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Estimation and assessment of vocal directivity variations as an effect of small body movements

Konstantinos Bokogiannis, Eleni Tavelidou, and Areti Andreopoulou

Laboratory of Music Acoustics and Technology (LabMAT), National and Kapodistrian University of Athens

Correspondence should be addressed to Konstantinos Bokogiannis (`k.bakogiannis@music.uoa.gr`)

ABSTRACT

Previous research has linked vocal sound quality to technique and expressiveness-related movements of singers. This study examines the effect of such movements on vocal directivity data collection and attempts to assess its impact by means of objective data comparisons and subjective user testing. Data was collected from 12 individuals in 29 directions and four elevation planes using a hemispherical microphone array. Data analysis showed that directivity variations range from 1.4 dB to 3 dB, depending on frequency and direction, and that the majority of the differences as measured by the chosen metrics are below the 1 dB JND threshold. The study also conducted auralizations and an audibility test, which confirmed that, in static listening conditions, variations introduced by small body and head movements do not lead to audible directivity artifacts. These findings suggest that measurement protocols allowing for small movements can still capture perceptually relevant and stable directivity data, without sacrificing sound quality.

1 Introduction

Research on the directivity of the singing voice emerged in the late 20^{th} century [1]. Since then, pitch, loudness, phoneme, vocal projection, singing genre, and room acoustics have been identified as the primary factors affecting it [2, 3, 4, 5]. The directivity of the singing voice varies with frequency and can be influenced by body posture, head position, and vocal tract shape [6, 7]. As a result, its measurements are often performed in strictly constrained conditions [2, 8].

Yet, the link between music / musicality and movement is well established and has been thoroughly studied under several scientific disciplines [9]. Physical movements impact musical perception and vocal production. Vocalists and singing instructors concur that there is a connection between a singer's body movements and their vocal quality [10]. Conscious and unconscious movements are employed by vocalists and musicians, in general, as a means for supplementing expressivity. It has been shown that an increase of movement by performers leads to higher ratings of expressivity by the audience [11]. Auralizations using dynamic sound directivity renderings have been found to exhibit audible differences to static ones [12] and to lead to more plausible auralizations [13].

Body and head movements as well as hand gestures have also been linked to beat perception and rhythm detection [14], the produced Sound Pressure Levels (SPL) [15], as well as to one's tonal accuracy, intonation, and timbre [16, 17]. Hence, body and head movements related to technique are integral to music production. Their constrain may affect one's sound quality in a destructive manner. Consequently, there have been several studies examining musical instrument [18, 19, 20] and vocal directivity [3, 4, 5], which rely on measurement protocols permitting small, technique-related movements. Nevertheless, there has not been a systematic attempt to assess the magnitude of the said variations on the collected data. This paper quantifies variations caused on vocal directivity as a result of small, technique-related body and head movements and attempts to assess their perceptual impact through a preliminary audibility study.

2 Data Collection

2.1 Measurement setup

Directivity measurements took place in a $10\,\mathrm{m} \times 7\,\mathrm{m} \times 5\,\mathrm{m}$ hemianechoic, sound-treated space at the facilities of the Laboratory of Music Acoustics and Technology (LabMAT), NKUA, which has a mean T30 of 0.45 s for frequencies up to 500 Hz and of 0.29 s onward. Potential interference of the surrounding surfaces (floor, ceiling, walls) and the measurement equipment with the collected data were minimized using additional sound absorptive material. The utilized hemispherical microphone array (radius 1.585 m) consisted of 29 RODE-M5, small diaphragm, condenser microphones, positioned symmetrically every $30°$on the horizontal plane and every $45°$on the $\pm30°$elevation planes. An additional microphone was placed directly above at $90°$elevation. The height of the array was adjustable such that the center of the hemispherical configuration be aligned with the acoustic center of each measured sound source [21].

Prior to measurements, impulse responses of all microphones were collected using ScanIR [22, 23], on an M1 Mac-Book Pro running Matlab 2021a. All input audio channels were level-calibrated within ±0.5 dB of each other, using pink noise (78 dBA), generated by a Brüel & Kjær omnidirectional loudspeaker (OmniPower SoundSource Type 4292-L) placed at the center of the hemispherical microphone array. Pink noise signals were recorded with all 29 channels such that any remaining level inter-channel imbalances be accounted for and corrected during data post-processing. Directivity data was captured using two Yamaha TF1 digital mixers (inter-connected via DANTE) and their built-in pre- amplifiers, on an i5 laptop running Cubase 11.

2.2 Measurements and Data Post-Processing

Twelve individuals took part in the singing voice directivity measurement process. Two of them were professionals in classical / operatic singing (tenor, soprano), two were professionals in popular / modern singing practices (baritone, mezzo soprano), two were professional byzantine chanters (bass, bass-baritone), two were scholars of classical / operatic singing (both soprani), two were untrained amateur singers (1 female), and the last two were children under the age of twelve (both female). The latter four have never received formal vocal training. Participants were standing inside the microphone array, such that their mouth be aligned with the center of the hemispherical configuration.

As discussed earlier, contrary to similar studies, which have employed stricter alignment methods constraining the position of the measured participants [2, 8], this project used a different alignment protocol, tolerant to body and head micro-movements, related to vocal production and breathing, which have been found to lead to more natural singing practices. Consequently, a plumb and laser beams were used to ensure that participants remained properly aligned with the array throughout the measurements. Every time participant misalignment was observed, the measurements were repeated.

The collected data consisted of two approximately 30 s long Greek song excerpts, selected by each participant based on the following instructions: a) the two songs were considered to be representative of the participants' singing style, b) they were as musically diverse as possible, and c) they covered a wide frequency and dynamic range. Additionally, participants were asked to intone in two different dynamic levels, piano (p) forte (f)the five Greek vowel monophthongs: /a/ (α), /e/ (ε, $\alpha\iota$), /i/ (ι, η, υ, $o\iota$, $\varepsilon\iota$), /o/ (o, ω), and /u/ ($o\upsilon$), on the following pitches: A2, E3, and C#4 for the male singers and A3, E4, and C#5 for the female singers, respectively, for about two seconds each. The latter data is not analyzed in this study.

Each of the 29 recorded audio channels was deconvolved with the corresponding microphone response to minimize the impact of the measurement setup on the analyzed data [19, 24]. The pink noise signals recorded at the center of the hemispherical microphone array during measurement setup were used for the calculation of the appropriate scaling factors such that the levels of all microphones were adjusted to the same Root

Mean Square (RMS) levels, accounting and correcting for potential inter-channel level imbalances. The same signals were also used to calculate calibration values for achieving equal RMS levels across $1/3^{rd}$ octave bands of the recorded signals, obtaining flat frequency microphone responses [2]. In order to suppress the impact of noise introduced in the data by frequency bands with insufficient energy, the signal-to-noise level of all recorded channels was calculated and a noise-floor threshold was derived suppressing any data within 3 dB of its level [21].

3 Data Analysis

In order to quantify the magnitude of the variations small body and head movements introduce to directivity data, each of the 24 song excerpts (12 participants x 2 songs) was split into five segments with a 50% overlap, resulting in a total of 120 segments. To ensure comparability of the data, all segments were level calibrated to the same global average RMS value.

Voice directivity patterns were extracted from all excerpts and analyzed per participant to quantify the range of variations per location and frequency band. Figure 1 shows an example of the said variations for the ten song segments of a classical female and a classical male singer, at 250 Hz, 1 kHz, and 4 kHz. The range (max to min) of directivity variations observed per segmented song was calculated per frequency band and microphone position, for the data that met the noise threshold criterion discussed in Section 2.2. The average range calculated across all songs and participants resulted in the estimation of the magnitude of variations introduced in the data by the singers' micromovements. These values are used in Section 4 for the objective and subjective evaluation of the resulting variations in singing voice directivity data. An overview of statistical measures that summarize these variations can be found in Table 1.

A more descriptive method of studying these variations is by expressing them in terms of their impact on three commonly used directivity metrics, namely: i) the Horizontal Directivity Index (HDI), defined as the ratio of the on-axis power to the average power of all recording positions on the horizontal plane, ii) the Front-to-Back Ratio (FBR), defined as the ratio of the average power radiated to the front and the back, iii) and the Upward-to-Downward ratio (UDR). defined as the average power radiated to the upper and the lower half-space, which in our case considered only the $+30°$ and $-30°$ elevation planes [25]. Variability in these metrics, calculated as the range (max - min) of the metric variations per song and frequency band and consolidated across all 24 song excerpts, are shown in Figure 2.

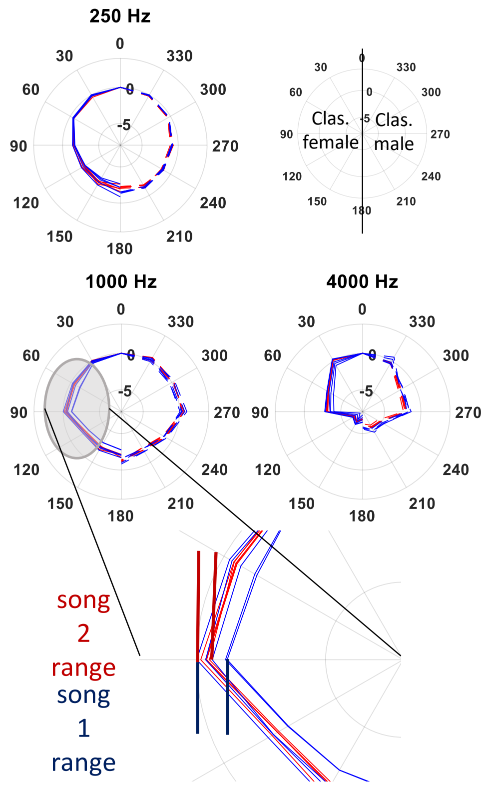

Fig. 1: Example of the directivity variations of a classical female singer (left side – solid lines) and a classical male singer (right side – dashed lines) at 250 Hz, 1 kHz, and 4 kHz, across the ten song segments. Segments of the first excerpt are illustrated in blue and of the second in red.

As can be seen, the said variations in all three metrics mostly lie below the Just Noticeable Difference (JND) threshold of 1 dB. This indicates that the natural body micromovements that were made during the measurement did not significantly affect the data, in general. However, certain exceptions can be observed in the Figure, which may be worth discussing. For example, looking at the HDI-range at the 1 kHz one-octave fre-

Table 1: Numerical measures of directivity variations calculated across all 29 microphones per one-octave frequency band.

Freq. band (Hz)	mean (dB)	max (dB)	min (dB)
125	2.5	3.0	2.1
250	1.9	2.2	1.7
500	2.4	2.6	2.3
1000	2.6	2.8	2.3
2000	2.8	3.0	2.6
4000	2.1	2.6	1.8
8000	1.8	2.2	1.4

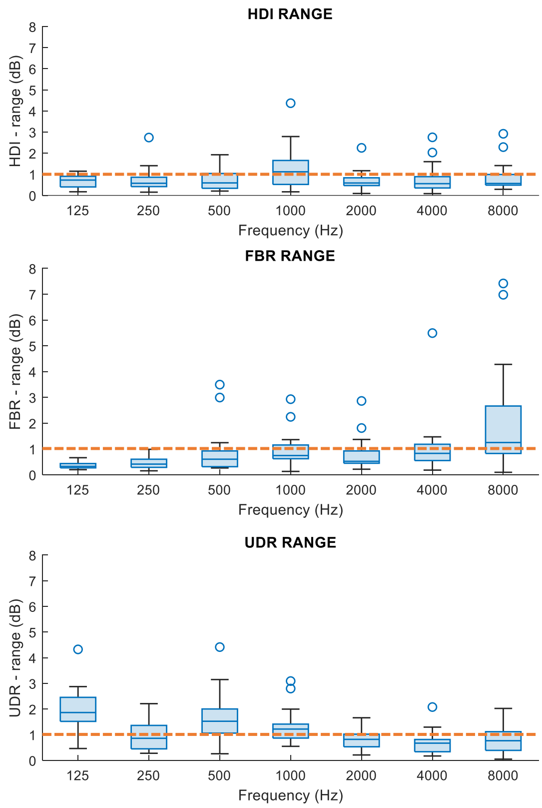

Fig. 2: Variability in HDI, FBR, and UDR, calculated as the range (max - min) of the metric variations per song and frequency band and consolidated across the 24 song excerpts. The dashed orange line marks the 1 dB JND threshold

quency band, greater variations can be found. These can be attributed to the fact that this frequency range marks a transitional point between the omnidirectional-like directivity nature of low frequency regions and the cardioid-like nature of the high frequency ones [21]. Another exception can be observed at the 8 kHz one-octave frequency band for the FBR-range. Further analysis of the measured directivity data revealed that in this frequency region the vocal projection of some of the measured singers on the $\pm 30^\circ$ elevation planes is less directional, forming somewhat circular instead of clear cardioid-like patterns. This phenomenon requires further examination. An additional finding is that the UDR-range exhibits higher variability compared to the HDI and FBR ranges, in the low and mid-frequency regions (up to 1 kHz). This suggests that the up-down head and maybe even body movements, which have a greater impact on the UDR metric, may result in more significant directivity variations than front-back movements, which primarily affect the HDI and FBR metrics.

4 Objective and Subjective Data Assessments

In order to assess the potential impact of the aforementioned data variations, created by small natural body and head movements, on singing voice directivity, two 10 s anechoic audio excerpts, one of a male singing voice[1] and the other of a female soprano[2] were used to create auralizations in a virtual space, designed to resemble the architectural design and acoustic properties of the $10\,\text{m} \times 7\,\text{m} \times 5\,\text{m}$ space, used for the directivity measurements (see Section 2.1). The estimation of the Binaural Room Impulse Responses (BRIRs) at pre-selected listening positions around the source as well as the auralizations using the two anechoic stimuli were computed in CATT-Acoustic^{TM} v9.1.

The virtual sound source was placed at a central position in the space at a height of 2 m. Auralizations of the two anechoic stimuli were computed for comparisons in the following four static positions around the source: *POS*1 was directly in front of the source (0°azimuth) on the horizontal plane at a distance of 1.5 m, *POS*2 at 90°to the right of the source on the horizontal plane at a

[1] http://audiogroup.web.th-koeln.de/anechoic.html . Last visited: 2023/2/1

[2] https://odeon.dk/downloads/odeon-zip-archives/. Last visited: 2023/2/1

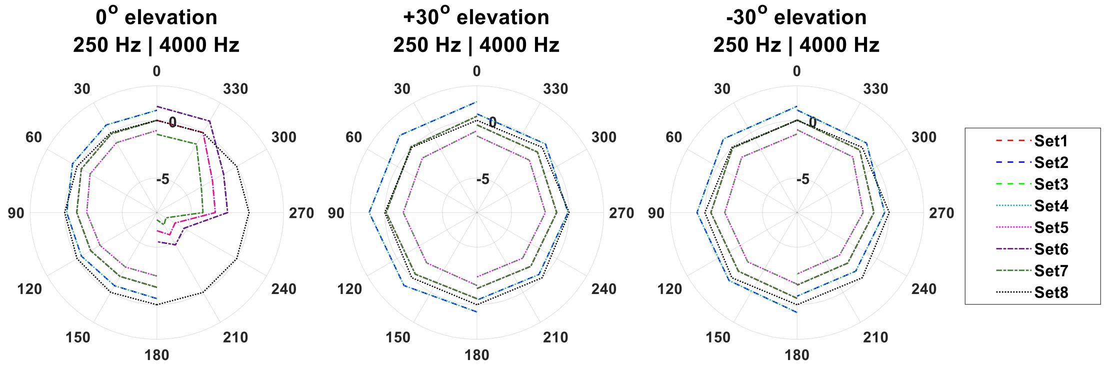

Fig. 3: Directivity patterns of the 8 sets across the 0°, +30°, and -30°elevation planes, for two representative one-octave frequency bands (250 Hz - left side and 4000 Hz - right side of the polar plot).

distance of 1.5 m, *POS*3 at 30°to the right of the source on -15°elevation at a distance of 3.5 m, and *POS*4 at 150°to the right of the source on +15°elevation at a distance of 3.5 m. The rendering at the listener positions was binaural, and was estimated using the 0°azimuth - 0°elevation filter set (ie. the listener was always facing the sound source) of the built-in CATT1_plain_44.DAT HRTF dataset provided in CATT-Acoustic^{TM}.

Based on the data analysis presented in Section 3 the following eight directivity patterns (Set 1 through Set 8) were created for assessment as representative of the observed data variations. Set 1, also referred to as the *Reference* directivity pattern, was created by averaging the directivity data of the two professional classical and the two professional modern style singers. The reason for this selection is twofold: first it led to an equal representation of male and female voice directivity data and second as professionals these singers resulted in highly repeatable directivty patterns, representative of their singing styles.

The directivity pattern of Set 1 (Reference) was used as a starting point for the design of alternative patterns (Sets 2 through 7) incorporating directivity variations introduced to the data due to the small body and head movements of the performer, as described in Section 3 and reported in Table 1. More specifically, Set 2 was created by adding $1/2$ of the variation values (i.e., the average range calculated across all songs and participants per frequency band and measurement location) to the Set 1 pattern, while Set 3 was created by subtracting $1/2$ of these variation values from the Set 1 pattern. Sets 4 to 7 were formulated by applying the said variations in different frequency ranges. That is, Sets 4 and 5 were identical to the reference pattern in the low-frequency region (up to 500 Hz), while in the mid and high-frequency region (starting off at 1 kHz), Set 4 shared the values of Set 2 and Set 5 those of Set 3. Inversely, Sets 6 and 7 were identical to the reference pattern in the mid and high-frequency region, while for low frequencies, Set 6 shared the values of Set 2 and Set 7 those of Set 3. Finally, an omnidirectional directivity pattern (Set 8) was computed, which served as a point of comparison for evaluating the variations of the other 7 directivity patterns in relation to a simplified and widely used option for sound directivity in virtual spaces. Figure 3 shows the directivity patterns of these eight sets across the three elevation planes (0°, +30°, and -30°) in two representative one-octave frequency bands (250 Hz and 4 kHz).

4.1 Objective Evaluation

Objective assessments of the impact of the aforementioned directivity variations on auralization were carried out by means of Binaural Room Impulse Response (BRIR) comparisons. The BRIR data was computed using CATT-Acoustic^{TM} in a modeled, acoustically treated space (see Section 4) at the four listening positions around a virtual sound source, using the eight directivity patterns under comparison.

A frequency domain comparison revealed variations between 0 and $\approx$ 5 dB, depending on listening position and frequency band. A summary of the observed

Table 2: Maximum magnitude differences observed between the 8 directivity Sets per one-octave frequency band, expressed in dB.

Freq. band (Hz)	POS1	POS2	POS3	POS4
125	5	3.6	6.5	4.3
250	2.8	2.6	2.8	5.3
500	1.5	1.4	4.5	3.2
1000	0	0.9	2.2	2
2000	0	0.3	0.1	0.2
4000	0	0.4	0.2	0.8
8000	2.5	2.5	1.4	1.8

variations can be found in Table 2. The following observations can be made. For the two listening positions on the horizontal plane (POS1 and POS2) considerable variations appear in the low frequency region (up to the 500 Hz one-octave band), while for elevation planes at $\pm15°$ (POS3 and POS4) this region expands to include the 1 kHz octave band. Noticeable variations appear also in high frequency content (8 kHz). The magnitude of these variations is slightly larger than that depicted in Table 1, possibly as an effect of the acoustic qualities of the virtual space used for the auralization, and implies possible perceptibility of the introduced directivity changes. Yet, its perceptual significance remains to be confirmed.

4.2 Subjective Evaluation

A listening test was carried out in an attempt to assess the impact of the objectively estimated variations discussed in Section 4.1 on the directivity perception of virtual sound sources. Twenty-nine assessors (13 female) took part in the listening test. The average age of the participants was 24 years (STD: 8 years). All were undergraduates at the Department of music Studies (NKUA), semi-experienced in critical listening tests. To investigate the perceptual impact of small body movements on the directivity of the singing voice, a MUSHRA (MUltiple Stimuli with Hidden Reference and Anchor) listening test was conducted, following the ITU-R BS.1534-3 recommendation [26].

Assessors were randomly divided into two groups; the first evaluated the MUSHRA test using the male singing voice as a basis for the creation of the auralized stimuli and the second the female soprano. During the listening test, subjects were presented with a labeled Reference (Set 1) and nine unlabeled test conditions (a hidden reference, Sets 2 through 8, and an anchor). The anchor was the monaural, anechoic, unprocessed audio sample used for the auralization of Sets 1 through 8 in that participant group. Subjects were asked to rate the similarity of the labeled Reference to the unlabeled Test Conditions using a numerical continuous scale from 0 to 100. The test was carried out at the facilities of LabMAT using the Go Listen online listening test platform [27]. Participants accessed the test material through their preferred personal portable device using a set of Sennheiser HD 270 pro headphones. The average duration of the test was 23 min (STD 9 min).

Upon preliminary inspection of the user responses, two participants had to be removed from the data pool, one because of self-reported severe hearing loss and the other because of unregistered responses. In addition, following the ITU-R BS.1534-3-recommendation, according to which any participants who rated the hidden reference with a score lower than 90 for more than 15% of the test items had to be excluded from any subsequent analysis, the data of five more participants was removed. This elimination process resulted in twenty two participants, eleven evaluating the male singer sound stimuli and eleven more the female soprano ones.

The residuals were tested against normality as well as sphericity. The residuals' deviation from normality was examined by means of Shapiro-Wilk tests as well as the investigation of skewness and kurtosis of their distributions. The preliminary analysis indicated that the data was not normally distributed, hence the non-parametric Friedman's test was applied as the alternative to the repeated measures ANOVA in order to examine the significance of the results [28].

The results of the Friedman's test for each of the positions examined are presented in Table 3. The p values, all of which lie below the alpha value of 0.05, indicate that at least one significant pairwise difference is observed in the studied levels of within subject factors. In order to examine the significance of the pairwise differences, Dunn's Multiple Comparison Test was implemented for each condition separately.

The majority of the pairs exhibiting a statistically significant difference in the perceived directivity of the auralized sound source concern mainly combinations of the anchor tested against directivity Sets 2 to 7. Considering the nature of the former, this behavior was anticipated. The p values of these pairs range between

Table 3: Results of the Friedman's test for each of the four listening positions examined.

Stimulus	Position	Chi-Square	Sig.
Female Singer	POS1	36.75	0.000
	POS2	31.99	0.000
	POS3	36.61	0.000
	POS4	52.28	0.000
Male Singer	POS1	45.67	0.000
	POS2	40.02	0.000
	POS3	48.02	0.000
	POS4	37.75	0.000

levels p<0.000 and p<0.05. What is interesting to mark, is that a statistically significant difference has not been noted between the pair Anchor – Set 8 (omni), as one might have expected. It should also be noted that out of the 36 pairwise comparisons performed, there was one case of significance between the pair Hidden Reference – Set 6 ($p = 0.034$), three cases of statistical significance between the Hidden reference – Set 8 (omni) ($p < 0.000$), and one case of marginal significance between the pair Set 8 (omni) – Set 4 ($p = 0.044$). These significant differences in similarity ratings between set 8 and the remaining sets were expected, especially in positions $POS2$ and $POS4$ located to the side and behind the virtual source, where directivity differences between these sets were maximal.

5 Conclusions and Future work

The connection between music and movement has been extensively researched. Movements related to technique play a crucial role in sound production. While studies have been conducted on the directivity of musical instruments and vocals, taking into account small movements related to technique, more work remains to be done on the impact of these movements on the collected data. This study aimed to quantify the effects of technique-related body and head movements on vocal directivity and evaluate their perceptual impact through both objective and subjective methods. The analysis was based on vocal directivity data collected from 12 individuals in 29 directions across four elevation planes, using a hemispherical microphone array.

Directivity variations were found to range between 1.4 dB and 3 dB, depending on frequency band and direction, implying a potential degree of perceptibility of the said changes. Yet, the examination of the variations in HDI and FBR showed that most differences lie below the 1 dB JND threshold, suggesting perceptual equivalence in the varying directivity datasets. An exception to this concerned the observed degree of variability in the UDR metric which exceeded the set JND threshold. This finding confirmed that singers tend to make a lot of technique or expressiveness-related up / down head and body movements even in controlled conditions, which may have an impact on directivity.

The said variations were auralized using CATT-Acoustic^{TM} v9.1. and the results were objectively and subjectively assessed by means of a BRIR comparison and an audibility user test. The latter confirmed that, in static listening conditions, variations introduced in the data by this type of controlled head and body movements cannot lead to audible directivity artifacts. Consequently, directivity measurement protocols permitting small, technique-related movements to their musicians can still capture perceptually relevant and stable directivity data, without sacrificing sound quality for stricter, constrained measurement protocols.

Future work includes a more detailed perceptual evaluation methodology, which will base directivity data assessments on different sound quality attributes, beyond audibility comparisons. An expansion of the assessor pool to include professional vocalists as well as singing instructors will also offer an opportunity for studying whether vocal experts can perceive directivity variations in more detail, when listening to auralized data in static and dynamic conditions.

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