

# DIRECTIVITY MEASUREMENTS OF THE SINGING VOICE

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# ABSTRACT

This work presents initial results of a detailed measurement study on singing voice directivity under various conditions in two- and three-dimensions. Unlike previous studies that have used average directivity data over sung phrases or crescendos, this work presents results that are measured and analyzed in finer detail. A professional opera singer (counter tenor) participated in the experiments. Measurements are based on simultaneous recording using an array of 24 microphones mounted on a movable semi-circular arch in an anechoic room. Video recordings serve for estimation of the mouth shape and opening. Details of the measurement protocol and post-treatment processing are presented. Specifically, the variations in directivity relative to pitch, level (piano, fortissimo, etc.), vowel, and controlled "voice projection" by the singer have been investigated. The application of directivity patterns to radiating sources in computer simulations and auralizations is common for loudspeaker models. Few applications include the directivity patterns of natural sources, partly due to the lack of sufficient data. Results of this work are applicable to vocal production research, simulator design, room acoustic sound field prediction, and virtual reality systems with musical applications.

# INTRODUCTION

While there have been numerous studies concerned with the directivity of musical instruments, there have been very few studies concerned with the directivity of the human voice. Human directivity measurements for 66 spatial positions and 13 frequency bands have been reported in the pioneering work of Dunn and Farnsworth [1] using one speaker repeating 15s of speech. The results show a greater variation in directivity patterns at higher frequencies. Directivity variations linked to the size of the mouth opening occurred above 5600 Hz. Flaganan [2] proposed new measurements with a calibrated artificial sound source in a mannequin. He also compared the results obtained with simple analytic models: piston in a sphere, baffled piston. Using an array of microphones mounted on a double arc Chu and Warnock [3] showed that similar directivities were obtained for both normal and loud voice levels but significant changes behind the talker were observed for low voice level. No significant differences in directivity were detected between male and female talkers although male and female voices had different spectra. An effect of the aperture size of the mouth has been studied [4]. Open and close vowels give different patterns above about 1000 Hz. This seemed in agreement with an analytic model of a piston (corresponding to mouth aperture) radiating on a sphere (with corresponding head radius). Finally, Kob and Jers [5,6] compared radiation patterns for an artificial singer head and real singers, showing comparable results for sustained vowels.

# MOTIVATION OF THE WORK

In the present work, we investigate several aspects of radiation patterns in singing. A first question is the difference between loud voice and soft voice, as discussed by Chu and Warnock [3]. A second question is the effect of the sung vowel as discussed by Halkosaari, Vaalgamaa, and Karjalainen [4]. A more challenging question arose from discussions with professional singers who are often called to sing in large rooms. In voice pedagogy, many singers are using the metaphor of voice "projection" or voice "focusing". This terminology seems to imply some sort of spatial effect or voice directionality control. A matter of serious interest with regards to directivity this metaphor is only a matter of singer's perception or whether it resulted in actual changes in voice radiation patterns. These conditions are studies using sustained vowel singing and 1/3<sup>rd</sup>-octave band analysis. This provides detailed results for these various conditions which has not previously been presented.

#### **MEASUREMENT PROTOCOL**

This study used a protocol previously established for human speech phoneme directivity [7]. Measurements were performed in the anechoic room of the *l'Institut de Recherche et Coordination Acoustique/Musique* (IRCAM). A 180° arc with 24 equally spaced microphones on a motorized arm capable of elevations from -45° to 90° (see Figure 1) was used. A chair was placed at the center of the arc, and the singer's mouth position was aligned to the exact center using fixed laser pointers. The chair was equipped with a head rest to assure a stable position throughout the measurement sessions (see Figure 1).The chair could be oriented either to the center of the microphone arc or to the end of the arc.

In addition to the 24 microphones along the arc, 2 reference microphones were also included. These microphones consisted of a calibrated measurement microphone at a fixed position infront of the singer, as well as a head-worn vocal microphone and were used for calibration between repetitions and all spectral analysis. The calibration procedure for the microphone arc used a small loudspeaker was placed at the signer's position. The arc was raised to 90°, such that the arc was coplanar with the diaphragm of the loudspeaker (the two being axis symmetric). Pink noise was played and the recorded signals were analyzed in 1/3<sup>rd</sup>-octave bands. Calibration levels were derived to obtain an omni-directional responses for each band.

A video camera at a fixed position, and high contrast lip make-up were used to help analyze lip forms. The position of the measurement reference microphone and camera are shown in Figure 1. The lip make-up and head-worn vocal microphone are visible in Figure 2.

To aid the singer in maintaining a constant vocal effort and pitch within the anechoic chamber two types of feedback were provided. An electric tuner display, located under the camera, was used to help subject maintain pitch. An audio return over closed headphones (to avoid contamination of the measurement signal) with which an artificial reverberation was also added (seen in Figure 2). This audio return was found to be useful by the singer over the 2 day measurement session. The artificial reverb (*Spat*, under Max/MSP) used the signal from the head-worn vocal microphone. The reverberation was adjusted to the comfort of the singer as being that of a quality large performance space. The reverberation time was approximately 1.7 sec, with a direct-to-reverberant ratio of approximately 19 dB.



Figure 1.– (a) Motorized measurement arc schematic. – (b) Anechoic chamber configuration. – (c) Signer alignment procedure. –(d) Reference microphone and camera placement.

#### RESULTS

While measurements were acquired for a large number of conditions, only several singing conditions have been chosen for presentation in this work to provide examples of effects either observed or not, as a function of singing parameters.



Figure 2.- Video extract of signer - sung note a, vowel /a/, Piano/Mezzoforte/Forte/Fortissimo.

#### Vowels

Variations in spectral content for sung vowels are well known. These spectral changes are linked, at least in some part, to changes in the mouth geometry of the singer. Whether there is an effect on the directivity is to be examined. Figure 3 shows the spectral analysis for the sung

note **a**, vowels /a/i/o/. (The French notation for the note was **siB2**, and was actually sung a  $\frac{1}{2}$  tone lower due to the baroque tuning used by the singer.) A fine detail spectral analysis is used to examine these variations which are not as evident in the  $1/3^{rd}$ -octave analysis which will be used for directivity pattern analysis. A noise-floor threshold has been applied to the  $1/3^{rd}$ -octave analysis results based on the signal-to-noise level in the measurement array (*not* the reference microphone used for spectral analysis) such that data within 3dB of the measured background noise-floor was suppressed. The same procedure was applied to all subsequent  $1/3^{rd}$ -octave and directivity results. Figure 4 presents the directivity pattern in the horizontal plane, in  $1/3^{rd}$ -octave bands. The data was measured on one side of the signer only and has been symmetrized to form a complete circle.





Figure 3.- Spectral analysis for sung note a, vowels /a/i/o/, forte.

Figure 4.- Horizontal plane directivity for sung note a, vowels /a/i/o/, forte.

It is clearly evident that there are variations in the spectral content. There are a number of observations that can be drawn from these results. First and foremost, it is clear that the directivity pattern varies with frequency. The low frequency region is near omni-directional, as one would expect, until 600 Hz~1000 Hz, or the region where the head dimensions are comparable to ½-wavelength. The mid-frequency region (1250 Hz – 4000 Hz) shows a range of patterns, with the upper frequency bands becoming more cardioid in nature. At the same time, there are not significant variations between vowels in the directivity patterns. The most marked differences are around 800-1000 Hz, at 2500 Hz, and somewhat at 4000 Hz. In analyzing the directivity data, it is often useful to return to the spectral analysis in Figure 3 in order take into account the amount of energy contained in the respective band. The *perceived* directivity of a sung note is a combination of the directivity pattern as a function of frequency and the energy in each band that contributes to each pattern. For example, the 315 Hz band is of little interest as there is little energy in this band for the given singing condition.

# Intensity

Variations in intensity of a sung note are a basic condition worth examining. In augmenting the intensity, a singer often changes their mouth geometry. This is seen in the video extracts shown in Figure 2, for the sung note **a**, vowel /a/, for four intensities: *piano*, *mezzoforte*, *forte*, and *fortissimo*. In addition to the change in intensity, there are also changes to the spectral content of the note when the intensity is augmented. A spectral analysis (see Figure 5) shows these variations.



Figure 5.- Spectral analysis for sung note a, vowel /a/ for different intensities.

Figure 6 presents the directivity pattern in the horizontal plane, in  $1/3^{rd}$ -octave bands, for the sung note **a**, vowel /a/, as a function of sung intensity. It appears that there is little variation in directivity as a function of intensity. The most noticeable differences occur in the 800 Hz and 1000 Hz bands.



Figure 6.- Horizontal plane directivity for sung note **a**, vowel /a/, (1/3<sup>rd</sup>-octave), 20dB scale.

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Note that the harmonic near 1000 Hz is slightly lower in frequency for *mezzoforte* than for the other intensities. This could explain why the directivity pattern *mezzoforte* resemble the 1250 Hz band more than the others. From Figure 2, it is clear that the mouth geometry for *fortissiomo* is different than lower intensities, and could explain the different pattern at 800-1000Hz.

#### Projection

The term "projection" or "projected voice" is often used in singing for expressing a vocal gesture, or voice quality, aimed at filling large concert space. The singer focuses his attention on the last rows of a concert hall with the idea of projecting the sound of his voice in order to obtain maximal power. Whether a projected voice actually exhibits different radiation patterns is investigated in this study. Our subject produced different sustained vowels with and without voice projection. Results for sung note **g1** (French notation **laB3**) are reported in Figures 7 and 8. The main observed effect of projection appears to be an increase in energy at higher frequencies. Radiation patterns with and without projection are almost identical. For frequencies above 5000 Hz, only the project voice conditions contained sufficient energy above the noise floor for showing measurable radiation patterns. There is a visible increase in energy in the spectrum for the /a/-projected in the region 5000-6300 Hz, and for /o/-projected in the region 6300-10000 Hz. In the spectrum for projected voice, two additional peaks are visible between the first and second hoarmonic and also between the second and third harmonic. More investigation seems necessary in order to decide if this is a significant feature of projected voice.



Figure 7.- Spectral analysis for sung note g1, vowels /a/o/, style : normal / projection.





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# Focusing

One of the main problems for singers in large rooms is voice projection, *i.e.* the ability to deliver a convenient sound level far from the scene. However, in other situations the singer is performing in relatively small rooms for a restricted audience, like chamber music or *Lieder* performed in music rooms. In this situation, the singer puts more attention on the voice quality and expressive nuance rather than to power and projection. The voice is "focused", with the idea of delivering the most exquisite timbre and the most excellent nuances, to a chosen and close audience. A spectral analysis of normal and "focused" for sung note **g1**, vowels /a/o/, is shown in Figure 9. The differences are very subtle. At most, the third harmonic for /a/-focused has more energy than the corresponding /a/-normal. In terms of directivity, there differences were equally subtle, and were similar enough to those presented previously that they are not shown here.



Figure 9.- Spectral analysis for sung note g1, vowels /a/o/, style : normal / focused.

# CONCLUSIONS

A striking feature of the results is the invariance of radiation patterns across different conditions. For instance, the 1250 Hz and 1600 Hz bands always show similar characteristic patterns. Contrary to previous studies, we did not found a significant difference for the different vowels. An analysis of phoneme dependant radiation patterns in speech is currently under study, and will be compared to the singing data. This more variations were for the 2500 Hz band. It is not yet clear why this measurement band is so affected.

Acoustic theory predicts that radiation patterns for vocal production depend mainly on the head radius and mouth aperture. This seems to be confirmed by our results. Despite the singer's sensation of projection or focusing, vocal gestures aimed at directing the sound in space, only minimal effect on the radiation patterns are noticeable. A combined spatial-frequency analysis could be used in an effort to interpret the perceived directivity of a sung condition.

The consistency of directivity patterns could be a feature related to the specific geometry of the singer's morphology. To the best of our knowledge, no detailed investigation or model on the face geometry or even on the mouth shape (rounded like in /o/ vs. stretched like in /i/) are currently available. More detailed models and measurement of the singer related radiation transfer functions could explain the invariance of radiation patterns across conditions.

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