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On the spherical directivity and formant analysis of the singing voice; a case study of professional singers in Greek Classical and Byzantine music

Konstantinos Bakogiannis[1], Giorgos Dedousis[1], Yiannis Malafis[1], and Areti Andreopoulou[1]

[1]*Laboratory of Music Acoustics and Technology (LabMAT), National and Kapodistrian University of Athens*

Correspondence should be addressed to Konstantinos Bakogiannis (kostasbako@uoa.gr)

ABSTRACT

This work presents the initial results of a study examining the spherical directivity and formant analysis of the Greek singing voice. The study aims to contribute to vocal production research and to the design of simulation, auralization, and virtual reality systems with applications involving speech and music. Unlike previous works focusing mainly on the horizontal plane, this study reports results on three elevation angles (+30°, 0°, and -30°). Six professional singers in Greek Classical and Byzantine music were recorded signing in a sound-treated space using a 29-microphone array mounted on a semi-spherical thin-shell structure. The collected dataset consists of short song excerpts and vowel sounds at different pitches. Directivity results across all elevation angles are reported based on overall and per third-octave band RMS levels. Formant analysis of the five Greek vowel sounds is also introduced.

1 Introduction

Research on the analysis, inteligibility, and radiation of the human voice existed since the late 18^{th} century. One of the first publications examining vocal directivity was the pioneering research of Dunn and Farnsworth [1] in 1939, proving that the relationship between vocal directivity and speech inteligibility was well understood back then. The work examined 15-second speech segments from a single speaker, looking at directivity variations as a function of vowel, frequency band, and mouth aperture. The latter was also explored in much later studies such as that of Halkosaari et al. [2]. Both indicated changes in directivity at higher frequencies as a function of the size of mouth opening. Directivity variations as a function of sex and loudness levels have also been examined [3]. Such works, which were mostly focused on the horizontal plane, have recently expanded over a complete sphere of high spatial and and spectral resolution [4, 5], providing a more complete understanding on the topic.

Research focusing on the directivity of the singing voice appeared much later (end of the 20^{th} century) [6, 7], demonstrating that, as with speech, the directivity of the singing voice is frequency dependent and can be affected by the anthropometric characteristics of each individual, their body posture, head position, and vocal track shape [8, 9]. When it comes to singing, vocal directivity has been examined as a function of several factors, including but not limited to pitch, loudness, phoneme, projection / focusing [10, 11], singing genre, training level [12, 11, 13], as well as performance space acoustic properties [12]. As with speech, most early studies had focused on the analysis of horizontal plane data. Following the modern research practice of analyzing directivity data across multiple elevation planes, this project aims to contribute to the spherical analysis of the singing voice by conducting a comprehensive study of the Greek singing voice, taking into consideration multiple singing styles and training levels.

Studies examining formants in Standard Modern Greek are also quite scarce, with the vast majority focusing on speech rather than singing. For reference, one can look at comparative studies between Standard Modern Greek and Cypriot Greek [14] or even across other Greek dialects [15]. In addition to that, the results from such studies are not always easily comparable, oftentimes due to the lack of a widely acceptable protocol and method for formant analysis [16]. Similar observations can be made for the limited studies on Greek Byzantine chant when focusing on formants [17], formant tuning [18], and their relation to vocal ornamentation [19].

2 Methodology

This work is part of a larger study investigating the sound projection and directivity characteristics of a wide variety of traditional Greek musical instruments and professional singers, performing in various common Greek music genres and in realistic performance scenarios, i.e. in places where musicians would be expected to perform and /or be recorded. For this reason following the practice of past studies [20, 11, 21, 9]), the data collection process of this project was not conducted in an anechoic chamber. Rather, measurements were carried out in the hemi-anechoic, 10 x 7 x 5 m live room of the recording studio at the facilities of the Laboratory of Music Acoustics and Technology (LabMAT), NKUA. The walls in this space are covered with absorptive panels, the floor with carpet, and the ceiling with 3 rows of skyline diffusers. The mean room reverberation time (T30) for frequencies up to 500 Hz is 0.45 s and from 1 kHz onward 0.29 s. Reflections from the floor, ceiling, walls, and equipment on the measured data were further minimized using additional sound absorptive material. This paper discusses vocal directivity and formant analysis of the Greek singing voice based on measurements on six trained professional singers (average years of training: 9) in Classical (tenor, bass-baritone, soprano, mezzo soprano) and Byzantine (bass, bass-baritone) music.

Fig. 1: The microphone array configuration.

2.1 Measurement setup

29 RODE-M5, small diaphragm condenser microphones were placed symmetrically on a hemispherical thin-shell structure with a radius of 158.5 cm (Figure 1), at four elevations (+90°, +30° , 0° , and -30°). 12 microphones were placed on the horizontal plane at 30° azimuthal increments, 8 microphones on -30° elevation, and 8 microphones on +30° elevation, each at 45° azimuthal increments. An additional microphone was placed directly above the participants' heads at +90° elevation. This last microphone is currently excluded from the reported results, resulting in 28 measurement positions across the remaining 3 elevations. The individual impulse responses of all microphones were collected using ScanIR [22, 23], a multi-channel Impulse-Response measurement tool, on an M1 MacBook Pro 2020 running Matlab 2021a.

Participants were placed standing at the center of the microphone array. The height of the configuration could be adjusted using elevation probes such that its center would be aligned with the position of each singer's mouth. A plumb and laser beams were used to ensure that participants remained properly aligned with the array throughout the measurements. This alignment method was preferred to stricter constraining methods [10] as a standing posture and the tolerance of small body movements, often related to singing and vocal projection, were found to lead to a more natural singing experience for the participants.

Prior to measurements all recorded input signals were level calibrated using pink noise (78 dBA), generated by a Brüel & Kjær omnidirectional loudspeaker (OmniPower SoundSource Type 4292-L) placed at the singer's position. The levels of all array microphones were matched to within ± 0.5 dB of each other. The recorded pink noise signals were analyzed in $1/3^{rd}$-octave bands and calibration levels were obtained, such that each band had equal RMS levels. The data was captured using two Yamaha TF1 digital mixers (inter-connected via DANTE), using their built-in pre-amplifiers, on and i5 laptop running Cubase 11.

2.2 Data collection and post-processing

Once aligned with the microphone array, participants were asked to choose two songs in the Greek language and sing a 30 second excerpt of each. They were advised to select songs of diverse singing styles, that covered a wide frequency and dynamics range, which in their opinion, were characteristic of their repertoire. Moreover, in order to specifically study the directivity and formant distribution of the Greek sung vowels, participants were asked to intone loudly, according to their interpretation of a forte (f) dynamic, the five Greek vowel sounds (monopthongs): /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 audio recordings per participant and microphone were deconvolved with the microphone responses to minimize the impact of the measurement setup on the analyzed data [24, 25] and level calibrated per $1/3^{rd}$-octave band, to obtain omni-directional responses [10]. 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.

3 Results

To examine the directivity patterns of the Greek singing voice, the data was analyzed in Root Mean Square (RMS) levels across its full frequency range as well as per $1/3^{rd}$-octave bands, ranging from 80 Hz to 10 kHz. For brevity, only the third-octave bands centered at 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz will be shown here. In the presented polar plots vocal radiation patters were normalized relative to the horizontal plane 0° azimuth microphone RMS level, which was always on-axis with the participants' mouths.

The formant analysis of the Greek singing voices was based on the audio recordings of the monopthongs /i/, /e/, /a/, /o/, /u/. The files were manually segmented, so as to preserve the onset and the outset of each vowel, while, at the same time, removing any unwanted sounds before or after the phonation. The extracted tokens were analyzed in Praat [26], where formants F1 and F2 were tracked using Fast Track [27] and manually compared and verified for improved accuracy and consistent records [28].

3.1 Overall vocal directivity patterns

Figure 2 shows the normalized vocal directivity patterns of the six participants, based on the overall RMS levels of the 2 song excerpts, calculated across the full frequency range. As can be seen, the collected data confirms the literature that the projection of the singing voice is left / right symmetric, even under the relatively more loose alignment conditions employed in this experiment. Looking at an inter-participant comparison, the observed differences are not significant (< 1 dB); all polar plots form similar directivity patterns. On the horizontal plane, an almost circular-shaped pattern is formed favoring the frontal plane projection by more than 2 dB for azimuth angles around 180°. Similar observations can be made for the other two elevation planes. They both favor projection towards the frontal plane, as expected, with the loss in the rear-plane of the -30° elevation angle being larger (mean: -2.9 dB) than that of the +30° elevation angle (mean: -1.5 dB). Yet, both planes have ovoid-shaped patterns narrower than the horizontal plane on both the right and left sides with the +30° elevation plane being slightly narrower, reaching -1.3 to -1.4 dB on the interaural axis, than the -30° one, which ranges between -1.1 and -1.0 dB.

Similar observations can be made on Figure 3, which plots the normalized vocal directivity patterns of the six participants intoning the vowels /a/e/i/o/u/ on either A2, E3, and C#4 (male) or A3, E4, and C#5 (female), based on their overall RMS levels, calculated across the full frequency range. The directivity plots of all singers irrespective of singing genre, sex, and vowel sound remain left / right symmetric, and present softer projections towards the rear by an average of -2 dB, as well as ovoid-shape patterns for elevations beyond the

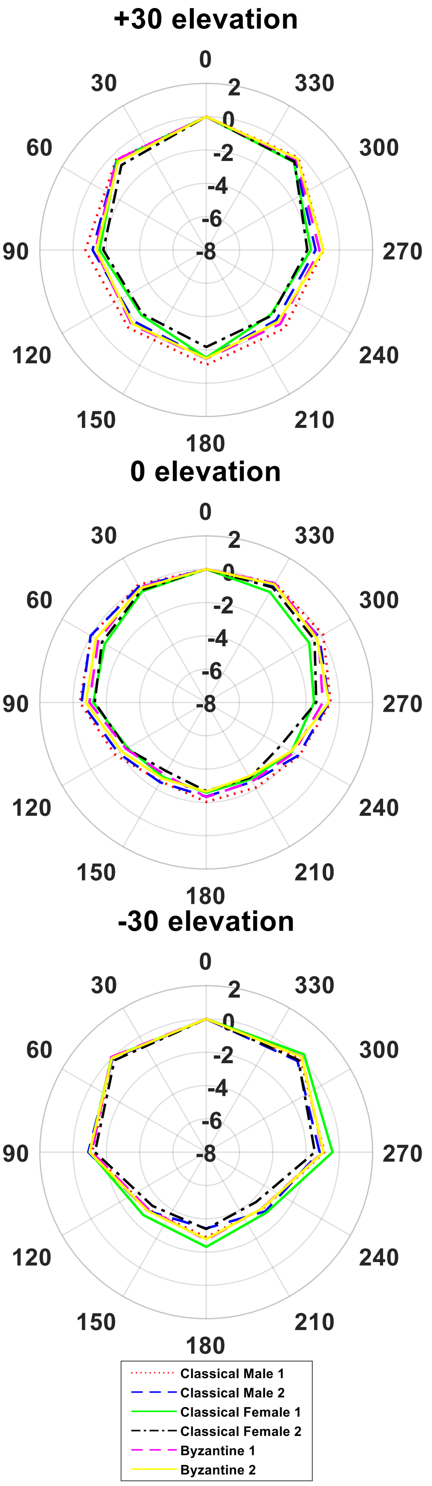

Fig. 2: Normalized vocal directivity patterns of the six participants, based on the overall RMS levels of the 2 song excerpts, calculated across the full frequency range

horizontal plane. This latter effect is stronger for female singers (see columns 3 and 4, Figure 3. Male singers show broader patterns, probably due to the presence of lower frequencies in their data which are more omni-directional in nature.

The observed directivity variations as a function of vowel are rather small for all singers, with the most notable pattern differences observed on the rear plane in the two female singers across all elevation planes and in the male singers on the -30° elevation. On the horizontal plane, for the 2 male classical singers vowel sounds /a/ and /e/ have a rather wide directivity pattern compared to the 2 male byzantine singers, despite the fact that they all had sung the exact same notes during measurements, fact which implies an impact of the singing technique on vocal directivity. Finally, the most homogeneous and symmetric radiation pattern across all participants and elevation planes is observed for the vowel sound /i/, with the exception of classical female singer 1, which exhibits the lowest left / right symmetries across all vowels and elevation planes. An examination of the video-recording documentation of the measurements revealed that this participant employed more prominent body and head movements as a means of vocal production and expressivity than others in this study, fact that has most likely impacted the symmetry in the directivity patterns of that data.

3.2 Vocal directivity patterns per 1/3rd-octave band

In order to minimize the domination of low-frequency content on the vocal directivity analysis, the collected data was also analyzed in 1/3rd octave bands. Figure 4 shows this analysis applied on the recorded song excerpts. As can be seen, low frequencies present a nearly omni-directional behavior (shown at the selected bands of 125 Hz, 250 Hz, and 500 Hz) across all elevation planes. The effect is more prominent at 125 Hz; at subsequent frequency bands the radiation progressively becomes softer towards the back. In the mid-frequency region (1 kHz and 2 kHz) the patterns have a narrower shape than that of the low-frequency region which progressively becomes cardioid and frontal plane focused for the upper-frequency bands (4 kHz and 8 kHz). Once again, the observed inter-participant variations are rather small, with the exception of the mid-frequency region, which acts as a transitional point between the omni-directional low-frequency radiation

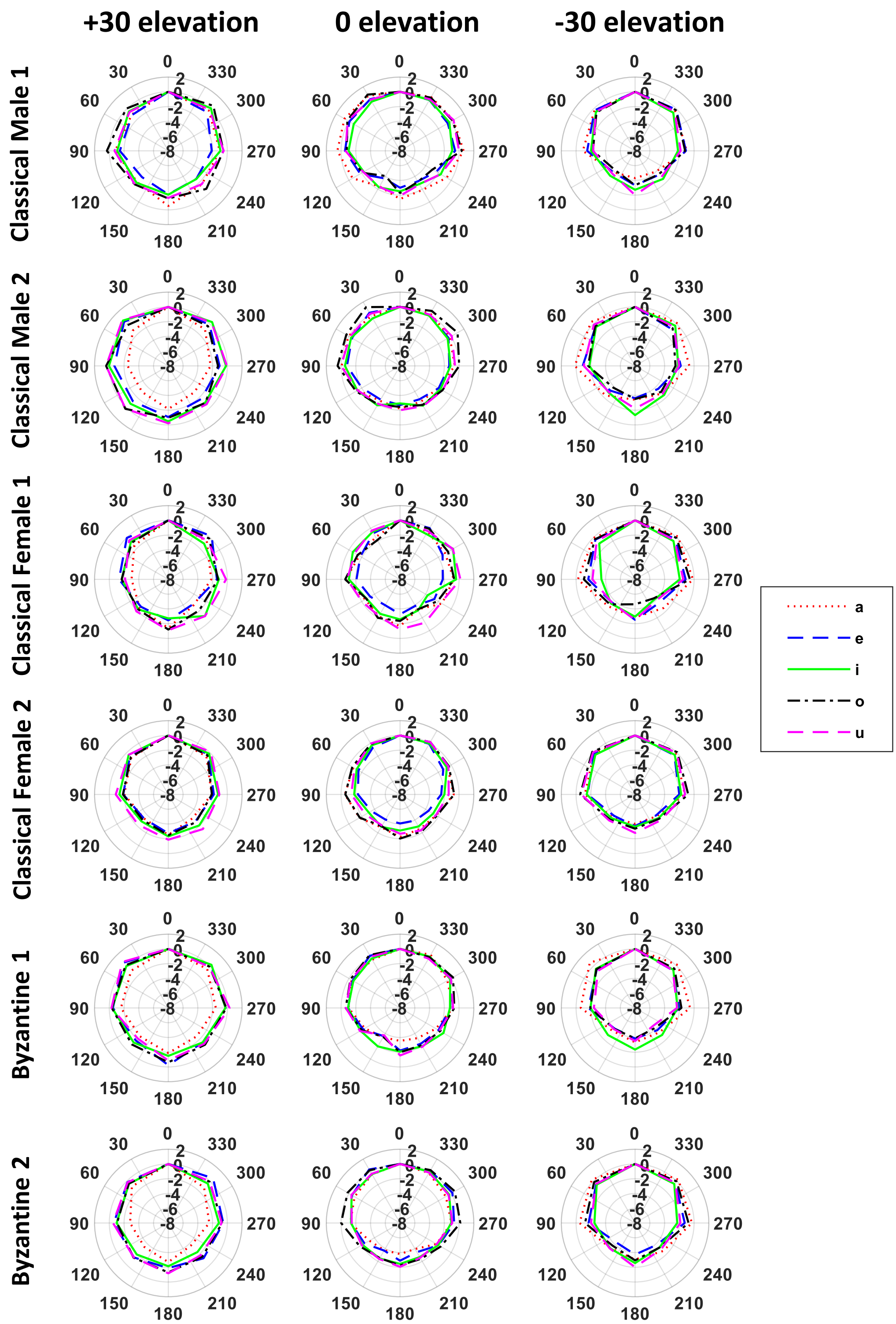

Fig. 3: Normalized vocal directivity patterns of the six participants intoning the vowels /a/e/i/o/u/ on either A2, E3, and C#4 (male) or A3, E4, and C#5 (female), based on their overall RMS levels, calculated across the full frequency range

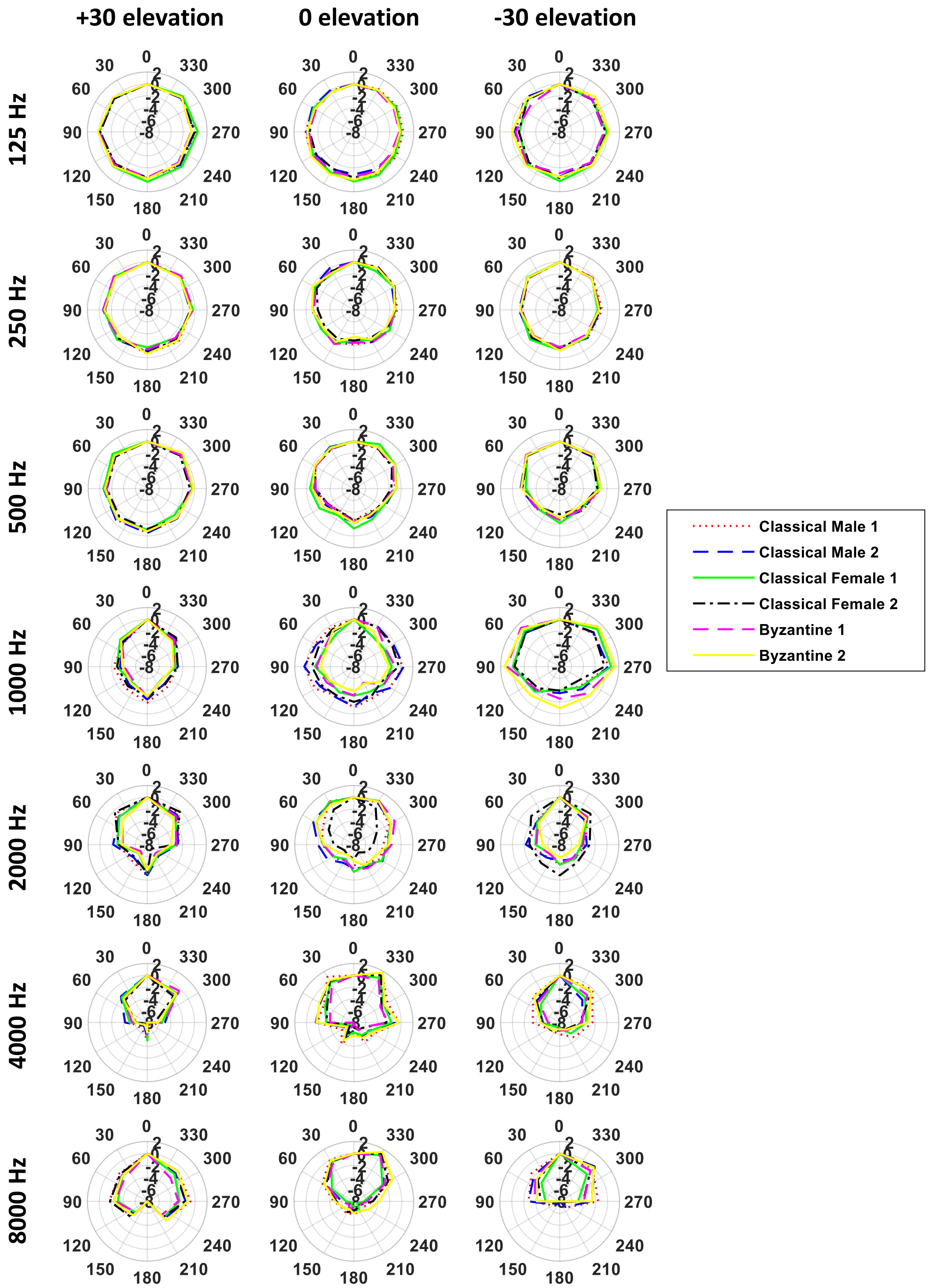

Fig. 4: Normalized vocal directivity patterns of the six participants, based on the overall RMS levels of the 2 song excerpts, calculated across $1/3^{rd}$ octave bands.

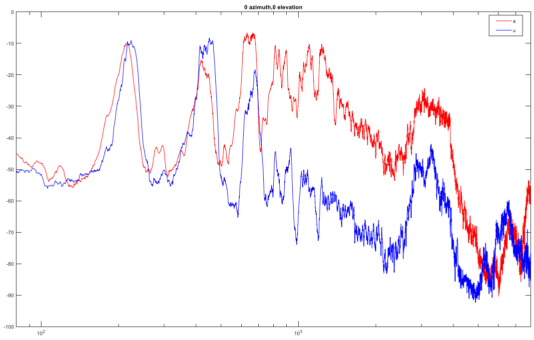

Fig. 5: Frequency spectrum of the /a/ and /u/ vowels on A3 on the horizontal plane 0° azimuth position for a single participant

pattern and the cardioid-shaped high-frequency content, where the observed aforementioned variations reach a maximum of 2.5 dB

Previous research has demonstrated a correspondence between the size of the mouth opening and vowel directivity for high frequency content [1, 2, 4]. In order to confirm this finding for vowels of the Greek singing language RMS-based directivity analysis per $1/3^{rd}$ octave band was performed on the /a/ (large mouth aperture) and /u/ (small mouth aperture) Greek vowels. Figure 5 shows the spectrum of the two vowels as captured by the microphone in front of the singers' mouths (0° azimuth position on the horizontal plane), for one of the experiment participants. As can be seen, vowel sounds vary significantly for frequencies above 5 kHz, with /u/ carrying significantly less energy than /a/, sometimes even lying below the set noise threshold. Similar observations can be made for the corresponding data of all microphone positions and participants in this study.

Figure 6 shows the normalized directivity patterns of vowels /a/ and /u/ when sung on A2 (male singers) or A3 (female singers), based on RMS levels calculated across $1/3^{rd}$ octave bands for all six participants. Closer inspection of the data leads to similar observations as before. The formed patterns are more omni-directional in-nature in the lower frequency region, especially for the horizontal and +30° elevation planes, while progressively favoring projection towards the frontal plane by at least 2 dB starting as early as at 250 Hz. Data across all elevation planes progressively becomes more cardiod-like at higher frequency bands. Our findings do not demonstrate any systematic significant differences linking mouth aperture to vowel directivity for the two vowels under examination, which could relate to frequency region as well as singing genre.

3.3 Formant Analysis

The F1 / F2 formant analysis of the monopthongs /i/, /e/, /a/, /o/, /u/, was run in Praat. The six singers were asked to intone each of the five vowel sounds twice, in three different pitches (male: A2, E3, and C#4; female: A3, E4, and C#5), for at least 2 seconds each, resulting in six audio recordings per vowel per singer. The resulting formant values for all tokens were aggregated and organized in three groups: Classical Female singers, Classical Male singers, and Byzantine singers. The corresponding plots are shown at Figure 7.

The data shows great formant dispersion in each vowel. In order to facilitate comparisons only mean F1 and F2 values will be reported here. For the two Classical Female singers the mean (F1, F2) values are (515 Hz, 1927 Hz) for /i/, (693 Hz, 1783 Hz) for /e/, (803 Hz, 1411 Hz) for /a/, (656 Hz, 1271 Hz) for /o/, and (554 Hz, 1154 Hz) for /u/. For the two Classical Male singers, the respective values are (413 Hz, 1761 Hz) for /i/, (553 Hz, 1482 Hz) for /e/, (627 Hz, 1139 Hz) for /a/, (554 Hz, 984 Hz) for /o/, and (451 Hz, 840 Hz) for /u/, while those for the Byzantine singers are (415 Hz, 1989 Hz) for /i/, (556 Hz, 1618 Hz) for /e/, (698 Hz, 1227 Hz) for /a/, (534 Hz, 834 Hz) for /o/, and (418 Hz, 798 Hz) for /u/. This data adds to the very limited published research on formant analysis on the singing voice in the Standard Modern Greek language for two popular Greek genres, classical and byzantine.

4 Discussion

This work discussed vocal directivity and formant analysis of the Greek singing voice, as a function of vowel, frequency range / pitch, and music genre, based on acoustic measurements on six professional singers, four trained in Classical music (two female), and two in Byzantine chant. Results were reported across 3 elevation planes (+30° , 0° , and -30°), for various azimuthal angles.

The reported results confirm the existing literature, according to which the projection of the singing voice is left / right symmetric [10, 11], This property of the data prevailed any possible variability / noise introduced by the relatively relaxed alignment controls employed in this study, which were chosen in order to allow for more

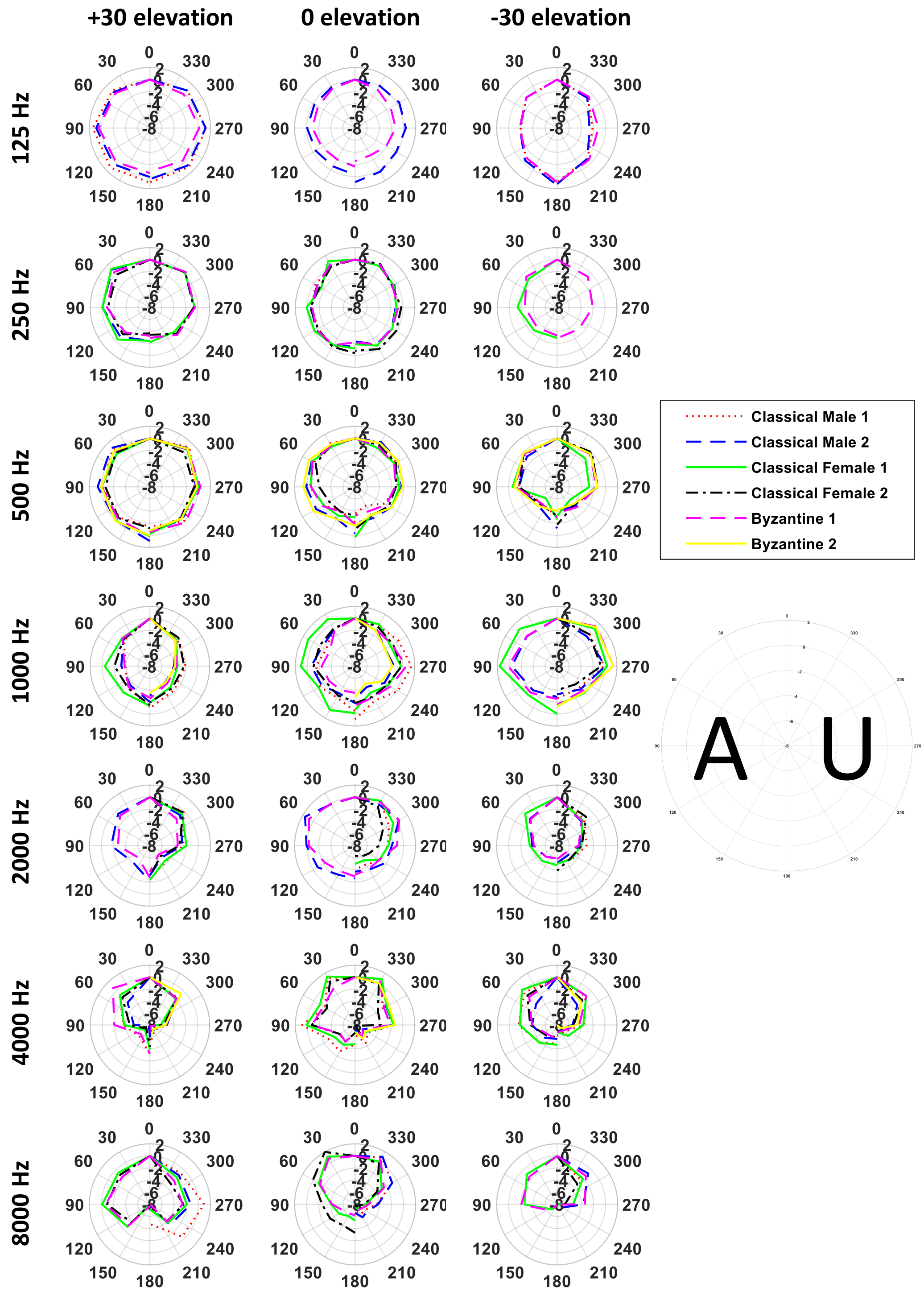

Fig. 6: Vocal directivity patterns of the six participants intoning the vowels /a/ and /u/ on either A2 (male) or A3 (female), based on RMS levels calculated across 1/3rd octave bands. The left side of each polar plot holds the radiation patterns of the /a/ sound and the right side that of the /u/ sound.

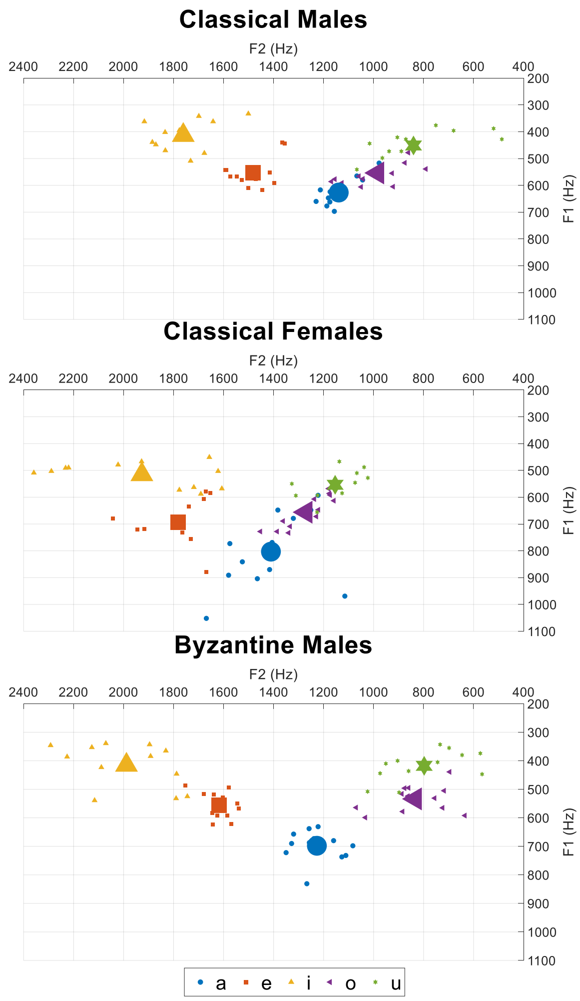

Fig. 7: F1 / F2 formant plots of the monopthongs /i/, /e/, /a/, /o/, /u/, aggregated in three groups: Classical Female, Classical Male, and Byzantine Male.The figure depicts both the original data as well as average values per vowel (larger symbols)

natural body postures and head micro-movements, as these have been shown to affect vocal projection and directivity [9].

A correspondence was also found between frequency range and vocal directivity. As expected, lower frequencies exhibit more omni-directional radiation characteristics than higher frequencies, which tend to form cardioid-shaped patterns [10, 11, 13]. As a result, when examining radiation characteristics across the full frequency range of the human voice, male singers show broader, more omni-directonal vocal directivity patters across all tested elevations, than female signers.

Previous research has demonstrated a correspondence between the size of one's mouth opening and vowel directivity for high frequency content [1, 2, 4]. Larger mouth aperture has been linked to narrower, front-focused radiation beams and to a shift of the projected energy towards lower elevations [9]. Such variations are more prominent when changes in mouth aperture are significant. In our study, a comparison between the /a/ and /u/ vowels was chosen to study these phenomena due to the largely different sizes of one's mouth opening when producing those phonemes. While such directivity changes are observable in the data, variations were not found to be significant, despite the fact that the observed differences in the spectral content of the data above 5 kHz were significant. A similar observation was reported in [10]. It should be noted, however, that in our analysis the polar plots of the /u/ vowel from 1 kHz onward contain fewer directivity patterns than those of /a/. This is a result of the noise-floor threshold applied which indicates that, for several singers, the /u/ sound does not carry enough energy above the noise floor to radiate compared to /a/ at higher frequency bands (Figure 5).

There exists a widespread anecdotal belief within the classical music circles that unamplified operatic singers can fill a concert hall with the sound of their voices, reaching audiences at any spot in the auditoriums. This quality is related to two vocal properties, loudness and directivity, In terms of loudness / vocal projection, this can be attributed to the singer's formant, which for the operatic singers (specially males), can be found in the region of 2 kHz to 4 kHz, a frequency range known for being very triggering to the human ear, thereby enhancing audibility [13]. In terms of directivity, operatic singers have been found to exhibit more omni-directional directivity patterns compared to singers of other music genres in several studies, such as [12, 11]. In addition, there has been evidence that the voice of these singers becomes more directional in the frequency region of the singer's formant (2 kHz to 4 kHz) [13]. The results of the present study, which revealed wider / louder and more omni-directional in nature vocal directivity patters for the male classical singers compared to the male byzantine singers, despite the fact that all experiment participants had sung the exact same content during measurements, is in agreement with the aforementioned past literature findings.

Analysis of the formant data revealed greater dispersion in the F2 values of vowels /i/ and /a/ for the two female classical singers compared to the two male classical ones, who had greater dispersion in the vowels /u/ and /e/. The F1 values of /a/ were also found to differ a lot among the two classical female singers. A comparison of the average F1 and F2 values between male and female classical singers showed lower values for the former. This can be an indication that the male classical singers place these vowels more backwards in their mouth cavities.

The vowel distribution observed in Figure 7 is well in agreement with other similar studies in the Standard Modern Greek language, showing that vowels /o/ and /u/ are back and rounded, /i/ and /e/ are front and unrounded [14] and /a/ is central [16]. Nevertheless, these studies concern spoken rather than sung vowels, as studies on singing in Greek are scarce and a matter that needs further investigation. According to the literature, when singing, the vowel space is in general reduced [29] and shifted towards lower formant frequencies, as a result of lowering one's larynx [30]. In one of the very few studies on the Greek singing language comparing professional Byzantine music singers (psaltes) to opera singers (tenor, baritone, bass) from another study [31], Delviniotis [17] showed that F1 values across all vowels lie higher in Byzantine compared to the Classical singing style, with the F1 of the tenor's vowel /a/ being the only exception to this rule. F2 values in Byzantine singing were also found to be higher than those of the classical singing genre for /o/ and /u/, lower for /e/, and comparable for the remaining vowels.

Based on the data in this study, Byzantine music singers demonstrate a greater vowel space than both the classical male and female singers. Their average value for /i/ is 415 Hz-1989 Hz (F1-F2), while for the male classical singers it ranges between 413 Hz and 1761 Hz and between 515 Hz and 1927 Hz (F1-F2) for female ones, fact which indicates that Byzantine singers produce vowels that are more towards the front and more open than those produced by the two classical singing groups.

One shortcoming of this work is the limited number of acoustically measured singers, fact that inevitably focuses the analysis of the data on individual results, rather than on overall statistics, as the latter requires much larger sample populations. While this limitation can be, to a certain extend, justified by the nature of this study, which requires expert, professional singers of various genres and lengthy measurement protocols in complicated setups, admittedly much larger sample sizes are necessary in order to render the reported observations generalizable and conclusive. Nevertheless, it should also be pointed out that the small sample size of the current study renders our results directly comparable to related research studies, the vast majority of which is also based on observations from a limited pull of individuals, for reasons explained above.

5 Future work

This work studied spherical directivity and formant analysis of the singing voice in two music genres Classical and Byzantine chant. The reported results added to related research in the field of analysis of the singing voice, with an emphasis on the Greek language. Future work will focus on expanding the collected data to include singers of various training levels and singing genres, in order to further investigate and highlight the potential impact of vocal training and singing style on directivity and vocal projection. Formant analysis will also be further explored in order to extend the limited, to date, such research on the Greek singing voice.

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