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Vocal Directivity of the Greek Singing Voice on the First Three Formant Frequencies†

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Abstract: This study explores the relationship between formant frequencies and the directivity patterns of the Greek singing voice. Recordings were conducted in a controlled acoustic environment with four professional singers, two trained in classical music and two in Byzantine chant. Using microphones placed symmetrically on a hemispherical structure, participants sang the Greek vowels across different registers. Directivity patterns were analyzed in third-octave bands centered on each singer's first three formant frequencies (F1, F2, F3). The results indicate that directivity patterns vary with register and center frequency, with differences observed across vowels and singers. These findings contribute to vocal production research and the development of simulation, auralization, and virtual reality applications for speech and music.

Keywords: voice directivity; formants; Greek vowels; singing voice

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1. Introduction

Voice directivity, referring to the spatial distribution and projection of sound energy across frequency bands, has been a subject of extensive research in both speech and singing voice. Studies have examined directivity across various spatial dimensions, including only the horizontal plane [1,2], both horizontal and vertical planes [3,4], or the complete sphere [5,6]. These studies highlight the complexity and unique characteristics of voice directivity, through comparative findings demonstrating distinct differences between spoken and sung voice [4].

Several factors contribute to voice directivity, encompassing both physiological constraints and articulatory adjustments. Mouth opening and vocal tract shape have been identified as such, affecting the directivity in both speech [2] and singing [7]. Additionally, directivity is influenced by posture, head inclination, and specific vocal tract adjustments [8]. While some variables with an impact on directivity, such as spectral modifications achieved through singing techniques, are adjustable, others, such as head and torso dimensions, are fixed [7]. The location of sound production within the oral cavity can also affect directivity. Front vowels exhibit more focused radiation patterns and higher pitch sounds are correlated with higher directivity. Although phonation type has a comparatively smaller influence, pressed phonation tends to exhibit increased directivity than breathy phonation [4].

Interestingly, many of the same factors affecting directivity, such as vocal tract configuration and mouth opening, also impact formant frequencies, which in turn affect the spectral

characteristics of vowels [9]. As formant tuning alters spectral content, it consequently influences directivity patterns [10]. Given this relationship, a systematic investigation of vocal directivity characteristics centered around formant frequencies is a subject of interest.

Formants are acoustic markers (spectral peaks) that reflect the resonance properties of the vocal tract [11], indicating articulatory features such as tongue position and the shape of the vocal tract [12]. Although there has already been some published work on the phonetic aspects of the Greek language and the corresponding formants [13], studies focusing on formants in singing remain scarce [14], especially when it comes to studies on the directivity of the Greek singing voice [15]. It should also be noted that a comparative analysis across the said studies is challenging, mainly due to the absence of a standardized data collection protocol [13].

This article is a revised and expanded version of a previous publication that examined the directivity patterns of four professional singers—two trained in classical singing and two in Byzantine chant—focusing exclusively on the horizontal plane [16]. In the current study, sound directivity is explored through the analysis of projection (i.e., the energy distribution across frequency bands) and radiation patterns (i.e., the spatial energy distribution for each frequency) [17]. The work focuses on the hemispherical directivity characteristics of the Greek sung vowels sounds (monophthongs) /a/ (α), /e/ (ε, αι), /i/ (ι, η, υ, οι, ει), /o/ (ο, ω), and /u/ (ου), when investigated on the relevant formant frequencies, considering the singing style of the same four professional singers.

Byzantine chant was selected as a representative Greek singing style, rooted in tradition and predominantly male, while classical singing was chosen as a baseline due to its extensive literature and well-documented techniques. Notably, studies examining formants [18], formant tuning [19] and vocal ornamentation [20] in Byzantine chant remain limited. Both styles follow well-defined training curricula, ensuring the participation of highly trained singers which enhances data reliability. Their selection enabled a focused analysis of per-participant and between-participant differences in directivity across the low, mid, and high registers of Greek vowels, while controlling for training level (professionals) and gender (male). Additionally, despite its small sample size, it attempted an initial exploration of the potential effects of genre on voice directivity.

2. Materials and Methods

This work is part of a broader study focusing on the sound directivity characteristics of various traditional Greek musical instruments and professional singers, replicating realistic performance scenarios encountered by musicians. In line with previous research [7,21], the data collection process was conducted in a hemi-anechoic sound-treated space (10 m by 7 m by 5 m) located at the facilities of the Laboratory of Music Acoustics and Technology (LabMAT), NKUA. The walls of this space are lined with absorptive panels, the floor is covered with carpet, and the ceiling is equipped with three rows of skyline diffusers. The mean room reverberation time (T30) for frequencies up to 500 Hz is 0.45 s, while for frequencies above 1 kHz, it is 0.29 s. Additional sound-absorptive material was used to further minimize the impact of reflections from the floor, ceiling, walls, and equipment on the measured data.

The measurements were conducted using 29 RODE-M5 (Røde, Sydney, Australia), small-diaphragm condenser microphones, placed left/right symmetrically on a hemispherical thin-shell structure (Figure 1) with a radius of 158.5 cm at fixed azimuthal increments on the elevation angles of +90°, +30°, 0°, and −30° (the terms elevation angle and azimuth angle refer to the angular positions of a point measured on the median and horizontal plane, respectively). Twelve of the microphones were placed on the horizontal plane at 30°azimuthal increments, eight on −30°, and eight more on +30° elevation, each at 45°

azimuthal increments. Additionally, one microphone was positioned directly above the participants' heads at an elevation of +90°. However, these microphone data are not included in the reported results. The individual impulse responses of the microphones were collected using ScanIR [22] on an M1 MacBook Pro 2020 running Matlab 2021a.



Figure 1. Microphone array configuration.

As previously mentioned, this study focuses on measurements from four participants: two male professional classical singers, Classical Male 1 (CM1) and Classical Male 2 (CM2), and two male Byzantine chant singers, Byzantine Male 1 (BM1) and Byzantine Male 2 (BM2). All participants are native speakers of Standard Modern Greek, with no noticeable pronunciation differences suggesting regional accents. BM1, in their mid-50s, was 170 cm tall, while BM2, in their mid-40s, was 177 cm, making them 7 cm taller than BM1. CM1, in their early 40s, was 175 cm, whereas CM2, in their early 30s, was 184 cm, making them 9 cm taller than CM1 and the tallest among all participants.

Participants were positioned at the center of the microphone array in a standing posture. The height of the configuration was adjusted using elevation probes to align with each singer's mouth position. A plumb and laser beams were used to maintain proper alignment throughout the measurements. This alignment method was preferable to a stricter one because it creates a more natural singing experience, and allows for small body and head movements related to technique and vocal projection. Participant alignment was actively monitored throughout data collection. When misalignments were observed, the measurement process was interrupted and repeated upon proper participant realignment. The permitted small body and head movements have been shown to have no perceptual impact on the collected directivity data [15] as the projection of the singing voice is left/right symmetric [21,23] minimizing the influence of minor movements on directivity data collection.

Prior to measurements, all input signals were level-calibrated using pink noise (78 dBA), generated by a Brüel & Kjær omnidirectional loudspeaker (OmniPower Sound-Source Type 4292-L) placed at the singer's position, ensuring consistent levels across the array microphones with a tolerance of ±0.5 dB. These variations were later accounted for and eliminated during data post-processing. The pink noise signals were analyzed in third-octave bands, and calibration levels were obtained to equalize the RMS levels in each band. Data collection was performed on an i5 laptop running Cubase 11, using the built-in preamplifiers of two Yamaha TF1 digital mixers interconnected via DANTE.

Once aligned with the microphone array, participants were instructed to sing twice each of the five vowel sounds /a/ (α), /e/ (ϵ, $\alpha\iota$), /i/ (ι, η, υ, $o\iota$, $\epsilon\iota$), /o/ (o, ω), and /u/ ($o\upsilon$)

on pitches A2, E3, and C#4 for approximately two seconds each, at a comfortable soft dynamic equivalent to mp-mf. The objective was to examine potential discrepancies between the low, middle, and high registers. However, one of the participants (BM2) was unable to produce a clear intonation of C#4, as it fell outside of their vocal range. Instead, an A3 was recorded, which can also be regarded as a high register tone for this particular participant. Participants could request the repetition of a measurement if they felt their performance was not optimal. When a clear difference in vocal quality was evident, the best recording was selected; otherwise, the selection was random. For each vowel and register, the directivity data were calculated on third-octave bands centered around the corresponding F1, F2, and F3 frequencies of each singer.

The audio recordings per participant and microphone were deconvolved with the corresponding microphone responses to minimize the impact of the measurement setup on the analyzed data and level calibrated per third-octave band to obtain omnidirectional responses [23]. In order to suppress the impact of noise introduced in the data by frequency bands with insufficient energy, the signal-to-noise level was calculated and a noise floor threshold was derived, suppressing any data within 3 dB of its level [15]. Formant analysis was conducted in Praat [24] using Fast Track [25], with the parameters adjusted for each participant and the results manually compared and verified to enhance accuracy [26]. The formant frequencies per vowel, register, and participant were calculated as the median of the nine front microphones (0°, 30°, and 330° azimuth on the horizontal plane, 0°, 45°, and 315° azimuth on the −30° and +30° elevations). The results are depicted in Table A1 of Appendix A. Since only one recording per vowel and singer was selected, no averaging was performed in estimating directivity data.

3. Results

The directivity of all vowels in the F1 region exhibits a more omnidirectional pattern, due to the low-frequency range of F1 (287 Hz to 715 Hz, as shown in Table A1 of Appendix A), while the F2 and F3 frequency bands exhibit varying directivity characteristics. In order to condense directivity information while facilitating data comparisons, this work observes differential directivity plots ($F2 - F1$ and $F3 - F1$) instead of absolute directivity data. Figure 2 provides a visual reference for how differential directivity plots are derived from absolute directivity data. The left plot presents the directivity patterns of F1, F2, and F3 for one participant singing /a/ in the high register at 0° elevation. The right plot shows the corresponding differential directivity plot, displaying relative intensity differences (in dB) for $F2 - F1$ (left) and $F3 - F1$ (right). This representation was selected to illustrate potential changes in directivity around the F2 and F3 regions relative to the F1 region of the Greek vowels.

The polar plots in Figures 3, 4, and 5 depict on the left side the difference in spherical sound projection in the F2 formant region in relation to F1 and on the right side in the F3 formant region in relation to F1 for the four measured participants, while Appendix B provides the numerical data underlying these polar plots. As illustrated, the radiation of the vowel /a/ in the F2 and F3 formant regions is typically less omnidirectional than in F1, though this is not always consistent. On the horizontal plane (Figure 3), in the F2 region, CM1 displays slight variations in comparison to the F1 region, with a slight indication of enhancing the projection to varying degrees across all registers on the sides and back. This trend also appears on the −30° elevation (Figure 4), particularly in the middle register.

For example, on the horizontal plane (Figure 3), the difference at 90° azimuth is 2.06 dB in the middle register and 0.28 dB in the high register compared to 0° azimuth, which is −1.07 dB and −2.45 dB, respectively. On the −30° elevation (Figure 4), the difference at 90° azimuth is 2.94 dB in the middle register and 1.45 dB in the high register, compared to

0° azimuth, which is 2.48 dB and 0.45 dB, respectively. In the F3 region, CM1 displays a more focused projection; that is, the energy distribution is more concentrated in 0° azimuth, with the two elevated vertical planes exhibiting the greatest breadth in the middle register, though still with less pronounced projection; that is, the energy distribution is less than in the F1 region, as depicted in Figures 4 and 5.

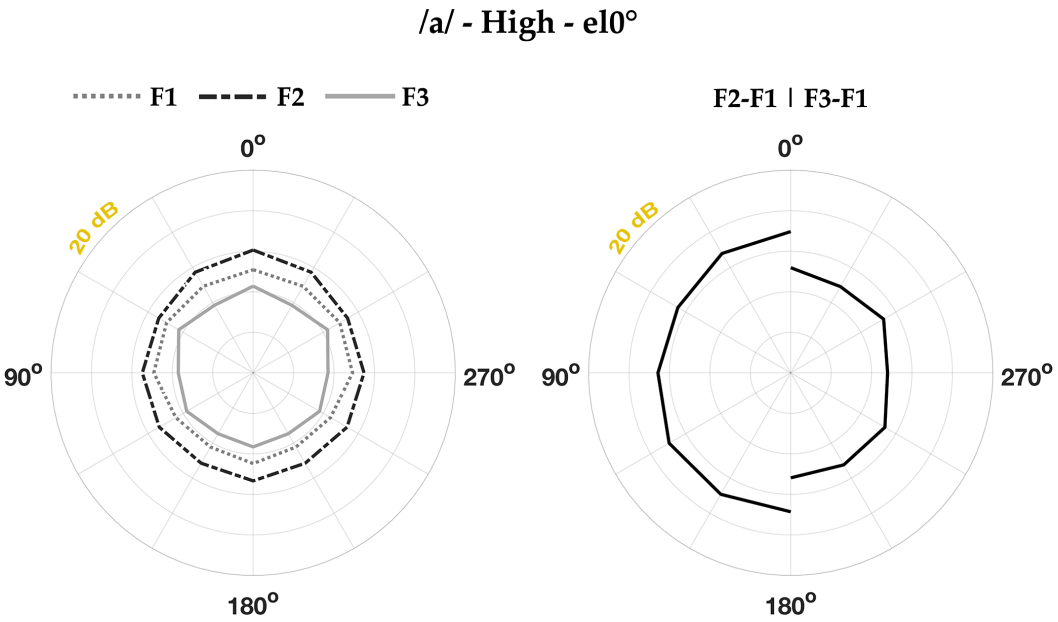


Figure 2. Derivation of differential directivity plots. Left: directivity patterns of F1, F2, and F3 for one participant singing /a/ in the high register at 0° elevation. Right: corresponding differential directivity plot, showing relative intensity differences (in dB) for $F2 - F1$ (**left**) and $F3 - F1$ (**right**). The outermost circle represents +20 dB, with each subsequent inner circle decreasing by 10 dB. Positive values indicate greater projection in the F2 or F3 region compared to F1 at specific azimuth and elevation angles, while negative values indicate greater projection in the F1 region.

CM2 appears to exhibit wider radiation in the F2 region in the high register on the horizontal plane (Figure 3), with $F2 - F1$ differences ranging from 2.23 dB (side) to 4.85 dB (front), and on the +30° elevation (Figure 5), with differences ranging from 2.51 dB (side) to 5.93 dB (front). Contrary to CM1, CM2's projection in the F3 region is slightly more focused but considerably less pronounced across all registers and elevations, as depicted in Figures 3–5.

The projection of BM1 appears somewhat pronounced in the front on the horizontal plane (Figure 3) and +30° elevation (Figure 5), across all three registers, in the respective F2 regions. However, the difference is mostly minimal (0.68 dB to 1.99 dB on the horizontal plane and 0.98 dB to 3.42 dB on the +30° elevation plane). Interestingly, the directivity seems to be more omnidirectional than that of CM1 and CM2. Additionally, in the F3 region, BM1 exhibits a reduction in projection compared to the F1 region, resulting in the loss of the broad pattern present in the F2 to F1 comparison. This indicates a more focused radiation to the front.

The omnidirectional pattern in the F2 region is also apparent with BM2, especially in the low register on the horizontal plane (Figure 3) and −30° elevation plane (Figure 4). However, this seems to change on the +30° elevation (Figure 5), where BM2 exhibits greater projection in the front in the low (5.02 dB) and middle (3.13 dB) registers (Figure 5), and the radiation is more focused. In the F3 region, BM2 shows similar directivity to BM1.

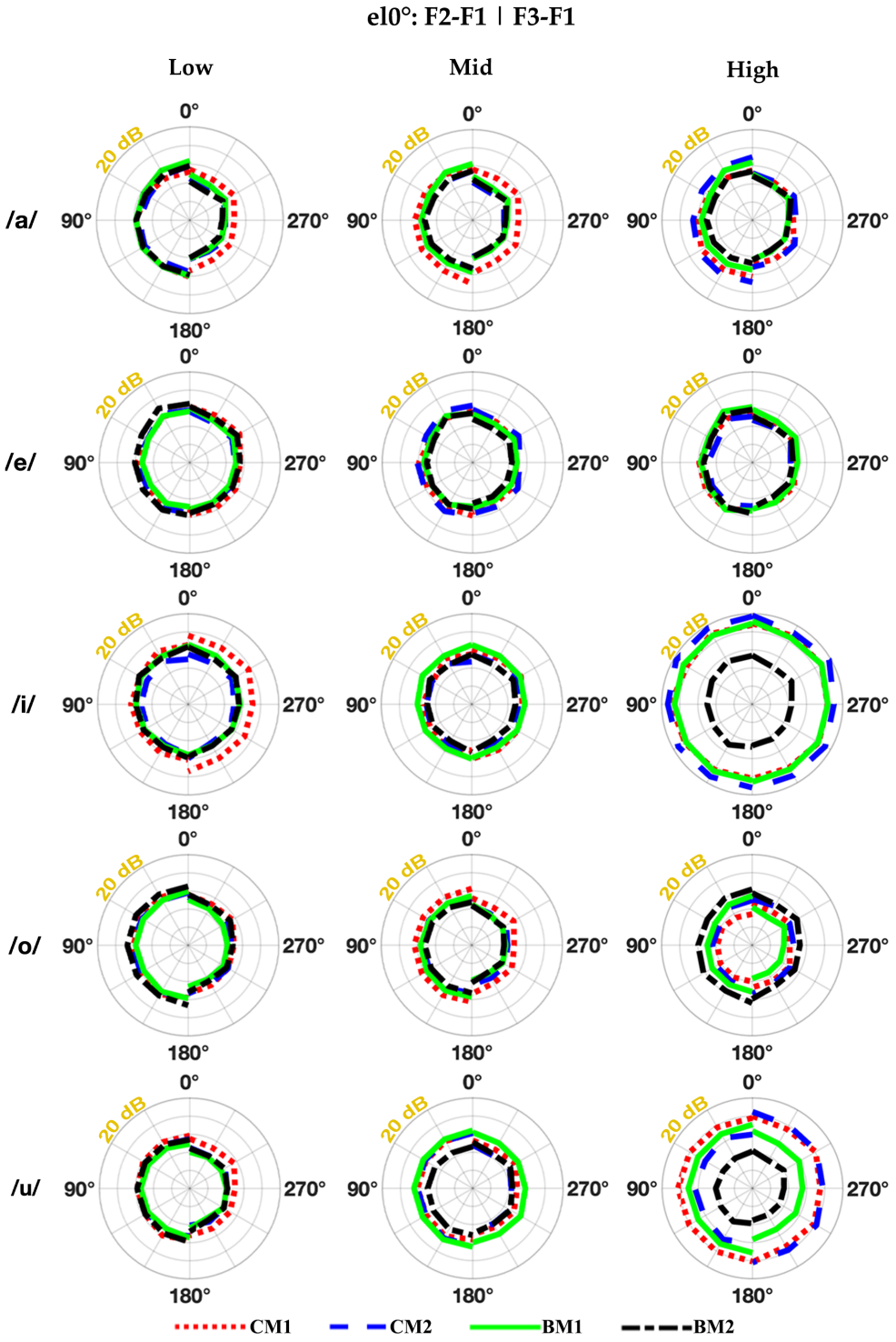


Figure 3. Directivity plots for the four singers on the horizontal plane (5 vowels, 3 registers). The left side of each plot shows the directivity of the 2nd formant relative to the 1st ($F2 - F1$), while the right side the 3rd formant relative to the 1st ($F3 - F1$). Concentric circles represent a decibel (dB) scale, with the outermost corresponding to 20 dB and each successive inner circle decreasing in 10 dB increments. Positive values indicate greater projection in the F2 or F3 region compared to F1 at specific azimuth and elevation angles, while negative values indicate greater projection in the F1 region.

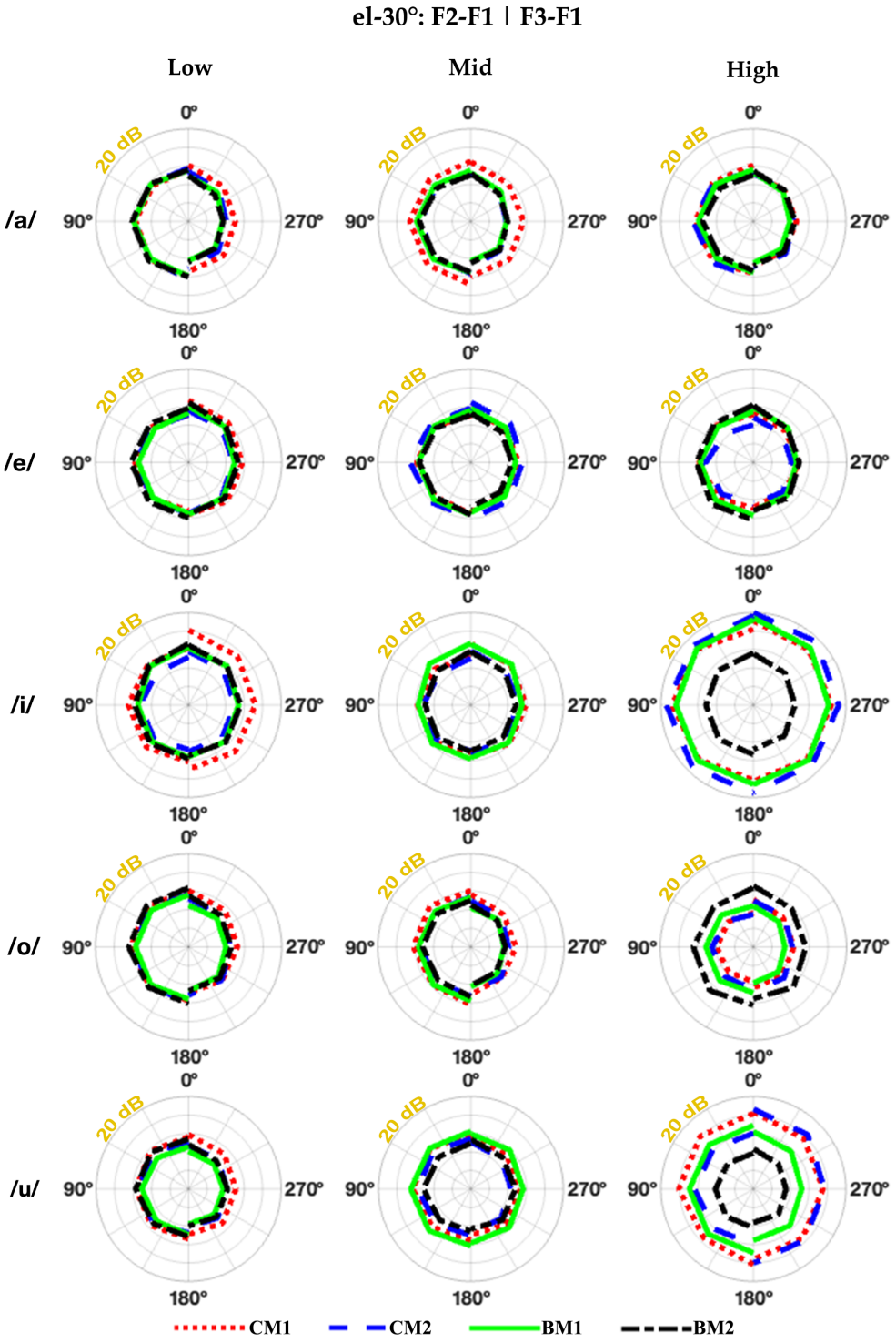


Figure 4. Directivity plots for the four singers on the -30° elevation (5 vowels, 3 registers). The left side of each plot shows the directivity of the 2nd formant relative to the 1st ($F2 - F1$), while the right side the 3rd formant relative to the 1st ($F3 - F1$). Concentric circles represent a decibel (dB) scale, with the outermost corresponding to 20 dB and each successive inner circle decreasing in 10 dB increments. Positive values indicate greater projection in the F2 or F3 region compared to F1 at specific azimuth and elevation angles, while negative values indicate greater projection in the F1 region.

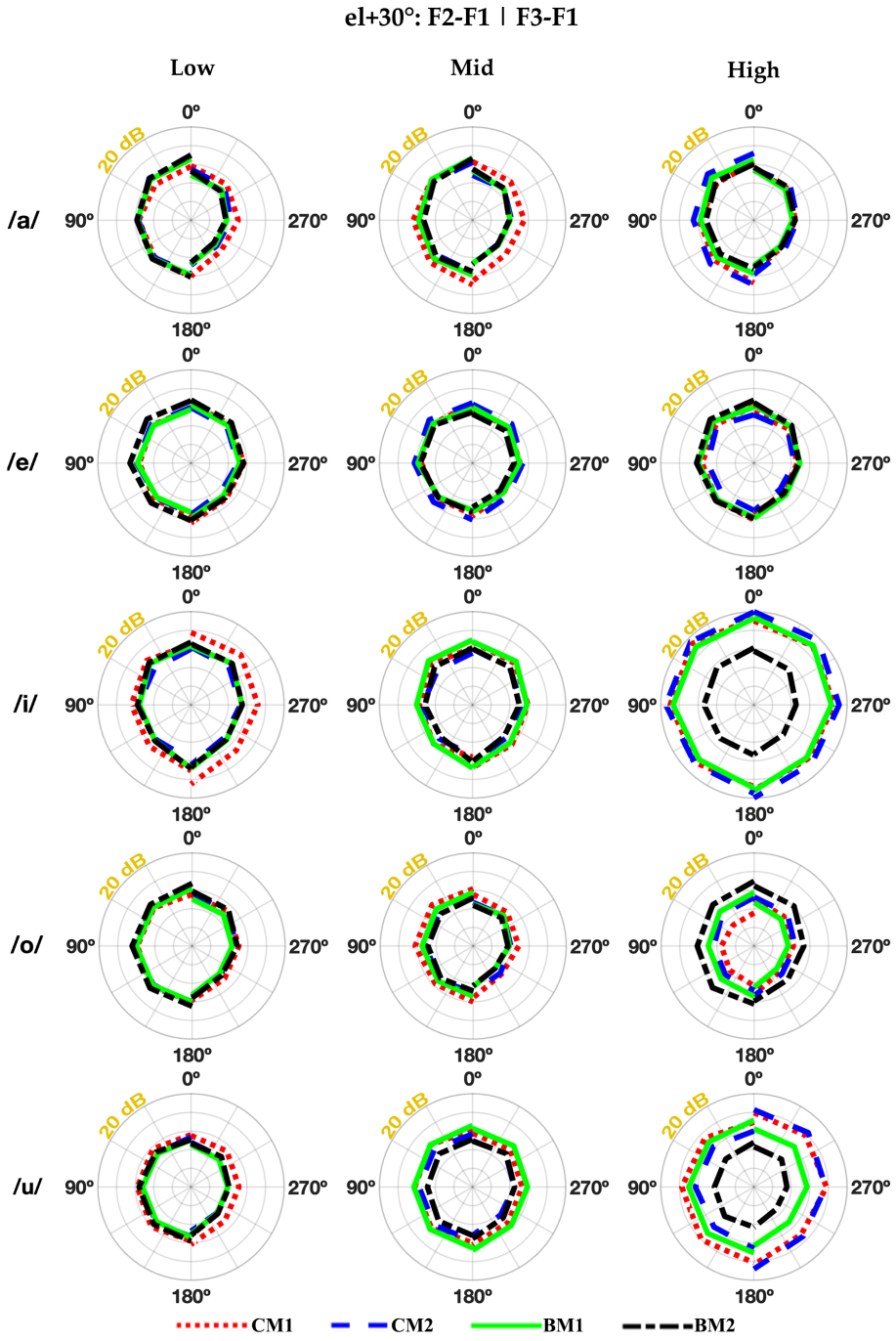


Figure 5. Directivity plots for the four singers on the +30° elevation (5 vowels, 3 registers). The left side of each plot shows the directivity of the 2nd formant relative to the 1st ($F2 - F1$), while the right side shows the 3rd formant relative to the 1st ($F3 - F1$). Concentric circles represent a decibel (dB) scale, with the outermost corresponding to 20 dB and each successive inner circle decreasing in 10 dB increments. Positive values indicate greater projection in the F2 or F3 region compared to F1 at specific azimuth and elevation angles, while negative values indicate greater projection in the F1 region.

Contrary to the projection peaks observed in /a/, the directivity of vowel /e/ in the F2 and F3 regions appears to be more similar to that of F1; that is, it appears to be mostly omnidirectional. CM1 and CM2 show a slight peak (1.92 dB and 2.33 dB, respectively) in the front at the F2 region in the middle register on the +30° elevation (Figure 5), while the latter also exhibits a peak in the middle register on the side of −30° elevation (2.74 dB) and in the front on the horizontal plane (2.83 dB) (Figures 4 and 5, respectively). In the F3

region, CM1 shows a notable peak in the front in the low register on the −30° elevation (3.42 dB), while CM2's most notable peak is in the front, in the middle register, on the −30° elevation (2.23 dB) (Figure 4).

Slight peaks can also be observed in the F2 region of BM1, on the horizontal plane (Figure 3) in the high register at 30° azimuth (2.44 dB) and on the −30° elevation (Figure 4) in the middle register at the same azimuth (1.34 dB). In the F3 region, BM1 displays also a peak on the +30° elevation, at 0° azimuth, in the low and high registers (1.37 dB and 1.01 dB, respectively), as illustrated in Figure 5.

As opposed to the rest of the participants, BM2 shows more peaks in the F2 region, occurring on the horizontal and +30° elevation planes in the low register (Figure 3 and Figure 5, respectively), and in the high register mainly on +30° elevation (Figure 5). In the F3 region, the peaks mainly appear at 0° azimuth in the low register on the −30° elevation (2.18 dB) (Figure 4), and on the +30° elevation planes (3.86 dB), as well as in the high register on +30° elevation (2.43 dB), as depicted in Figure 5.

With regard to vowel /i/, it appears that all participants, with the exception of BM2, exhibit significantly greater projection in the F2 and F3 regions, towards all azimuth angles. More specifically, in the high register on the horizontal plane, differences range from 10.94 dB to 18.61 dB in the F2 and from 10.55 dB to 19.06 dB in the F3 region, respectively (Figure 3). In the middle register on the −30° elevation plane, variations range from 10.98 dB to 18.29 dB in the F2 region and from 10.69 dB to 20.47 dB in the F3 region, and on the +30° elevation plane they range from 11.55 dB to 19.85 dB and from 10.03 dB to 21.09 dB, respectively (Figures 4 and 5). The largest peaks are systematically observed in the data of CM2. Moreover, CM1 shows greater dispersion in the low register, across all elevation planes and formant regions and BM2 displays some minor peaks in the F2 and F3 regions in the low register, especially on the +30° elevation plane (Figure 5).

The data of vowel /o/ show that the F2 and F3 regions appear to have smaller projection than that of F1 for most of the singers, with the least being that of CM1, in the F2 region in the high register. However, the same participant exhibits a slightly more pronounced projection in the middle register on the horizontal plane (ranging from 0.52 dB to 1.89 dB) (Figure 3). BM2 shows notable peaks in the F2 region, in the low register, at all elevations and directions (ranging from 0.52 dB on the −30° elevation plane at 135° azimuth to 3.66 dB on the +30° elevation plane at 0° azimuth), and in the high register on the −30° plane (ranging from 0.24 dB at 45° azimuth to 3.09 dB at 135° azimuth) and the +30° elevation plane (ranging from 0.59 dB on the side to 4.84 dB in the front) (Figures 4 and 5, respectively). With regard to the F3 region, except for two peaks in BM2's projection in the high register, at 0° azimuth, on the −30° (2.89 dB) and the +30° elevation planes (2.33 dB), the rest of the data show limited projection (Figures 4 and 5, respectively), similar to the /a/ vowel.

Vowel /u/ displays similar characteristics to vowel /i/, especially in the high register. It appears that CM1 and BM1 have greater projection in the F2 region in the high register across all elevation planes, while CM1 and CM2 also show pronounced projection in the F3 region, in the high register. Additionally, BM1's projection in the F2 region in the middle register is also pronounced across all elevation planes, but to a lesser extent. The directivity characteristics of the classical singers in the F2 region are quite omnidirectional across all registers and elevation planes.

4. Discussion

The findings presented offer insight into the directivity characteristics of the Greek singing voice. The analysis focused on participant-specific results to avoid overgeneralization (because of the small sample size), while observing any emerging patterns that

may inform future research. When considering each vowel individually, the following distinctions can be observed. The observations for vowel /a/ indicate that the F2 and F3 regions of the participants exhibit less pronounced projections and more focused radiation (especially in the F3 region), across all elevation planes and all azimuthal angles than the F1, albeit to a different extent. There appear some peaks common to both classical and Byzantine chant singers across all registers in the F2 region on the +30° elevation at 0° azimuth (Figure 5). However, classical singers continue this trend in the F2 region across the entire horizontal plane and all elevations in the high register (Figure 3). Radiation appears almost omnidirectional in the low register in the F2 region, especially on the horizontal and −30° elevation planes (Figures 3 and 4, respectively), and becomes quite focused when measured in the F3 region. Classical singers tend to hold their projection in the F2 and F3 regions more than Byzantine chant singers.

The data for vowel /e/ indicate that sound radiation is more uniform than that of vowel /a/, particularly in the F3 region, and its projection peaks are less pronounced than in /a/. The directivity characteristics of classical and Byzantine chant singers in the F2 and F3 regions in the low register are quite similar. However, Byzantine chant singers display less focused radiation, especially in the high register in the F2 region at all elevations.

The directivity characteristics of the participants at the /i/ vowel appear to differ significantly from those observed at the /a/ and /e/ vowels. With the exception of BM2, the rest of the participants display pronounced projection in the high register in both F2 and F3 regions, as illustrated in Figures 3, 4, and 5. The significantly different patterns of BM1 and BM2 make the direct comparison between the classical and Byzantine chant singers difficult, although both Byzantine chanters seem to have similar characteristics in the low register in both the F2 and F3 regions, i.e., slightly focused projection with minimal peaks.

The data for the /o/ vowel show comparable directivity characteristics (almost omnidirectional), for both the classical and Byzantine chant singers, in the low register in the F2 region, across all elevation planes. In the middle register in the F2 region, classical singers tend to maintain this omnidirectional characteristic, whereas Byzantine chant singers seem to keep their projection in the high register consistent.

As already mentioned, the directivity of vowel /u/ shows similar characteristics to those of vowel /i/. The high register of the classical singers exhibits notable peaks in both the F2 and F3 regions across all elevation planes, while Byzantine chant singers—mainly BM1—follow this trend only in the F2 region. In the low register, classical and Byzantine chant singers also share similar directivity characteristics, but classical singers tend to have more pronounced projection.

The results align with the existing literature on the left-right symmetrical projection of the singing voice [15,21,23]. Consistent with previous studies, directivity varies with pitch and center frequency [3,4]. However, identifying the influence of singing style (Byzantine chant, classical) on directivity remains challenging, as no definitive patterns have been identified. The data suggest that even among singers of the same genre, there may exist significant differences, with the vowel /e/ being the one with the least variability in both the F2 and F3 regions and vowels /i/ and /u/ the ones with the most.

Nevertheless, there is some evidence to suggest that classical singers tend to show more pronounced projection, mostly in the F3 region, across all elevation planes in the high register of the Greek vowels /i/ and /u/. The values for BM1 and BM2 of the vowel /i/ in the F2 region, particularly in the high register across all elevation planes, are quite different. Although both are Byzantine chant singers, BM1 appears to follow the classical singers' pattern. BM2 did not sing the same high note as the other participants—all were instructed to sing A2, E3, and C#4, but BM2 sang A3 instead of C#4. As previously noted, A3 can be considered BM2's high register. While a different articulatory strategy that could

potentially influence the results cannot be ruled out, any strategy BM2 would have used for C#4 would likely also apply to A3. A larger sample of Byzantine chant singers would allow for a more detailed examination of this variation.

A comparison of the horizontal plane with the other two elevations (-30° and $+30^\circ$) shows that directivity patterns do not differ significantly, which is in line with the relevant literature [6]. There is a slight indication that sound radiation is more omnidirectional on the -30° elevation and sound projection is less pronounced than that on the $+30^\circ$ elevation, where directivity is more focused. However, on the horizontal plane, directivity patterns are typically more omnidirectional and pronounced than on other elevations.

Previous research has indicated that, on a scale from the highest to the lowest directivity, vowels tend to follow the sequence /a/, /e/, /i/, /o/, /u/ [6,23], a pattern that appears to correspond with the degree of mouth opening [6,7]. The results of this study support this finding when all elevation planes are being considered. However, when examining each plane individually, the Greek vowels /u/ and /i/ exhibit lower directivity, especially in the high register in the F3 region on the horizontal plane. Conversely, /e/ demonstrates the highest directivity relative to F1, as also suggested in [3]. This finding can partly be attributed to variations in mouth opening, as previous studies suggest that a larger opening (such as in the production of /a/) results in a more concentrated radiation pattern [7], and, partly, to the way the Greek vowels are pronounced compared to other languages researched [13], which also has implications on the formant frequencies.

A limitation of this study is its small sample size, which confines the extent to which the results can be generalized. A larger sample size could provide more broadly applicable findings. The calculation of formant frequencies as an average of nine microphones, instead of a single microphone positioned directly in front of the singer's mouth, could also be considered a study limitation. Yet, it has been shown that while recording distance can influence formant frequencies, this effect primarily impacts weaker formants, with deviations remaining within the range of intra-speaker variability [27].

5. Conclusions

This study considered the directivity patterns of Greek sustained vowels in third-octave bands centered on the first three formant frequencies (F1, F2, F3) on three elevations (0°, -30°, $+30^\circ$) as a function of sound projection and radiation. The analysis was conducted on four professional male singers from two distinct vocal styles: classical singing and Byzantine chant. The findings expand the existing literature, addressing the scarcity of research on formant and directivity analysis on the singing voice in Standard Modern Greek and Byzantine chant. This work provides practical insights for optimizing microphone placement and improving spatial audio and virtual reality technologies. It contributes to the limited research on Greek speech and singing by analyzing directivity in relation to formant frequencies rather than standard frequency bands, offering a vowel-specific perspective.

The data show that directivity patterns vary across singers, vowels, pitch, and frequency regions (F1, F2, F3). The vowel /e/ shows the least variability in the F2 and F3 regions, while /i/ and /u/ exhibit the most. Byzantine chant singers tend to differ more from each other than the classical singers, especially for vowels /i/ and /u/ in the high register of the F2 and F3 regions. Classical singers exhibit stronger projection, particularly in the F3 region, for vowels /i/ and /u/ in the high register across all elevation planes. However, given the small sample size, these observations should be interpreted as participant-specific trends rather than generalized patterns. Moreover, sound radiation is more omnidirectional at -30° elevation, with weaker projection compared to $+30^\circ$ elevation. On the horizontal plane, directivity is generally stronger and more omnidirectional. Vowels are ordered in terms of directivity as /a/, /e/, /i/, /o/, /u/, consistent with the

relevant literature. However, on the horizontal plane, in the high register, in the F3 region, vowels /u/ and /i/ exhibit reduced directivity, while /e/ appears to be the most directive in relation to F1.

Future research will include the fourth and fifth formants (F4, F5), and explore the directivity of the singer's formant region. Furthermore, the study will also incorporate a more diverse group of singers, covering different training levels and singing genres, with the aim of exploring potential links between the Greek language, formant analysis, singing styles, training, and vocal directivity patterns.

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Appendix A. Formant Data

Table A1. Formant frequencies per vowel, participant, and register.

Vowel	Participant	Low Register			Middle Register			High Register		
		F1 (Hz)	F2 (Hz)	F3 (Hz)	F1 (Hz)	F2 (Hz)	F3 (Hz)	F1 (Hz)	F2 (Hz)	F3 (Hz)
a	CM1	546	935	2383	494	875	2221	574	1046	2354
	CM2	618	1091	2309	620	1046	2347	547	857	2039
	BM1	715	1108	2389	677	1224	2337	654	1306	2404
	BM2	636	1100	2291	635	1080	2343	652	1094	2350
e	CM1	415	1314	2309	433	1315	2245	544	1369	2226
	CM2	505	1572	2478	499	1541	2448	574	1423	2278
	BM1	519	1696	2355	486	1782	2264	609	1669	2323
	BM2	469	1619	2304	486	1551	2280	533	1709	2279
i	CM1	287	1684	2606	296	1663	2474	313	1419	2213
	CM2	357	1892	2493	329	1995	2655	325	1943	2418
	BM1	322	2334	2696	365	2304	2734	434	1839	2250
	BM2	309	2003	2359	323	1852	2368	358	1894	2353
o	CM1	431	695	2421	411	668	2319	554	853	2468
	CM2	459	792	2316	479	790	2484	509	876	2725
	BM1	508	766	2654	493	715	2526	555	1069	2408
	BM2	458	758	2437	478	722	2485	476	857	2446
u	CM1	408	661	2452	366	728	2358	364	673	2523
	CM2	383	677	2114	360	628	2199	314	767	2547
	BM1	349	674	2608	391	951	1569	499	971	2528
	BM2	340	687	2457	336	746	2481	440	841	2460

Appendix B. Directivity Data

Table A2. Directivity data for the vowel /a/. Gradient colors (red to green) visually represent the differences in dB values, where positive values indicate greater projection (energy distribution per frequency, i.e., intensity) in the F2 or F3 region compared to F1 region at a specific azimuth angle and elevation, while negative values indicate greater projection in the F1 region.

		Vowel /a/												
	Participant	CM1			CM2			BM1			BM2			
	Register	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	
		$F2 - F1$ (dB)												
Azimuth	0°	−3.95	−1.07	−2.45	−0.79	−2.70	4.85	1.77	1.22	1.99	−0.76	−2.71	−3.02	Elevation 0°
Azimuth	30°, 330°	−4.05	−0.61	−2.72	−2.21	−4.20	4.00	0.68	0.44	1.61	−1.84	−3.66	−2.49	Elevation 0°
Azimuth	60°, 300°	−2.93	−0.43	−1.93	−4.55	−4.95	2.23	−1.47	−2.05	−2.65	−2.67	−5.32	−5.87	Elevation 0°
Azimuth	90°, 270°	−1.21	2.06	0.28	−2.80	−3.41	2.84	−1.14	−1.59	−1.72	−1.27	−3.43	−4.76	Elevation 0°
Azimuth	120°, 240°	−0.84	2.41	2.49	−2.17	−2.98	4.72	−0.64	−1.22	−1.67	−1.28	−3.72	−5.34	Elevation 0°
Azimuth	150°, 210°	−1.30	2.11	1.58	−3.78	−4.88	4.60	−1.23	−2.44	−2.04	−1.57	−4.85	−6.05	Elevation 0°
Azimuth	180°	0.35	5.26	1.17	−2.15	−2.70	4.28	−0.13	−1.19	−2.61	−0.73	−3.30	−6.11	Elevation 0°
Azimuth	0°	−1.13	2.55	1.19	4.63	1.05	5.93	2.88	3.42	2.36	5.02	3.13	0.18	Elevation +30°
Azimuth	45°, 315°	−2.94	0.98	−1.95	1.77	−0.20	5.10	0.87	0.98	2.12	1.51	−0.66	−1.00	Elevation +30°
Azimuth	90°, 270°	−2.01	1.93	−0.72	−1.67	−1.98	2.51	−1.26	−1.13	−1.34	−0.96	−3.74	−4.25	Elevation +30°
Azimuth	135°, 225°	−2.23	2.17	0.26	−1.82	−3.39	3.08	−0.92	−0.85	−1.91	−0.65	−2.37	−4.45	Elevation +30°
Azimuth	180°	0.66	4.72	3.67	−1.27	−2.17	4.76	−0.64	−0.52	−1.39	0.45	−2.42	−3.90	Elevation +30°
Azimuth	0°	−2.15	2.48	0.45	−1.18	−3.75	−2.70	−2.26	−2.36	−1.94	−2.08	−4.96	−4.89	Elevation −30°
Azimuth	45°, 315°	−2.71	1.73	0.45	−1.10	−3.50	0.00	−1.55	−2.37	−1.42	−1.16	−4.39	−4.58	Elevation −30°
Azimuth	90°, 270°	−1.46	2.94	1.45	−0.62	−2.83	2.45	−0.35	−0.71	−0.32	0.44	−2.22	−2.68	Elevation −30°
Azimuth	135°, 225°	−0.83	3.10	0.88	−0.68	−2.12	1.73	−1.20	−1.16	−1.81	0.16	−2.56	−3.60	Elevation −30°
Azimuth	180°	−0.48	4.15	−1.86	1.27	−1.76	−0.17	−0.33	−2.27	−2.30	0.05	−2.51	−3.29	Elevation −30°
		$F3 - F1$ (dB)												
Azimuth	0°	−2.84	−1.98	−4.01	−7.63	−9.07	−4.06	−5.43	−5.74	−4.56	−9.25	−7.48	−5.58	Elevation 0°
Azimuth	30°, 330°	−5.01	−3.34	−6.05	−10.70	−12.07	−5.44	−8.50	−9.18	−7.78	−12.42	−10.77	−8.10	Elevation 0°
Azimuth	60°, 300°	−2.85	−1.19	−4.69	−8.96	−9.95	−3.48	−7.99	−7.69	−6.81	−9.50	−8.61	−5.69	Elevation 0°
Azimuth	90°, 270°	−6.09	−4.71	−7.50	−10.93	−12.68	−6.05	−10.94	−10.85	−10.25	−12.62	−11.89	−9.83	Elevation 0°
Azimuth	120°, 240°	−4.65	−2.68	−3.80	−8.20	−9.53	−3.12	−10.37	−10.30	−9.43	−11.93	−10.91	−9.03	Elevation 0°
Azimuth	150°, 210°	−5.54	−4.14	−5.19	−10.49	−11.71	−3.79	−11.27	−10.71	−9.91	−12.51	−12.05	−10.58	Elevation 0°
Azimuth	180°	−2.97	−0.76	−5.65	−9.21	−9.81	−4.10	−9.45	−8.88	−8.18	−9.86	−9.60	−7.96	Elevation 0°
Azimuth	0°	−0.72	1.42	−3.20	−2.55	−5.86	−2.39	−5.81	−3.43	−2.98	−3.63	−2.47	−1.61	Elevation +30°
Azimuth	45°, 315°	−2.93	−1.01	−5.28	−4.65	−6.27	−2.75	−6.83	−6.25	−6.38	−7.80	−5.94	−4.70	Elevation +30°
Azimuth	90°, 270°	−4.66	−2.22	−7.59	−8.68	−9.07	−6.59	−10.79	−9.85	−9.30	−11.26	−10.31	−7.85	Elevation +30°
Azimuth	135°, 225°	−7.04	−4.54	−9.27	−10.55	−11.34	−6.98	−11.65	−10.79	−10.14	−12.75	−11.15	−9.40	Elevation +30°
Azimuth	180°	0.03	2.66	−2.14	−5.91	−6.54	−0.91	−6.44	−6.82	−5.76	−7.32	−6.31	−4.78	Elevation +30°
Azimuth	0°	0.40	2.23	−3.58	−3.05	−4.09	−4.09	−5.51	−3.76	−3.51	−5.23	−4.12	−2.72	Elevation −30°
Azimuth	45°, 315°	−3.35	−1.26	−6.61	−6.57	−7.93	−6.30	−7.90	−6.98	−7.29	−9.76	−8.53	−6.21	Elevation −30°
Azimuth	90°, 270°	−4.61	−1.43	−6.55	−9.59	−10.87	−8.36	−11.51	−10.57	−10.27	−11.13	−9.96	−7.50	Elevation −30°
Azimuth	135°, 225°	−3.47	−0.76	−7.04	−7.14	−7.68	−5.29	−9.69	−8.83	−8.73	−9.45	−7.83	−6.54	Elevation −30°
Azimuth	180°	−3.04	−0.16	−5.81	−4.47	−5.02	−5.66	−8.63	−8.56	−7.46	−7.95	−7.59	−6.07	Elevation −30°

Table A3. Directivity data for the vowel /e/. Gradient colors (red to green) visually represent the differences in dB values, where positive values indicate greater projection (energy distribution per frequency, i.e., intensity) in the F2 or F3 region compared to F1 region at a specific azimuth angle and elevation, while negative values indicate greater projection in the F1 region.

		Vowel /e/												
	Participant	CM1			CM2			BM1			BM2			
	Register	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	
		$F2 - F1$ (dB)												
Azimuth	0°	−1.38	−1.72	−2.08	−1.07	1.50	−4.51	−1.63	−2.79	0.70	2.47	−2.76	−0.77	Elevation 0°
	30°, 330°	−0.59	−1.51	−1.88	1.02	2.83	−2.22	−0.37	−0.37	2.44	4.44	−0.83	0.65	
	60°, 300°	−3.44	−3.54	−3.24	−3.38	−0.35	−7.55	−3.61	−3.38	−2.22	0.62	−5.19	−3.63	
	90°, 270°	−0.98	−0.29	−0.53	−1.07	0.61	−5.33	−3.70	−2.98	−1.28	0.35	−4.61	−3.00	
	120°, 240°	−2.83	−1.44	−0.28	−2.74	0.37	−4.26	−5.10	−4.18	−2.29	−0.13	−4.36	−2.67	
	150°, 210°	−2.08	−1.42	0.02	−0.97	1.05	−3.06	−3.95	−3.15	0.04	0.17	−3.29	−1.51	
	180°	−3.88	−0.58	−3.99	−1.86	−0.79	−5.83	−5.55	−5.67	−3.29	−0.76	−4.33	−1.70	
Azimuth	0°	−0.97	1.92	0.74	−0.01	2.33	−4.08	−1.21	−0.71	0.04	3.50	−2.66	3.79	Elevation +30°
	45°, 315°	−1.06	−0.20	−1.11	−0.19	2.84	−1.83	−1.45	0.00	1.34	3.40	−1.09	3.19	
	90°, 270°	−2.29	−2.51	−2.19	−0.80	1.27	−5.11	−1.31	−0.68	−0.09	2.76	−2.00	0.78	
	135°, 225°	−2.33	−3.44	−1.64	−3.73	−0.38	−6.10	−4.04	−4.23	−2.23	0.23	−3.86	−1.22	
	180°	−1.63	−2.22	0.54	−2.63	0.46	−4.63	−3.60	−4.63	−0.83	0.88	−3.72	−0.30	
Azimuth	0°	−4.67	−4.88	−4.21	−4.42	−0.81	−9.82	−3.30	−2.01	−2.59	−0.76	−4.50	0.92	Elevation −30°
	45°, 315°	−2.62	−2.41	−1.90	−3.59	−0.21	−8.22	−4.28	−2.33	−2.97	−0.84	−3.75	−0.52	
	90°, 270°	−1.16	−0.87	−0.76	−1.26	2.74	−4.54	−3.04	−1.90	−1.38	0.88	−2.29	0.67	
	135°, 225°	−2.38	−3.59	−2.94	−2.52	0.34	−5.86	−3.13	−1.85	−1.12	−0.03	−3.49	1.73	
	180°	−4.21	−2.47	−5.41	−2.15	−0.28	−7.93	−2.45	−1.80	−1.50	−0.12	−1.91	1.02	
		$F3 - F1$ (dB)												
Azimuth	0°	0.88	−2.64	−2.76	−1.84	−0.70	−6.49	0.28	−3.34	−0.71	0.96	−6.02	−4.41	Elevation 0°
	30°, 330°	−0.18	−4.09	−4.70	−4.54	−3.43	−7.60	−3.38	−5.56	−3.64	−1.99	−8.27	−7.05	
	60°, 300°	1.68	−4.00	−4.64	−3.04	−0.67	−5.59	−2.08	−3.86	−2.51	0.16	−6.66	−5.32	
	90°, 270°	−2.10	−5.88	−7.16	−4.98	−4.16	−8.99	−4.39	−5.51	−5.08	−2.26	−8.36	−7.64	
	120°, 240°	−0.74	−3.85	−3.29	−3.58	−1.27	−5.25	−4.72	−5.43	−5.11	−2.67	−8.22	−7.10	
	150°, 210°	−1.04	−4.32	−4.27	−4.08	−2.12	−5.58	−4.60	−5.79	−4.51	−3.37	−8.19	−7.86	
	180°	−1.05	−2.66	−5.71	−2.13	−1.74	−6.35	−4.22	−5.13	−4.35	−2.01	−7.41	−5.09	
Azimuth	0°	1.75	−1.52	−2.72	−0.20	1.60	−4.11	1.37	−0.15	1.01	3.86	−3.71	2.43	Elevation +30°
	45°, 315°	−0.55	−2.66	−4.06	−2.71	−0.26	−4.43	−1.64	−2.74	−2.17	0.65	−5.29	−1.41	
	90°, 270°	−1.59	−4.57	−6.64	−4.79	−2.98	−8.30	−3.83	−4.78	−5.33	−1.81	−7.68	−5.71	
	135°, 225°	−3.10	−6.94	−7.63	−7.52	−4.07	−10.14	−5.31	−7.11	−5.79	−3.84	−9.19	−7.09	
	180°	2.14	−1.59	−2.38	−2.41	0.95	−4.47	−0.59	−3.94	−0.39	0.60	−6.34	−2.72	
Azimuth	0°	3.42	−1.78	−3.12	−2.15	2.23	−5.92	−0.11	−1.00	−0.49	2.18	−3.64	0.45	Elevation −30°
	45°, 315°	0.11	−4.19	−5.92	−4.49	−0.12	−8.17	−2.78	−3.53	−3.82	−2.02	−6.81	−4.35	
	90°, 270°	−1.12	−4.32	−5.56	−6.26	−2.25	−9.54	−5.28	−6.02	−6.77	−3.27	−8.02	−5.37	
	135°, 225°	−0.69	−4.80	−6.66	−4.63	−1.00	−7.56	−3.54	−4.20	−4.68	−2.77	−7.60	−3.14	
	180°	−2.07	−3.43	−5.92	−2.44	0.52	−7.77	−2.08	−3.27	−4.01	−2.09	−5.88	−4.23	

Table A4. Directivity data for the vowel /i/. Gradient colors (red to green) visually represent the differences in dB values, where positive values indicate greater projection (energy distribution per frequency, i.e., intensity) in the F2 or F3 region compared to F1 region at a specific azimuth angle and elevation, while negative values indicate greater projection in the F1 region.

		Vowel /i/												
	Participant	CM1			CM2			BM1			BM2			
	Register	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	
		$F2 - F1$ (dB)												
Azimuth	0°	2.77	−2.31	13.79	−5.07	−6.49	18.53	2.45	2.89	14.58	1.92	−2.45	−3.19	Elevation 0°
	30°, 330°	3.70	−0.83	15.00	−2.51	−4.12	18.61	0.28	0.82	13.83	−0.63	−4.78	−2.71	
	60°, 300°	0.65	−5.11	11.85	−3.75	−4.66	18.46	0.28	1.57	13.80	1.24	−3.11	−4.32	
	90°, 270°	1.54	−2.71	14.90	−3.92	−4.92	16.57	−1.14	0.06	12.92	−1.01	−5.43	−5.19	
	120°, 240°	0.42	−3.78	12.77	−3.97	−4.12	17.03	−2.14	−0.48	12.11	−1.61	−5.42	−5.60	
	150°, 210°	0.90	−1.73	11.83	−4.64	−4.84	16.17	−3.40	−1.64	12.63	−2.57	−6.53	−4.20	
	180°	0.60	−4.50	10.94	−2.01	−3.35	16.04	−2.15	0.22	12.13	−0.47	−3.45	−6.42	
Azimuth	0°	2.58	0.65	16.40	−0.06	−2.14	19.85	1.92	4.89	16.44	3.70	0.49	0.62	Elevation +30°
	45°, 315°	3.67	1.11	16.58	−2.30	−3.47	17.97	1.24	3.39	14.02	1.86	−1.20	−1.85	
	90°, 270°	2.04	−1.37	14.94	−1.77	−3.13	17.31	−2.32	0.05	13.39	−1.27	−4.46	−3.20	
	135°, 225°	1.53	−0.41	14.05	−3.58	−4.42	14.83	−2.78	−0.50	11.55	−2.64	−5.73	−4.49	
	180°	5.33	−2.03	13.85	−0.39	−2.62	17.50	4.02	3.88	14.64	4.15	0.67	−2.96	
Azimuth	0°	0.85	−4.39	10.98	−4.03	−4.71	18.29	1.22	3.51	16.16	3.18	−0.93	−1.93	Elevation −30°
	45°, 315°	1.05	−2.25	12.71	−5.57	−5.87	15.64	−0.42	1.63	13.21	0.19	−4.02	−3.31	
	90°, 270°	2.64	−1.14	13.84	−3.61	−4.20	17.06	−2.60	−1.56	11.90	−0.90	−5.24	−4.32	
	135°, 225°	2.35	−1.77	11.66	−3.78	−3.70	16.79	−1.88	−0.47	12.55	−0.70	−4.92	−3.68	
	180°	0.77	−4.27	10.60	−5.88	−5.07	17.88	−1.65	−0.69	12.82	−0.97	−4.71	−3.13	
		$F3 - F1$ (dB)												
Azimuth	0°	8.01	−0.22	14.67	−2.28	−2.67	19.06	3.02	2.79	15.90	1.61	−2.60	−3.01	Elevation 0°
	30°, 330°	6.15	−0.83	13.68	−3.71	−3.91	15.61	0.88	0.81	12.40	−1.21	−5.01	−6.51	
	60°, 300°	8.47	1.21	14.08	−1.94	−1.41	18.98	−0.04	0.79	14.22	0.29	−3.52	−4.86	
	90°, 270°	5.54	−2.14	11.58	−4.69	−4.40	15.10	−1.34	−0.67	11.74	−2.01	−5.89	−8.22	
	120°, 240°	5.83	−0.76	12.41	−3.04	−2.05	16.56	−2.17	−1.10	12.05	−2.39	−5.70	−8.11	
	150°, 210°	4.27	−0.85	10.55	−5.24	−4.19	15.40	−3.67	−2.44	11.53	−3.52	−7.05	−7.88	
	180°	7.02	0.22	11.14	−0.13	−0.50	16.85	−1.97	−0.28	12.92	−1.18	−3.77	−7.17	
Azimuth	0°	8.82	3.86	15.01	0.99	0.04	21.09	1.43	3.93	16.92	2.75	0.10	−1.10	Elevation +30°
	45°, 315°	7.87	1.73	14.64	−1.26	−1.80	18.88	1.32	3.02	15.01	1.27	−1.48	−3.34	
	90°, 270°	5.95	−0.27	13.14	−3.48	−3.68	15.71	−2.62	−0.79	11.62	−2.47	−4.93	−7.38	
	135°, 225°	4.44	−0.06	10.95	−4.99	−4.77	14.13	−3.18	−1.40	10.03	−3.48	−6.04	−7.59	
	180°	12.51	3.72	15.66	2.20	0.49	19.93	4.06	3.37	16.14	3.42	0.30	−3.54	
Azimuth	0°	10.45	3.03	15.66	−0.92	−0.73	20.47	0.76	2.69	17.19	2.37	−1.34	−2.33	Elevation −30°
	45°, 315°	7.27	0.49	12.31	−3.50	−3.42	18.21	−0.39	1.16	13.66	−0.62	−4.36	−5.68	
	90°, 270°	6.12	−0.15	12.18	−5.05	−4.44	16.07	−2.96	−2.27	10.69	−1.81	−5.66	−7.49	
	135°, 225°	5.67	−0.53	11.33	−4.58	−3.22	15.27	−2.01	−1.23	12.22	−1.62	−5.26	−6.31	
	180°	4.84	−1.76	11.41	−4.75	−3.64	17.13	−1.98	−1.42	12.92	−2.49	−5.22	−6.10	

Table A5. Directivity data for the vowel /o/. Gradient colors (red to green) visually represent the differences in dB values, where positive values indicate greater projection (energy distribution per frequency, i.e., intensity) in the F2 or F3 region compared to F1 region at a specific azimuth angle and elevation, while negative values indicate greater projection in the F1 region.

Vowel /o/													
	Participant		CM1			CM2			BM1			BM2		
	Register	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	
							$F2 - F1$ (dB)							
Azimuth	0°	0.59	1.24	−12.82	−0.89	−4.37	−5.22	−0.09	−2.71	−2.63	2.53	−6.24	0.86	Elevation 0°
	30°, 330°	0.58	0.52	−12.37	−1.29	−3.72	−5.79	−1.32	−3.24	−4.20	2.38	−5.86	0.02	
	60°, 300°	0.50	1.00	−10.93	−0.55	−2.72	−9.08	−1.34	−3.02	−6.25	3.31	−4.82	−1.51	
	90°, 270°	0.24	1.80	−10.76	0.86	−2.35	−7.98	−0.97	−1.71	−5.20	3.61	−4.04	−0.17	
	120°, 240°	−0.38	1.74	−9.76	0.18	−3.11	−7.17	−1.72	−1.37	−4.44	2.88	−4.14	0.98	
	150°, 210°	1.27	1.89	−9.45	−0.50	−2.40	−6.79	−0.50	−0.96	−4.79	2.10	−3.87	−0.84	
	180°	−1.04	1.24	−9.85	1.62	−3.49	−4.68	−0.66	−1.36	−4.21	3.14	−3.48	1.97	
Azimuth	0°	−2.27	0.75	−12.24	3.55	−3.26	−3.89	1.04	−1.14	−1.13	3.66	−4.12	4.84	Elevation +30°
	45°, 315°	−0.99	1.30	−14.07	0.70	−4.24	−5.77	−0.47	−1.91	−3.90	1.66	−5.40	1.43	
	90°, 270°	−0.55	1.24	−12.31	0.22	−4.61	−8.32	0.07	−2.48	−5.31	2.29	−5.66	0.59	
	135°, 225°	0.79	−1.22	−11.49	−0.44	−3.53	−8.12	−0.20	−3.38	−4.88	2.01	−5.40	1.69	
	180°	−0.13	0.08	−8.52	1.29	−5.28	−6.07	0.04	−3.00	−2.88	2.41	−5.81	1.18	
Azimuth	0°	−0.12	0.30	−11.68	−1.59	−2.93	−12.48	−1.93	−3.30	−7.91	1.83	−4.99	1.82	Elevation −30°
	45°, 315°	1.09	1.11	−10.93	−1.20	−2.49	−10.18	−1.83	−2.85	−5.69	1.70	−4.59	0.24	
	90°, 270°	1.07	0.97	−10.21	−0.37	−3.24	−7.71	−1.52	−1.87	−4.42	2.09	−4.04	2.23	
	135°, 225°	−0.32	−1.18	−11.03	−0.16	−3.36	−7.82	−1.40	−1.45	−4.47	0.52	−4.96	3.09	
	180°	−1.13	1.08	−11.24	−0.60	−3.72	−7.17	−1.98	−1.04	−5.40	0.49	−3.18	1.16	
							$F3 - F1$ (dB)							
Azimuth	0°	−1.97	−3.97	−6.75	−3.39	−8.22	−4.58	−4.79	−7.53	−8.93	−1.95	−8.03	−1.20	Elevation 0°
	30°, 330°	−3.87	−6.05	−8.49	−5.36	−9.91	−5.07	−6.83	−10.47	−12.36	−4.67	−11.62	−4.09	
	60°, 300°	−1.80	−3.37	−5.86	−4.48	−8.05	−6.08	−7.81	−10.42	−9.48	−3.12	−9.90	−1.45	
	90°, 270°	−4.72	−6.59	−9.30	−5.93	−10.30	−7.08	−8.24	−11.34	−12.52	−5.36	−12.23	−3.64	
	120°, 240°	−4.55	−4.47	−6.05	−4.60	−8.21	−5.77	−7.45	−10.31	−12.29	−5.43	−10.87	−2.89	
	150°, 210°	−4.59	−5.85	−7.25	−5.45	−9.04	−5.65	−8.33	−11.88	−12.51	−7.23	−12.53	−4.28	
	180°	−3.38	−3.10	−6.58	−3.31	−8.06	−3.15	−7.18	−10.52	−11.54	−4.12	−9.26	−0.29	
Azimuth	0°	−3.05	−2.29	−5.02	−1.81	−6.57	−3.71	−4.77	−7.64	−6.61	−0.51	−8.10	2.33	Elevation +30°
	45°, 315°	−3.17	−4.28	−7.48	−3.51	−7.02	−4.99	−6.18	−6.89	−9.65	−2.44	−8.53	0.30	
	90°, 270°	−4.87	−5.51	−8.89	−6.01	−9.81	−7.91	−8.43	−10.58	−11.61	−5.81	−11.32	−3.28	
	135°, 225°	−5.32	−8.57	−10.45	−8.50	−9.42	−8.85	−9.14	−13.25	−12.82	−7.59	−13.18	−4.50	
	180°	−0.80	−2.28	−3.99	−2.79	−5.40	−3.23	−3.75	−8.14	−7.79	−2.11	−8.69	−0.36	
Azimuth	0°	0.39	−1.75	−4.59	−4.08	−5.27	−5.31	−7.52	−8.88	−7.98	−2.35	−7.36	2.89	Elevation −30°
	45°, 315°	−2.30	−5.28	−7.57	−5.66	−7.19	−6.62	−8.35	−9.37	−10.81	−5.78	−9.95	−0.94	
	90°, 270°	−3.83	−5.78	−8.22	−7.50	−9.67	−9.12	−9.99	−12.15	−13.12	−7.06	−11.45	−1.90	
	135°, 225°	−4.63	−6.49	−8.31	−4.91	−6.97	−6.60	−7.50	−9.99	−11.08	−6.39	−10.90	0.42	
	180°	−5.45	−4.68	−7.97	−4.08	−6.74	−6.38	−6.36	−8.79	−10.65	−6.44	−9.38	−2.25	

Table A6. Directivity data for the vowel /u/. Gradient colors (red to green) visually represent the differences in dB values, where positive values indicate greater projection (energy distribution per frequency, i.e., intensity) in the F2 or F3 region compared to F1 region at a specific azimuth angle and elevation, while negative values indicate greater projection in the F1 region.

		Vowel /u/											
	Participant	CM1			CM2			BM1			BM2			
	Register	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High	
		$F2 - F1$ (dB)												
Azimuth	0°	−0.73	0.51	8.98	−2.69	0.56	−0.19	−5.37	2.05	5.32	−2.95	−6.92	−9.52	Elevation 0°
Azimuth	30°, 330°	−0.30	0.15	8.99	−1.92	0.28	2.11	−4.23	1.31	4.67	−2.02	−7.32	−10.80	Elevation 0°
Azimuth	60°, 300°	−0.24	0.01	10.05	−1.76	0.71	0.19	−3.52	1.65	4.82	−1.45	−5.95	−11.17	Elevation 0°
Azimuth	90°, 270°	−0.94	0.52	11.23	−2.61	0.59	1.88	−2.88	2.50	5.49	−0.84	−5.05	−9.65	Elevation 0°
Azimuth	120°, 240°	−1.50	−0.29	10.45	−3.20	0.02	0.81	−3.46	2.00	4.68	−1.58	−4.98	−9.83	Elevation 0°
Azimuth	150°, 210°	0.13	0.55	10.27	−1.33	1.98	2.63	−4.15	2.65	5.53	−1.25	−3.87	−8.81	Elevation 0°
Azimuth	180°	−1.60	−1.65	10.51	−3.63	1.62	0.49	−2.71	2.38	5.65	−0.38	−4.05	−10.56	Elevation 0°
Azimuth	0°	−1.95	0.50	4.74	−3.22	−1.54	0.01	−4.63	3.03	5.87	−4.62	−4.36	−6.05	Elevation +30°
Azimuth	45°, 315°	−1.08	1.99	7.21	−4.30	−1.14	0.75	−4.71	2.04	4.17	−3.48	−4.76	−8.66	Elevation +30°
Azimuth	90°, 270°	−1.18	1.08	8.70	−4.20	−1.24	1.45	−3.99	1.50	4.98	−2.09	−5.79	−8.79	Elevation +30°
Azimuth	135°, 225°	0.22	1.19	9.93	−3.21	−0.93	0.36	−3.71	2.18	5.14	−1.71	−4.21	−7.76	Elevation +30°
Azimuth	180°	−1.03	−0.04	10.64	−3.28	−1.21	2.97	−2.95	2.64	5.30	−0.93	−4.02	−8.46	Elevation +30°
Azimuth	0°	−1.75	−0.55	10.91	−4.56	−2.72	0.17	−7.15	1.16	4.42	−2.95	−5.33	−10.68	Elevation −30°
Azimuth	45°, 315°	−0.96	0.94	10.45	−2.94	−1.11	0.64	−6.17	1.30	3.86	−1.75	−5.45	−10.43	Elevation −30°
Azimuth	90°, 270°	−1.58	1.41	10.30	−2.60	−1.43	1.78	−4.72	2.46	4.60	−1.37	−4.41	−9.41	Elevation −30°
Azimuth	135°, 225°	−1.84	−0.70	7.71	−3.39	−3.13	0.39	−5.42	2.00	4.46	−3.34	−6.15	−9.10	Elevation −30°
Azimuth	180°	−3.03	−2.43	10.93	−6.25	−4.97	0.05	−5.22	0.80	4.55	−4.24	−7.07	−8.87	Elevation −30°
		$F3 - F1$ (dB)												
Azimuth	0°	−2.46	−3.52	9.93	−7.44	−6.02	12.36	−9.85	0.95	1.73	−7.78	−4.55	−9.14	Elevation 0°
Azimuth	30°, 330°	−4.24	−5.21	7.88	−9.05	−8.79	10.12	−10.10	−1.08	−1.44	−9.22	−8.00	−12.28	Elevation 0°
Azimuth	60°, 300°	−1.81	−2.64	10.40	−7.24	−6.52	11.01	−9.88	−0.96	−0.16	−7.84	−6.00	−9.98	Elevation 0°
Azimuth	90°, 270°	−4.94	−5.45	7.48	−9.62	−8.56	8.90	−9.62	−0.87	−2.31	−9.19	−8.07	−12.61	Elevation 0°
Azimuth	120°, 240°	−4.24	−3.82	9.34	−8.35	−6.16	10.83	−8.45	0.66	−2.41	−8.22	−6.00	−12.59	Elevation 0°
Azimuth	150°, 210°	−4.60	−5.19	7.05	−8.66	−7.36	9.44	−10.98	−0.80	−3.83	−9.82	−7.23	−13.04	Elevation 0°
Azimuth	180°	−3.91	−4.56	10.80	−9.54	−5.95	11.04	−8.06	0.02	−1.68	−6.15	−4.92	−12.27	Elevation 0°
Azimuth	0°	−2.37	−1.14	9.87	−5.96	−5.16	11.48	−7.34	1.40	1.16	−6.63	−5.37	−8.32	Elevation +30°
Azimuth	45°, 315°	−2.77	−1.58	9.11	−7.44	−4.83	11.21	−8.93	1.22	0.65	−6.99	−4.61	−9.02	Elevation +30°
Azimuth	90°, 270°	−4.27	−3.37	8.94	−9.65	−7.63	8.50	−10.26	−0.54	−1.53	−9.61	−7.43	−12.26	Elevation +30°
Azimuth	135°, 225°	−4.32	−3.02	5.92	−10.30	−8.78	7.36	−10.12	−0.68	−3.40	−9.70	−6.71	−13.15	Elevation +30°
Azimuth	180°	0.83	1.04	11.69	−6.32	−4.06	14.02	−4.75	3.98	1.57	−4.04	−2.28	−8.44	Elevation +30°
Azimuth	0°	−0.60	−1.22	11.80	−6.40	−4.55	13.25	−9.72	−0.19	1.11	−5.92	−3.18	−8.31	Elevation −30°
Azimuth	45°, 315°	−3.04	−3.36	8.57	−7.62	−6.80	11.50	−10.71	−0.25	−1.20	−8.57	−5.77	−10.92	Elevation −30°
Azimuth	90°, 270°	−4.50	−3.10	7.70	−9.12	−8.31	8.45	−11.19	−1.77	−3.87	−8.97	−5.97	−12.36	Elevation −30°
Azimuth	135°, 225°	−3.99	−3.10	7.51	−7.84	−7.17	9.18	−10.40	−0.51	−2.06	−8.65	−6.03	−10.79	Elevation −30°
Azimuth	180°	−5.40	−5.08	8.10	−9.45	−6.44	10.18	−10.99	−0.71	−2.14	−9.91	−8.43	−11.80	Elevation −30°

References

1. Monson, B.B.; Hunter, E.J.; Story, B.H. Horizontal directivity of low- and high-frequency energy in speech and singing. *J. Acoust. Soc. Am.* **2012**, *132*, 433–441. [CrossRef] [PubMed]
2. Kocon, P.; Monson, B.B. Horizontal directivity patterns differ between vowels extracted from running speech. *J. Acoust. Soc. Am.* **2018**, *144*, EL7–EL12. [CrossRef] [PubMed]
3. Marshall, A.H.; Meyer, J. The Directivity and Auditory Impressions of Singers. *Acta Acust. United Acust.* **1985**, *58*, 130–140.
4. Brandner, M.; Frank, M.; Sontacchi, A. Horizontal and Vertical Voice Directivity Characteristics of Sung Vowels in Classical Singing. *Acoustics* **2022**, *4*, 849–866 . [CrossRef]
5. Leishman, T.W.; Bellows, S.D.; Pincock, C.M.; Whiting, J.K. High-resolution spherical directivity of live speech from a multiple-capture transfer function method. *J. Acoust. Soc. Am.* **2021**, *149*, 1507–1523. [CrossRef] [PubMed]
6. Pörschmann, C.; Arend, J.M. Investigating phoneme-dependencies of spherical voice directivity patterns. *J. Acoust. Soc. Am.* **2021**, *149*, 4553–4564. [CrossRef] [PubMed]
7. Brandner, M.; Blandin, R.; Frank, M.; Sontacchi, A. A pilot study on the influence of mouth configuration and torso on singing voice directivity. *J. Acoust. Soc. Am.* **2020**, *148*, 1169–1180. [CrossRef] [PubMed]
8. Blandin, R.; Brandner, M. Influence of the vocal tract on voice directivity. In Proceedings of the 2019 23rd International Congress on Acoustics—ICA, Aachen, Germany, 9 September 2019; pp. 1795–1801.

9. Sundberg, J. The Singing Voice. In *The Oxford Handbook of Voice Perception*, 1st ed.; Frühholz, S., Belin, P., Eds.; Oxford University Press: Oxford, UK, 2019; Volume 1, pp. 117–142. [CrossRef]
10. Cabrera, D.; Davis, P.J.; Connolly, A. Long-Term Horizontal Vocal Directivity of Opera Singers: Effects of Singing Projection and Acoustic Environment. *J. Voice* **2011**, *25*, e291–e303. [CrossRef] [PubMed]
11. Ladefoged, P.; Johnson, K. *A Course in Phonetics*, 7th ed.; Cengage Learning: Stamford, CT, USA, 2015.
12. Kent, R.D.; Vorperian, H.K. Static Measurements of Vowel Formant Frequencies and Bandwidths: A Review. *J. Commun. Disord.* **2018**, *74*, 74–97. [CrossRef] [PubMed]
13. Arvaniti, A. Greek Phonetics, The State of the Art. *J. Greek Linguist.* **2007**, *8*, 97–208. [CrossRef]
14. Kalozakis, S.; Georgaki, A.; Kouroupetroglou, G. Formant Tuning in Cretan Rizitiko Singing. In Proceedings of the Models and Analysis of Vocal Emissions for Biomedical Applications: 12th International Workshop, Manfredi, C., Ed.; Firenze , Italy, 14–16 December 2021; pp. 127–130.
15. Bakogiannis, K.; Dedousis, G.; Malafis, Y.; Andreopoulou, A. On the spherical directivity and formant analysis of the singing voice; a case study of professional singers in Greek Classical and Byzantine music. In Proceedings of the Audio Engineering Society Convention 153. Audio Engineering Society, Online, 19 October 2022 .
16. Dedousis, G.; Bakogiannis, K.; Andreopoulou, A.; Georgaki, A. Examining The Directivity Characteristics of Greek Sung Vowels on Formant Frequencies. In Proceedings of the 13th International Workshop Models and Analysis of Vocal Emissions for Biomedical Applications, Firenze, Italy, 12–13 September 2023.
17. Malafis, Y.; Pierroutsakou, P.M.; Bakogiannis, K.; Andreopoulou, A. Exploring the Directivity of the Lute, Lavta, and Oud Plucked String Instruments. In Proceedings of the AES 157th Convention, New York, NY, USA, 8 October 2024.
18. Delviniotis, D. Analysis of Byzantine Music—Greek Orthodox Chant—By Using Signal Processing Techniques. Ph.D. Thesis, Department of Informatics and Telecommunications, National and Kapodistrian University of Athens (NKUA), Athens, Greece, 2002. [CrossRef]
19. Chrysochoidis, G.; Kouroupetroglou, G.; Delviniotis, D.; Theodoridis, S. Formant tuning in Byzantine chant. In Proceedings of the Stockholm Music Acoustics Conference 2013 (SMAC 2013), Stockholm, Sweden, 30 July–3 August 2013 ; pp. 217–223.
20. Delviniotis, D.S.; Theodoridis, S. On Exploring Vocal Ornamentation in Byzantine Chant. *J. Voice* **2019**, *33*, 256.e17–256.e34. [CrossRef] [PubMed]
21. Boren, B.B.; Roginska, A. Sound radiation of trained vocalizers. *Proc. Meet. Acoust.* **2013**, *19*, 35025. [CrossRef]
22. Vanasse, J.; Genovese, A.; Roginska, A. Multichannel Impulse Response Measurements in MATLAB: An Update on ScanIR. Presented at the International Conference on Immersive and Interactive Audio, York, UK, 27–29 March 2019.
23. Katz, B.; d' Alessandro, C. Directivity measurements of the singing voice. In Proceedings of the 19th International Congress on Acoustics (ICA 2007), Madrid, Spain, 2 September 2007; p. 6.
24. Boersma, P.; Weenink, D. Praat: Doing Phonetics by Computer. 2022. Available online: https://www.fon.hum.uva.nl/praat/ (accessed on 2 July 2022).
25. Barreda, S. Fast Track: Fast (nearly) automatic formant-tracking using Praat. *Linguist. Vanguard* **2021**, *7*, 20200051.
26. Duckworth, M.; McDougall, K.; De Jong, G.; Shockey, L. Improving the Consistency of Formant Measurement. *Int. J. Speech Lang. Law* **2011**, *18*, 35–51. [CrossRef]
27. Brixen, E.B.; Christensen, S. Influence of Recording Distance and Direction on the Analysis of Voice Formants—Initial Considerations. In Proceedings of the Audio Engineering Society Convention 131, Audio Engineering Society, New York, NY, USA, 20 October 2011.

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