frequency bands is more stable than the sound pressure levels themselves, with 37% of the values in the reverberant room and recital hall having less than 1-dB deviation from the anechoic room and 77% having less than 2-dB deviation. Note that these observations reflect the confounded effects of measurement error (because of potential microphone movement) and changes in voice power.

### Effect of subject

The most notable result of this study lies in the differences among subjects, including those between their directivity patterns. Nevertheless, differences in directivities are much smaller than the differences in sound power level or spectral distribution of power. These differences can be seen in most of the result figures presented in this article.

**Acoustic power and pressure of singers.** Opera soloists can produce an extraordinary amount of sound. Equivalent (ie, long-term average) broadband sound pressure levels of up to 100 dB were recorded over the duration of the song at a distance of 1 m in the anechoic room and up to 118 dB at the head-mounted microphone. The apparent equivalent broadband sound power levels of the singers, as inferred from the reverberation room measurements, are up to 107 dB (referenced to $10^{-12}$ W). In octave band analysis, the greatest sound power for the female singers is generally found in the 1-kHz band and, for the male singers, in the 500-Hz band. Octave band sound power levels of the singers for each condition in the reverberation room are shown in Figure 4. S2 (male), who had a cold on the day of the measurements, produced consistently lower sound power levels. Excluding the male singer results, the sound power levels in the 1-kHz octave band are quite consistent among singers, especially for condition C, where they sang with greatest power. Greater variation in power occurs above this frequency band. S6, who is a female singer, has a sound power spectrum that has some similarity to the male spectra.

The broadband-equivalent sound pressure levels produced by the singers in the audience area of the recital hall (represented by microphones at 10- and 15-m distance) were generally in the range 75–85 dB. The sound pressure level at 15 m was about 1 dB less than at 10 m. Figure 5 shows the sound pressure levels for each singer, exponentially averaged over the eight microphones, for the 0- to 2-kHz and 2- to 4-kHz bands. There are clear differences in the singers' projection to the audience area, especially in the 2- to 4-kHz band, which are determined more by the singer than by the singer's vocal projection.

**Directivity of singers.** Although it is possible to see differences in the singers' directivities in the polar plot figures, single number ratings of directivity provide a more succinct

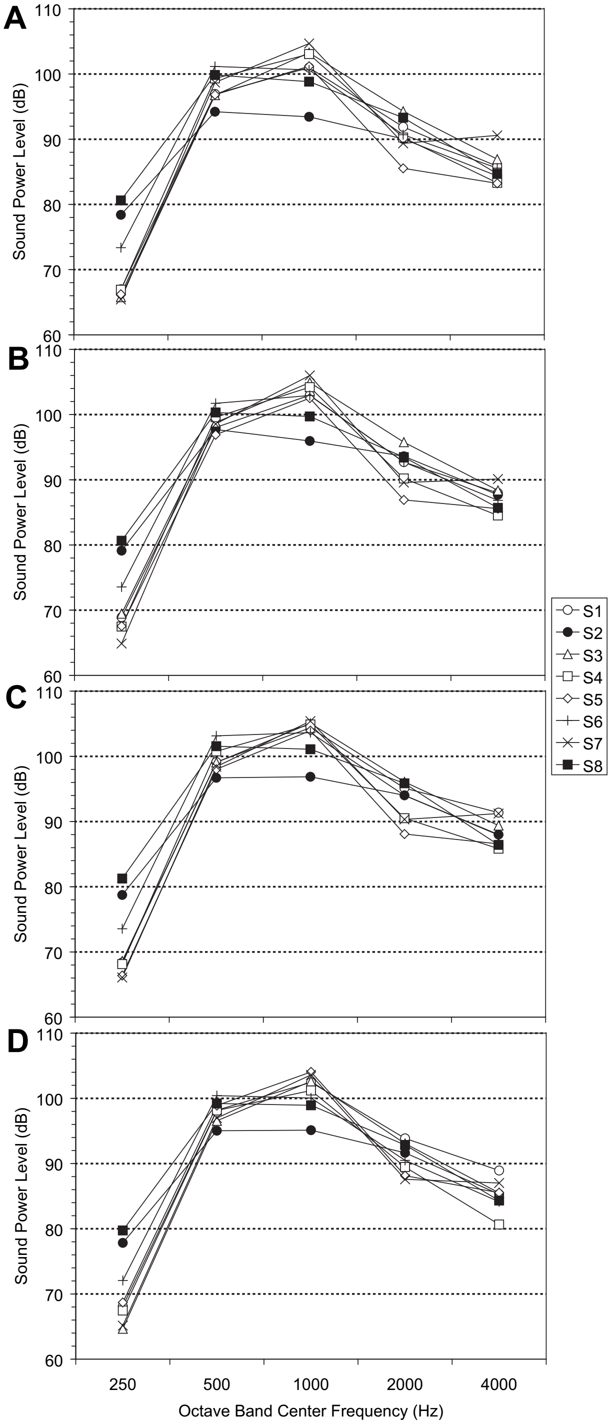


**FIGURE 4.** Octave band sound power levels of the singers measured in the reverberation room for the four singing modes A to D.

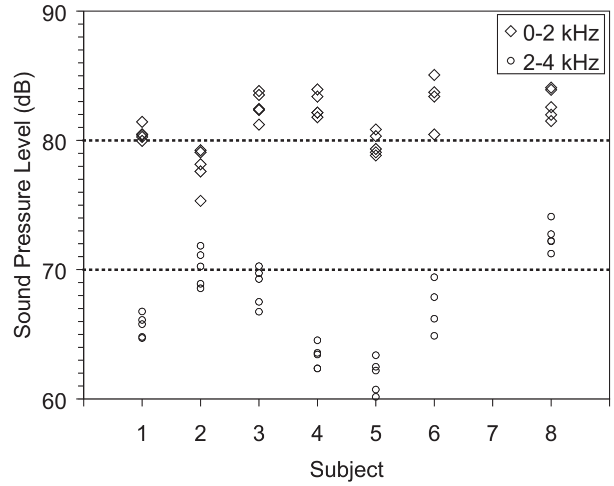


**FIGURE 5.** Sound pressure level of each singer in the audience area of the auditorium, with 0- to 2-kHz and 2- to 4-kHz bands shown separately. Each data point represents the equivalent level over one rendition of the song, determined from the exponential average of eight microphone positions at 10- and 15-m distance from the singer.

representation of singer directivity, making the results easier to digest. However, there exist various options for reducing a polar plot to a single number. One approach, which is widely used in room acoustics theory and audio transducer specification, is the directivity index (DI, in decibels), derived from the directivity factor, $Q$. This is the ratio of the frontally radiated sound intensity to that which would be radiated were the singer's sound omnidirectional. A DI of 0 dB (or $Q = 1$) would be found for an omnidirectional source, although this value does not necessarily mean that the source is omnidirectional.

Using our anechoic room measurements, it is possible only to determine a horizontal directivity index (HDI), as measurements were only made on the horizontal plane. The reverberation room measurements integrated sound radiated in all directions from the singer and, hence, might be combined with the anechoic room measurements to estimate a full DI. For a sound source of fixed directivity, the relationship between sound power level (measured in the reverberant room) and frontal sound pressure level at 1 m in the anechoic room should be linear, with a regression coefficient of 1. Figure 6 shows the measured relationship for the 1- and 2-kHz octave bands for equivalent performances in the two rooms. As noted previously, the 1-kHz octave band has the greatest sound power in almost all cases. At 2 kHz, the relationship follows the expected pattern for fixed directivity well, with directivity indices mainly between 6 and 9 dB. At 1 kHz, the relationship varies somewhat more, with most results having a DI close to 3 dB. This pattern of variation is also found for the HDI—measured entirely in the anechoic room, as shown in Figure 7. The HDI results tend to be lower than equivalent full DI results, which could be expected, as the HDI results do not include acoustic shadowing of the torso (below the horizontal behind the subject).

DI and HDI use the 0° microphone as the reference for directivity. Many of the polar plots show more sound radiated to 15° or 30° than 0°, and DI does not discriminate between these small angles and sound radiated behind the subject. Nevertheless, alternative single number ratings (such as front-back ratios or measures based on circular harmonic decomposition) yield results correlated with HDI. Hence, this article restricts discussion to the more widely used DI values.

Figure 8 shows that HDI values vary more than approximately 4 dB in the 0- to 2-kHz band, and more than 2 or 3 dB

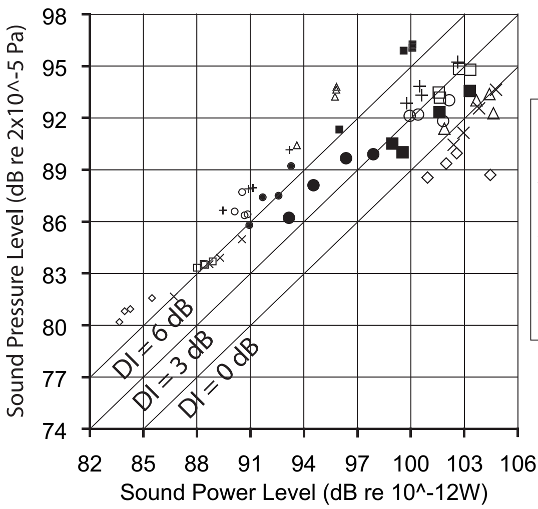


**FIGURE 6.** Apparent relationship between sound pressure level (0°, 1 m in the anechoic room) and sound power level (reverberation room, adjusted using the head microphone difference between equivalent anechoic and reverberant performances). The reference values for sound power level and sound pressure level are 1 picowatt and 20 micropascals, respectively. *Small symbols* are for the 2-kHz octave band, and *large symbols* are for the 1-kHz octave band. Functions for three directivity indices are plotted.

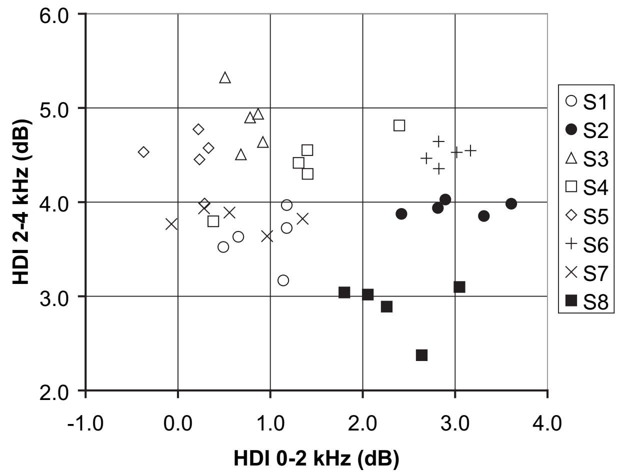


**FIGURE 8.** Horizontal directivity indices for the 0- to 2-kHz and 2- to 4-kHz bands, measured in the anechoic room (*large symbols*) and recital hall (*small symbols*). Note that S7 was not measured in the recital hall.

in the 2- to 4-kHz band in the anechoic room. This range of results is preserved in the recital hall for the 2- to 4-kHz band but disappears for the lower-frequency band. This may be partly explained by the greater directionality of the shotgun microphones in the higher-frequency band, presumably resulting in better measurements of directivity in that range. Results for individual subjects are generally found in clusters, and there is correspondence evident in the subject HDI values between the 2- and 4-kHz results for the two recording contexts. Singing style yields no consistent effect in HDI.

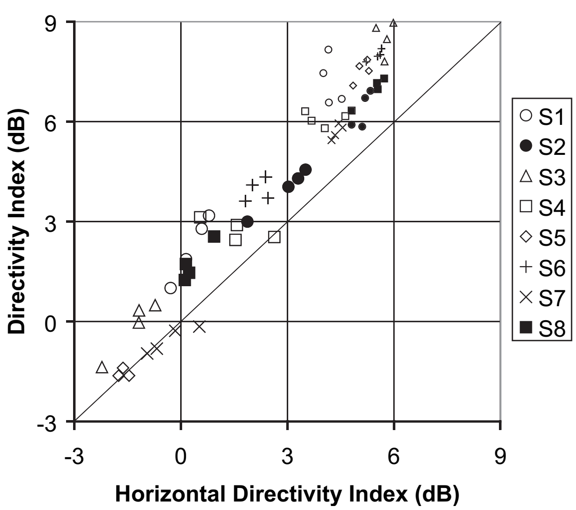


**FIGURE 7.** Apparent relationship between horizontal directivity index (measured in the anechoic room) and directivity index (measured using the reverberation room for sound power level and anechoic room for frontal sound radiation pressure at 1 m). Small symbols are for the 2-kHz octave band, and large symbols are for the 1-kHz octave band.

## Effect of performance style

Figures 9 and 10 show, in polar form, the anechoic room directivity patterns for each subject as they vary among contrasting singing modes. There is little or no effect evident on the directivity of the frequency bands between the modes (ie, there is no consistent change in the shape of the polar plots). However, there is a tendency for the amount of energy in the 2- to 4-kHz band to increase more than that in the 0- to 2-kHz band when comparing small-hall versus large-hall projection (Figure 9). Table 4 quantifies this change in the ratio between the two bands in the anechoic room and auditorium as the singer's projection changes, showing that the effect occurs in most cases, and that a larger effect occurred in the auditorium. Because the higher-frequency band is more directional than the lower-frequency band, this can be interpreted as a small increase in voice directivity. A similar comparison between technical singing and singing with emotional connection (Table 5) yields smaller and less-consistent changes (with a small tendency for technical singing to have relatively less energy in the 2- to 4-kHz band).

## Average directivity and comparison with previous studies

As noted in the introduction, there exists little published data on singing directivity and a modest amount of data on speech directivity. Marshall and Meyer[20] present the best data on singing, and Chu and Warnock[8] present the best data on conversational speech. Figure 11 compares the opera soloists of the present study (average of all singers), the choral singers of Marshall and Meyer, and the conversational speakers of Chu and Warnock in the horizontal plane. Results are similar in the four octave bands compared, but there appears to be some divergence among studies in the 2-kHz octave band, the opera

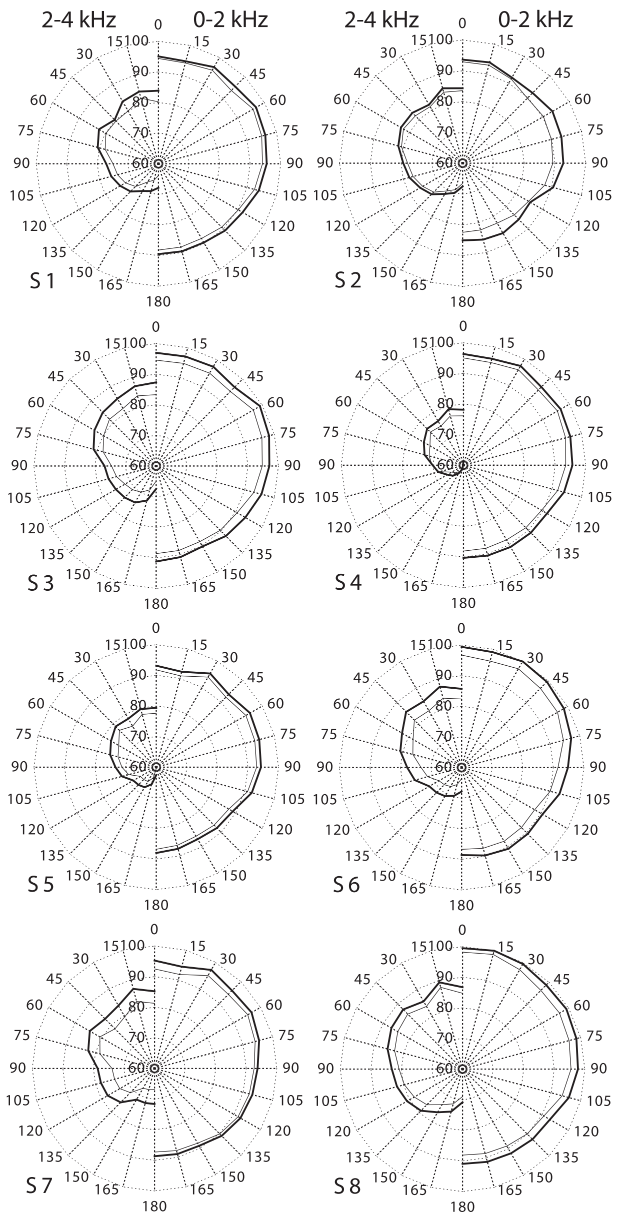


**FIGURE 9.** Horizontal directivities for each subject (anechoic room) for small-hall projection (*thin line*) and large-hall projection (*thick line*). Values are sound pressure levels at 1-m distance.

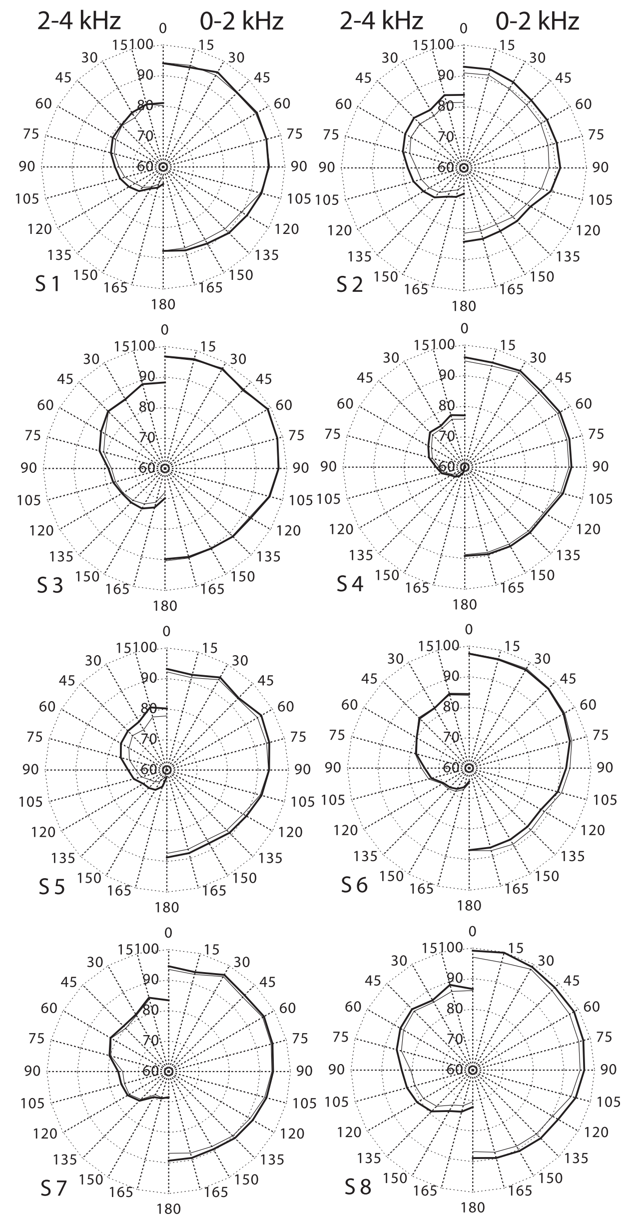


**FIGURE 10.** Horizontal directivities for each subject (anechoic room) for technical singing (*thin line*) and singing as in performance, with all the emotional connection intended by the composer (*thick line*). Values are sound pressure levels at 1-m distance.

soloists having the narrowest directivity of the three groups. The choral singing is characterized by a broad frontal lobe in this octave band, whereas the operatic singing has a narrow frontal projection, with the speech in between. The approximately 6 dB of separation between the choral singing data and opera soloist data for many of the angles in the 2-kHz octave band should be too large to be attributed to measurement error, and hence, this divergence suggests that there is some scope for human talkers and singers to control their vocal directivity—presumably through the shape and size of the mouth opening or the distribution of energy within octave bands. The potential for energy to be distributed differently within a given octave band is a potential pitfall of octave band analysis, and it can be argued that voice directivity analysis is best restricted either to very broad frequency bands or to bands derived from the peak structure of the power spectrum.[24] The signal content of the voice may also contribute to the differences (eg, the relative energy of vowels vs consonants in speech and song and the selection of vowels used in singing). The fact that this divergence occurs close to the singer's formant range indicates that this directivity control may be of particular relevance to singing projection.

## DISCUSSION

Compared with other components of vocal projection, vocal directivity is a relatively weak effect. For the subjects of this study, directivity indices had a range of roughly 3 dB in the 2- to 4-kHz

**TABLE 4.**
**Change in the Ratio of Energy in the 2- to 4-kHz Band to That in the 0- to 2-kHz Band for Singing Mode D (Small-Hall Projection or Singing to the Mannequin in the Audience Area of the Hall) Compared With Singing Mode C (Large-Hall Projection), Measured Using the 0° Microphone in the Anechoic Room and the 15° Microphone in the Auditorium**

| | Subject | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Room | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | Mean |
| Anechoic room | +3.0 | +0.1 | +1.6 | +0.7 | +0.4 | +0.6 | +1.2 | +0.7 | +1.1 |
| Auditorium | +2.1 | +1.4 | +1.5 | +1.2 | +1.9 | −0.7 | | +2.1 | +1.4 |

A positive value indicates that there is a greater increase in the 2- to 4-kHz band than the 0- to 2-kHz band as the singer changes from mode D to mode C. Values are in decibels.

band. In contrast, the sound pressure level within this band varied over a range of almost 15 dB. Although the effect is weak, it is clearly observable, and we can consider it in terms of three questions. First, within a given frequency range (eg, 2–4 kHz), is there substantial variation in long-term directivity among singers? Second, within a given frequency range, does singing projection affect directivity? Finally, is there evidence that singers incidentally control their directivity by controlling the amount of energy in the most directional part of their singing spectrum range? The answer to the first and third questions is "yes"; the answer to the second question is "no."

With regard to the first question, the differences among the directivities of the singers in particular frequency ranges are likely to be the result of differences in their physical features, such as the mouth, head, and torso shape and size. The physical model measurements of Halkosaari et al[11] and Stewart and Cabrera[16] confirm that the mouth aperture does substantially affect vocal directivity. However, human ethics clearance was not obtained to make these physical measurements of the singers in this study; hence, the specific effects of physical differences cannot be examined. Of course, singers have little control over such features; hence, this observation is probably inconsequential for voice training.

With respect to the effect of singing style, the results of this study indicate no directivity effect within the given frequency ranges—that is, directivity did not change, for example, within the 2- to 4-kHz range for a singer when his or her projection changed. Perhaps, this is not surprising, because, to change a singer's directivity at a given frequency, his or her physical features would need to change, and probably, the only practical change might be one in the mouth aperture. If average mouth aperture did change between singing projections, this change was not great enough to yield observable measured effects.

Nevertheless, singing projection did have an observable effect on voice directivity, because the singers shifted the spectral distribution of energy as they changed projection. Shifting energy to a higher-frequency range yields greater directivity, because the voice is more directional at higher frequencies. Such a change in spectral content for different singing projections is consistent with the findings of Thorpe et al.[25] The fact that the singer's formant region is more directional than the lower-frequency range means that enhanced vocal directivity is acquired incidentally as part of operatic soloist training.

The comparison with other studies (of choral singing and conversational speech) provides more evidence for a role for directivity in vocal projection—tentatively suggesting that the operatic style of singing tends to be somewhat more directional than other forms of vocal projection in the frequency region near the singer's formant. One should bear in mind that Marshall and Meyer's[20] study was of three singers, and hence, the comparison with their results may be vulnerable to individual characteristics of singers (rather than statistical group characteristics). On the other hand, much choral singing probably would not usually benefit from vocal directivity in the way that opera solo singing might; hence, the observation of less directivity in choral singers is consistent with the respective demands of the performance contexts.

The extent to which vocal directivity may be advantageous in an opera theatre can be assessed by considering its effect on acoustic clarity. As mentioned in the introduction, clarity index is the ratio of early sound energy in a room impulse response (ie, its pattern of echoes and reverberation) to late sound energy, expressed in decibels. By convention, either 50 milliseconds

**TABLE 5.**
**Change in the Ratio of Energy in the 2- to 4-kHz Band to That in the 0- to 2-kHz Band for Singing Mode B (Singing With Emotional Connection) Compared With Singing Mode A (Technical Singing), Measured Using the 0° Microphone in the Anechoic Room and the 15° Microphone in the Auditorium**

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | Mean |
|---|---|---|---|---|---|---|---|---|---|
| Anechoic room | −1.1 | −0.5 | +0.2 | 0.0 | −1.4 | −0.6 | +0.7 | +1.6 | 0.0 |
| Auditorium | −1.4 | −0.1 | −2.3 | −0.7 | −1.7 | −1.3 | | +0.8 | −0.8 |

A positive value indicates that there is a greater increase in the 2- to 4-kHz band than the 0- to 2-kHz band as the singer changes from mode B to mode A. Values are in decibels.

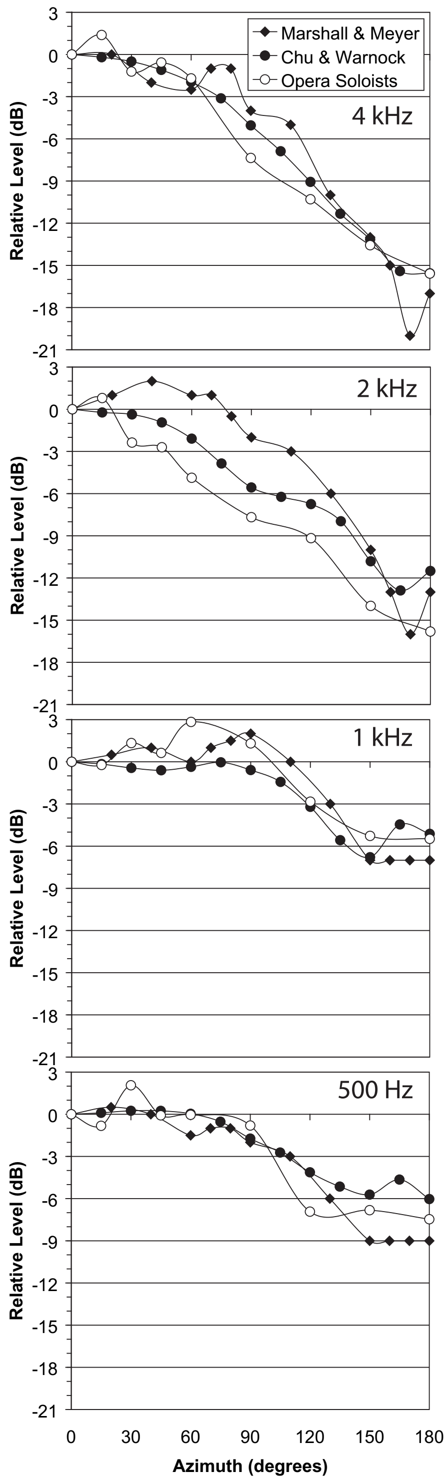


**FIGURE 11.** Comparison between the overall mean anechoic measurements of the present study, the choral singer measurements of Marshall and Meyer,[20] and the conversational speech measurements of Chu and Warnock.[8] Data are in octave bands, showing the relative level of each microphone relative to the 0° microphone.

(for speech) or 80 milliseconds (for music) is taken as the boundary between early and late energy (known as C50 and C80, respectively). Room acoustical data for 23 opera theatres are given by Beranek.[26] Using Barron and Lee's formula for clarity index,[27] the clarity index at a fixed distance from a source can be estimated using room volume, source directivity, and reverberation time. For these 23 theatres, an increase in a singer's DI from 0 to 3 dB yields an average increase in C80 of 1.5 dB or an increase in C50 of 1.8 dB (using a fixed distance of 10 m). A further increase in DI, from 3 to 6 dB, yields increases of 2.0 dB for C80 and 2.2 dB for C50. Because the just-noticeable difference for clarity index in auditoria is assumed to be 1 dB,[28] this rough estimation suggests that vocal directivity does make a small contribution to singer vocal quality in practical performance situations, given the 3-dB range of directivity indices measured in the present study.

One strength of this study is that it uses professional opera singers, including some of high profile. The consequent limitation is that only eight subjects were tested, only two of whom were males. Hence, there is an emphasis on individual subject results rather than sample group statistics in the analysis. Although this sample size compares favorably with previous studies on singer directivity, there would be some benefit in obtaining a larger set in future work (such as the 40 subjects in Chu and Warnock's[8] conversational speech study) so that statistical generalizations can be made with confidence.

Several studies of directivity use a fixed reference microphone, with the remaining microphones moved between measurements of the human subject, so that many measurements can be made with limited channels. The disadvantage of that process is that it is very demanding on the subject—and was considered too demanding for the present study. A potential advantage of a fixed microphone array is that the time-varying directivity pattern of a singer can be studied. However, this article has not presented an analysis of the time-varying directivity patterns of the singers, which would be enormously more complex. Nevertheless, there may be some value in extending the study of Marshall and Meyer[20] in examining the directivity of specific phonemes and how formant strength and tuning might be used to control directivity. Results could potentially be applied in room acoustic auralization.

## CONCLUSION

This study presents data on the directivity of operatic soloists, including some soloists of high standing. Results indicate that directivity varies among singers, but not to a large degree. Singing mode has a small effect on vocal directivity for the range of vocal projections tested, especially comparing large-hall projection with small-hall projection. Results infer that the singer's formant, which has relatively high directivity, plays a role in the directivity of opera soloists.

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