Long-Term Average Spectrum Characteristics of Portuguese *Fado-Canção* from Coimbra

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Summary: Descriptions of acoustical characteristics of Fado, a Portuguese urban style sung in Lisbon and Oporto, are scarce, particularly concerning Fado-Canção, a related style sung in Coimbra. The present study aims at describing long-term average spectrum (LTAS) parameters of 16 professional singers while singing and reading the lyrics of a typical Fado-Canção. LTAS parameters were investigated in terms of: (1) equivalent sound level (L_{eq}); (2) spectral differences between 3 frequency bands 0−2, 2−5, and 5−8 kHz; and (3) quantification of spectral prominence between 2 and 4 kHz, calculated as the level difference between the peak in this frequency region and a reference trendline between 1 and 5 kHz, henceforth *Formant Cluster Prominence* (FCP). Given that Fado-Canção, besides Fado and traditional styles, originated also from classical singing, and that previous studies on Fado suggest the absence of a singer's formant cluster, the averaged LTAS for all Fado-Canção singers was further compared to the LTAS of two world-touring opera baritones singing an operatic aria and a *lied*. Results show that Fado-Canção is commonly sung with a L_{eq} of 86.4 dB and a FCP of about 10 dB, values significantly higher when compared to reading. The FCP in Fado-Canção, although smaller than for the two classical opera singers' examples (14.8 and 20 dB, respectively), suggests that the style preserved some of its original lyrical influence. However, because younger singers present higher energy in the 5−8 kHz region relative to the remaining frequency bands as compared to older singers, it seems that Fado-Canção may be drifting towards non-classical vocal practices. FCP seems to be a promising straightforward method to quantify the degree of formant clustering around the region of the singer's formant in LTAS, allowing comparisons between different singers and singing styles.

Key Words: Fado-Canção— Long-Term-Average Spectrum—Singer's formant cluster—Formant Cluster Prominence.

INTRODUCTION

Fado is a Portuguese music style recognized by UNESCO as 'World's Intangible Cultural Heritage'. [1] It is commonly sung in Lisbon and in Oporto. A related style called *Fado-Canção* is sung in Coimbra. It originated from Fado, but also from traditional and classical singing. [2] Unlike the Lisbon and Oporto Fado, the Fado-Canção is mainly performed in a setting of a serenade (*Serenata*), i.e., sung outdoors for up to a thousand spectators. According to tradition, the Fado-Canção is sung exclusively by males, preferably tenors, current or former students who are deeply involved in the academic cultural life of the University of Coimbra. The accompaniment of Fado-Canção is played on a pear-shaped 12-stringed guitar, with both neck and a resonance box longer than those of the guitar used for accompanying the Fado from Lisbon and Oporto. A special tuning of the Portuguese guitar is used for the accompaniment of the Fado-Canção, allowing a variety of musical developments.[3] The lyrics of the Fado-Canção are commonly of a romantic nature, but can also describe various aspects of academic bohemian life.[4] At the beginning of the 20th century, recordings of Fado-Canção started to have a prominent place in the national and international music industry, with some interpreters standing out as national celebrities (e.g., António Menano, Zeca Afonso and Luis Góis).[5]

Historical, sociological and ethnomusicological reports on the origins, influences and musical characteristics of Fado can be found elsewhere,[2,4–7] while descriptions of its acoustical characteristics are scarce, particularly concerning Fado-Canção. By contrast, acoustical properties of the Fado from Lisbon have been described by Mendes and associates (2013), who investigated jitter, shimmer and harmonics-to-noise-ratio (HNR) and also maximum phonation time in 13 amateur and 2 professional singers. The phonatory tasks for both speech and singing were sustained vowels.[8] Mean jitter values were higher for Fado singers than for country, music theatre, soul, and jazz singers, whereas mean shimmer was lower than for pop singers and western

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classical singers. Mean HNR was found to be similar to western classical singing. These authors further inspected the spectral content using the long-term average spectrum (LTAS) option of the Multi-Speech. Results suggested absence of a singer's formant cluster. Also, inefficient coordination between respiratory and laryngeal systems was reported.[8] A more comprehensive sample of singers was investigated in a subsequent study in which cepstral peak prominence (CPP) was analysed in both speech and singing. The results suggested that, particularly male and young Fado singers, had CPP values close to the threshold of pathological voice.[9]

Much research has been carried out on acoustical and physiological aspects of classical singing. For traditional styles of singing, however, the situation is entirely different. The currently missing acoustical descriptions of Fado-Canção remains a concern; the preservation of such an orally transmitted singing style would profit also from scientific documentation.[10] LTAS analysis of the radiated sound has been used to allow the identification of various salient voice characteristics.[11] For example, LTAS can reveal the presence and/or absence of a singer's formant cluster, as defined as the level difference between the maximum peaks in the frequency ranges 0−2 kHz and 2−4 kHz, which has been defined as the *Hammarberg's index*.[12] According to Bartholomew (1934), concentration of energy around 3kHz is a characteristic of good classically trained male singers' voices.[13] Acoustically speaking, this spectrum peak has been referred to as the singer's formant.[14] It results from a clustering of vocal tract resonances R_3, R_4 and R_5.[15] This spectrum envelope peak is highly beneficial to singers as it makes the singer's voice easier to discern against a background of a loud accompaniment.[16] A gain in this frequency region is highly beneficial in terms of loudness as the hearing has its maximum sensitivity between 2 and 4 kHz (Robinson & Dadson, 1957). Lowering the larynx and narrowing the aryepiglottic cross-sectional area contribute to creating the singer's formant cluster.[14,17] Studying this cluster seems important also to Fado-Canção. The style evolved from a mixture of different musical genres, among which classical singing was one.

To study the frequency region 5−8 kHz may be also relevant. A peak in this frequency range has been found in some other non-classical singing styles, e.g., Peking Opera (Sundberg et al, 2012). In addition, even small level differences in the 8 kHz octave band have been shown to be perceptible [18] and therefore worthwhile to investigate. Moreover, the results of an early investigation on relationships between LTAS parameters and perceptual judgements of pathological voices found that hyperfunctional voices significantly correlate with high spectral level in LTAS frequency bands of 0−2, 2−5 and 5−8 kHz.[11] Given that Mendes et al found that male Fado singers, especially younger ones, present CPP values near the threshold of pathological voices,[9] inspections for the levels of these LTAS frequency bands seems appropriate. Therefore, the present investigation aims at documenting resonatory and phonatory strategies used by Fado-Canção singers, considering LTAS measures of equivalent sound level (L_{eq}), spectral differences between 3 frequency bands (0−2, 2−5, and 5−8 kHz), and spectral prominence between 2 and 4 kHz, quantified as the level difference between the peak in this frequency region and a reference trendline between 1 and 5 kHz, henceforth *Formant Cluster Prominence* (FCP). The ultimate goal is to provide answers to the following research questions: (1) how loudly is Fado-Canção singing; and (2) how similar are the LTAS properties to those of classical and non-classical singing.

METHODS

Participants

Twenty Fado-Canção singers were initially contacted; of these, four baritones and twelve tenors volunteered to be recorded, age range from 23 to 58 years (M = 36.06; SD = 11.01). Their experience as Fado-Canção singers varied from 3 to 25 years of public performances, all having non-commercial recordings available on YouTube. The singers older than 40 years had at least one commercial recording and all but one had taken singing lessons. At the recording day, all reported to be in good vocal and physical conditions. Table 1 summarizes general information regarding participants' characterization.

As mentioned, Fado-Canção evolved from a wide variety of singing styles, including classical, traditional and Fado from Lisbon and Oporto. As the acoustical characteristics of classical singing have been well documented,[19] it seemed worthwhile to compare the averaged LTAS of Fado-Canção singing and respective FCP with the LTAS and FCP of representative examples of classical singing style. Therefore, two world-touring professional classically trained baritone singers were also recorded.

Recordings and procedures

Prior to the recordings, ethical approval was obtained from the Centre for Social Sciences at the University of Coimbra, Portugal, and participants signed a consent form complying with the requirements of all applicable European data protection and privacy laws.

After a short warm-up (about 5 minutes) of raspberries and lip trills starting at different pitches, sung as ascending and descending five-note scales, participants were asked to read the lyrics of a Fado-Canção song, *Saudades de Coimbra* (lyrics by António de Sousa, music by Mário Faria Fonseca). This song was well-known to all singers. They were also asked to sing that song while listening to a guitar accompaniment in one headphone covering one ear. The accompaniment was available in three keys - F Major, F# Major and G Major − and was chosen according to each singer's voice type and individual preference. Both singing and reading tasks had durations exceeding 40 seconds, thus sufficient for a representative LTAS analysis.[20]

All recordings were carried out in an anechoic chamber at the *Institute for Research and Technological Development for*

TABLE 1.
Participants' age, voice type, history of voice training and performance experience.

Identification	Age [years]	Voice Type	Singing Lessons [years]	Performance Experience [years]
S01	52	Baritone	< 5	> 20
S02	45	Tenor	6-10	> 20
S03	28	Tenor	< 5	6-10
S04	48	Tenor	6-10	> 20
S05	27	Tenor	< 5	6-10
S06	42	Tenor	6-10	16-20
S07	25	Baritone	< 5	< 5
S08	31	Tenor	< 5	11-15
S09	25	Tenor	< 5	< 5
S10	43	Tenor	11-15	> 20
S11	24	Baritone	< 5	> 20
S12	27	Baritone	< 5	< 5
S13	34	Tenor	< 5	< 5
S14	23	Tenor	< 5	< 5
S15	45	Tenor	< 5	> 20
S16	58	Tenor	Never	> 20

Construction, Energy, Environment and Sustainability (*Itecons)* in Coimbra, Portugal.

A head-mounted omnidirectional electret condenser microphone (Knowles model EK3132) was used to collect the audio signal. A steady 1 kHz sinusoid from a tone generator program (*Tone* from www.tolvan.com), was recorded for sound pressure level (SPL) calibration, the SLP of which determined at the recording microphone by means of a sound level meter (AZ instrument, model 8928). In some cases, the microphone-to-mouth distance had to be adjusted in order to avoid clipping, but was then kept the same throughout the recording. This distance was noted for each singer and later used for the level calibration of the audio signal.

The audio signal was recorded with a Laryngograph microprocessor (www.laryngograph.com) at a sampling rate of 16 kHz and a resolution of 16 bits, transferred to a computer via an USB connection and saved as a wav file. During the recording, the signal was monitored in real time using the Speech Studio software by Laryngograph.

Recordings of the two world-touring opera singers were made in a sound treated studio in KTH, Sweden, using an omnidirectional condenser microphone OM1 Line. The two baritones sang two samples of a lyrical character, an operatic aria (*Deh, vieni alla finestra*, from D. Giovanni by W.A. Mozart) and a *lied* (*Skogen Sover*, by Hugo Alfvén), respectively. The criteria to selected these particular pieces were two-fold. First, their expressive character were comparable to that of the Fado-Canção song *Saudades de Coimbra*. Second, they were both sung with L_{eq} comparable to the ones of Fado-Canção singing. This is particularly important given the substantial effects of loudness in LTAS characteristics.[21]

Recordings were calibrated and compensated for different mouth-to-microphone distances using the same procedure as described for the recordings of the Fado-Canção singers. Besides LTAS curves, FCP was also calculated.

Individual LTAS

All recordings were calibrated with the different mouth-to-microphone distances recalculated to a 30 cm mouth-to-microphone distances, following the methodological recommendations described elsewhere, using the formula 20*log10(d_1/30), where d_1 w mouth-to-microphone distance used in the recording.[22] To avoid effects of unvoiced sounds on the LTAS,[23] all unvoiced segments were eliminated from the recording using a *Sopran* script (www.tolvan.com). Then, the equivalent sound level (L_{eq}) of both singing and reading was measured using C-weighting [22] and an LTAS analysis was run for each singer applying a Hanning window and 350 Hz bandwidth.

The LTAS data obtained for each singer and task were copied and transferred to an excel file. As shown in Figure 1, the LTAS curves were divided into three frequency bands,

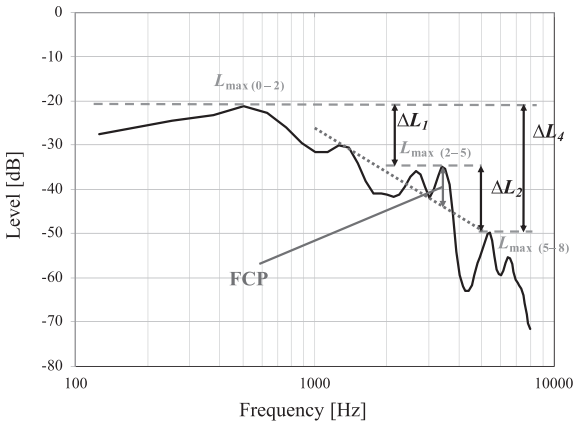

FIGURE 1. Example of a long-term average spectrum (LTAS) displaying the maximum level for three frequency bands, 0 to 2, 2 to 5 and 5 to 8 kHz, hence $L_{max(0-2)}$, $L_{max(2-5)}$ and $L_{max(5-8)}$. The differences between the peaks are also represented, i.e., ΔL_1 and ΔL_2 and ΔL_4. The formant cluster prominence (FCP) is also represented by an arrow.

delimited by the frequencies of 0, 2, 5 and 8 kHz, following previous methods for analysing perceptual and acoustical correlates of different voice qualities.[11] Then, the maximum LTAS level was measured in each of these frequency bands, henceforth $L_{max(0-2)}$, $L_{max(2-5)}$ and $L_{max(5-8)}$.

Also the differences between these peaks were calculated. The ΔL_1, defined as the difference between $L_{max(0-2)}$ and $L_{max(2-5)}$, also known as the *Hammarberg's Index*, has been used as a measure of the level of the singer's formant cluster (Eyben et al, 2016). This measure reflects the spectral balance between lower partials and the singer's formant cluster but is strongly dependent on vocal loudness (SPL). In order to compensate for this effect, a trendline was calculated for the frequency range 1−5 kHz. Then, the maximum difference was measured between this trendline and the LTAS within 2−4 kHz region, i.e., in the region where the singer's formant cluster has been shown to appear (Sundberg, 2013). When a clustering of formants occurs, the LTAS amplitude in the cluster increases and reduces the LTAS amplitude in the frequency range where the formants would normally appear.[24] Thus, the difference between the trendline and the LTAS within 2−4 kHz region can be expected to reflect the effect of clustering; henceforth, it will referred to as the *Formant Cluster Prominence*, FCP. It provides a measure compensated for the spectral slope of the voice source. Thus, it also allows comparisons between tasks, singers and singing styles, as they will be less sensitive to variation of vocal loudness. It should be observed that FCP will reflect formant clustering as the trendline extends beyond the frequency of the formant cluster. Also, it should be noted that ΔL_1 is heavily dependent on R_1 and R_2 [14], and that FCP reduces this sensitivity. Bloothooft and Plomp (1986) proposed a level difference exceeding 20 dB between SPL and the level in the 2.2−3.6 kHz range as a criterion for a singer's formant.[25] However, this criterion fails to take into account variation of overall SPL. Furthermore, given the continuous effect of vocal loudness variation on overall LTAS slope,[21] applying a fixed threshold for the presence a singer's formant seems debatable.

As mentioned in the introduction, also LTAS peaks appearing at frequencies above that of the singer's formant cluster may be relevant for the Fado-Canção style. Previous investigations of various non-classical singing styles have shown that important LTAS peaks occur also in the 5 −8 kHz range.[26] According to Monson et al (2011), even small differences in the region between 5.7 and 11.3 kHz are relevant to perceived voice quality.[18] Also, as suggested by Mendes et al (2020), male Fado singers, especially younger ones, tend to have CPP near the threshold of pathology.[9] In addition, Hammarberg et al (1980) showed the relevance of higher LTAS frequency bands in perceptual judgements of pathological voices.[11] Therefore, also the difference between $L_{max(2-5)}$ and $L_{max(5-8)}$, henceforth ΔL_2, was measured. This measure reflects the dominance of the singer's formant cluster over $L_{max(5-8)}$. Also, the level difference between ΔL_1 and ΔL_2, i.e., ΔL_3, was determined, as well as the level difference between $L_{max(0-2)}$ and $L_{max(5-8)}$, henceforth ΔL_4. A peak within the region of the singer's formant would result in a lower ΔL_3. A lower ΔL_4 would reflect the presence of energy in the higher spectral frequencies (see Figure 1).

Averaged LTAS

To identify LTAS characteristics of the Fado-Canção singing style, the power value of each frequency band of the 16 singers' LTAS curves were averaged. The averaged power value in each frequency band were then converted to dB. Singing and reading were averaged separately.

Statistical analysis

Differences between reading and singing with respect to LTAS characteristics and L_{eq} values were analysed by means of a paired sample *t*-test. This particular statistical test was chosen because the results of a Shapiro-Wilk test did not reveal a deviation from a normal distribution. In addition, to assess whether there was a relationship between singer's age (and thus performance experience), and either of L_{eq} and LTAS characteristics of the Fado-Canção singing, a Pearson's correlation was made. All tests were carried out using a significance level of $\alpha = 0.05$.

RESULTS

Individual LTAS

Figure 2 presents the individual LTAS curves for singing and reading the lyrics of the Fado-Canção *Saudades de Coimbra*. The dotted lines correspond to the trendlines between 1 and 5 kHz used to calculate the FCP. The dashed curves highlight the frequency ranges at which the LTAS curves of reading and singing differed.

Tables 2 and 3 represent L_{eq} values and all LTAS parameters, extracted for individual singers for both singing and reading tasks, respectively.

The L_{eq} and LTAS parameters' differences between singing and reading were analysed by means of a statistical paired sample *t*-test. The results show significant differences for all parameters, except for ΔL_2 (see Table 4).

Visual inspection of the individual LTAS of the Fado-Canção song seem to suggest that FCP in singing can be related to age. Figure 3 provides an example; the FCP of tenor S11, age 24, is 5.3 dB whereas that of tenor S15, age 45, is 13.1 dB of (Figure 3A. and 3B., respectively). However, a closer analysis reveal age dependence neither for FCP nor for ΔL_1, whereas ΔL_2 and ΔL_4 increase and ΔL_3 decreases with age, Table 5.

Averaged data

The dashed curve in Figure 4 illustrates the LTAS difference between singing and reading the lyrics of Fado-Canção, averaged across all 16 singers. The difference is greater for frequencies above 400 Hz, which is consistent with the

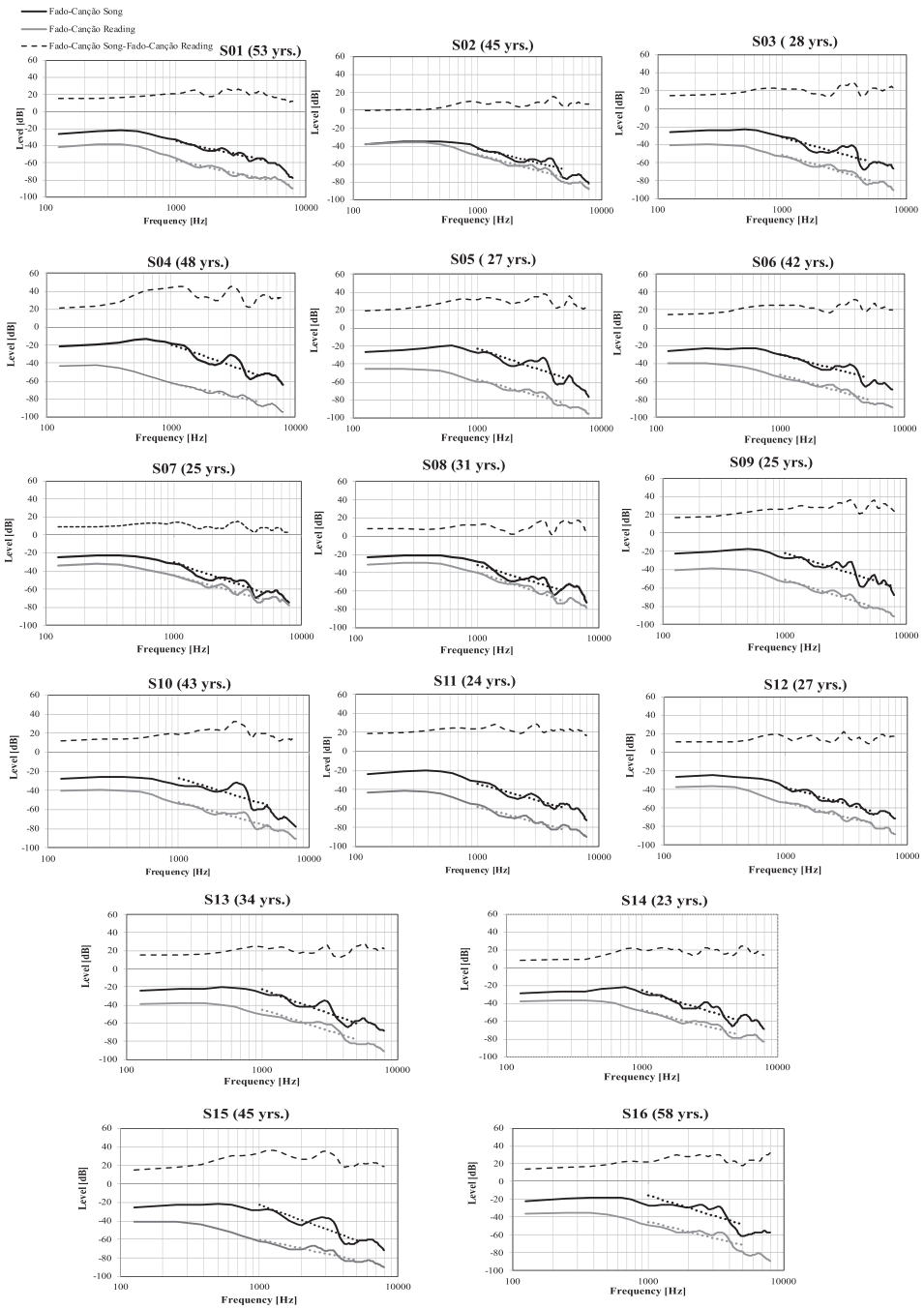

FIGURE 2. Individual long-term average spectra (LTAS) for all 16 singers. Solid black lines represent LTAS for the Fado-Canção song; solid grey lines represent the LTAS for the Fado-Canção lyrics. Dotted lines represent the difference between Fado-Canção song and Fado-Canção reading.

louder singing voice. The dashed line also shows two dips close to 2 and 4 kHz and an increase around 3 kHz, observations consistent with a singer's formant cluster of R_3, R_4 and R_5 around 3 kHz in singing. Figure 4 also displays a higher FCP in singing than reading, 9.7 and 4.2 dB.

Figure 5 compares the average LTAS for all Fado-Canção singers in singing with LTAS of two classically trained world-touring opera baritones, singing excerpts of lyrical songs. The FCP for both classical singers is higher than the one averaged across all 16 Fado-Canção singers. The mean L_{eq} for the Fado-Canção singers was 86.4 dB and for the baritones, 89.7 dB and 77.6 dB, respectively.

DISCUSSION

In this study, two main questions were raised: (1) how loudly is Fado-Canção singing; and (2) how similar are the LTAS properties to those of classical and non-classical singing. Thus, L_{eq} and LTAS characteristics were analysed in

TABLE 2.
Equivalent Sound Level (L_{eq}) and LTAS parameters for singing the Fado-Canção *Saudades de Coimbra,* for each singer. Mean (*M*) and standard deviations (*SD*) calculated across the 16 singers are also presented. Definitions of symbols are given in Figure 1.

Singer	$L_{eq@30cm}$ [dB]	$L_{max(0-2)}$ [dB]	$L_{max(2-5)}$ [dB]	$L_{max(5-8)}$ [dB]	ΔL_1 [dB]	ΔL_2 [dB]	ΔL_3 [dB]	ΔL_4 [dB]	FCP [dB]
S01	85.0	−21.9	−43.1	−59.0	21.3	15.9	5.4	37.1	3.7
S02	73.3	−34.8	−53.8	−71.5	19.0	17.7	1.2	36.7	8.2
S03	84.2	−23.1	−40.9	−59.3	17.7	18.5	−0.7	36.2	12.3
S04	93.7	−12.8	−31.2	−51.6	18.4	20.3	−1.9	38.7	11.8
S05	87.8	−19.8	−33.2	−52.8	13.4	19.6	−6.2	33.0	14.3
S06	86.4	−22.6	−41.1	−58.1	18.5	17.0	1.6	35.5	9.8
S07	84.2	−22.6	−47.1	−61.0	24.5	13.9	10.6	38.4	7.0
S08	88.0	−21.1	−44.4	−52.5	23.3	8.2	15.1	31.4	8.1
S09	89.7	−17.4	−31.1	−46.0	13.7	14.9	−1.2	28.6	13.2
S10	81.9	−25.6	−31.6	−60.0	6.0	28.5	−22.5	34.4	14.1
S11	87.3	−20.2	−44.7	−54.7	24.5	10.1	14.4	34.5	5.3
S12	82.0	−24.8	−50.1	−63.0	25.3	12.9	12.4	38.2	4.4
S13	88.7	−20.5	−34.7	−54.8	14.3	20.1	−5.8	34.3	12.9
S14	87.8	−21.9	−38.7	−52.3	16.8	13.6	3.2	30.4	9.2
S15	88.9	−21.7	−35.8	−59.6	14.2	23.8	−9.6	37.9	13.1
S16	93.0	−17.7	−25.8	−55.5	8.1	29.7	−21.6	37.8	13.1
M	86.4	−21.8	−39.2	−57.0	17.4	17.8	−0.4	35.2	10.0
SD	4.7	4.5	7.5	5.7	5.5	5.7	10.9	3.0	3.5

recordings of 16 Fado-Canção singers' singing and reading the lyrics of a typical Fado-Canção song.

The results of this investigation show that singers performed the Fado-Canção song at 86.4 dB, while the corresponding value for reading was 15.6 dB softer (70.8 dB), thus similar to connected speech.[27] Leino and associates (2011) reported an average SPL of 85.5 dB (recalculated to 30 cm distance) for actors' voices, thus quite similar to the L_{eq} for the Fado-Canção song.[20] It is interesting that the song was performed that loud even though an amplification system is typically used. Probably it is relevant that Fado-Canção singing is performed outdoors.[28]

Apart from L_{eq}, also ΔL_1, ΔL_3, ΔL_4 and FCP were significantly different between Fado-Canção lyrics and song.

TABLE 3.
Equivalent Sound Level (L_{eq}) and LTAS parameters for reading the lyrics of the Fado-Canção *Saudades de Coimbra,* for each singer. Mean (*M*) and standard deviations (*SD*) calculated across the 16 singers are also presented. Definitions of symbols are given in Figure 1.

Singer	$L_{eq@30cm}$ [dB]	$L_{max(0-2)}$ [dB]	$L_{max(2-5)}$ [dB]	$L_{max(5-8)}$ [dB]	ΔL_1 [dB]	ΔL_2 [dB]	ΔL_3 [dB]	ΔL_4 [dB]	FCP [dB]
S01	69.5	−38.4	−64.4	−77.1	26.0	12.7	13.3	38.7	2.9
S02	72.9	−36.2	−60.7	−80.1	24.5	19.4	5.1	43.8	5.3
S03	68.8	−39.5	−62.4	−80.9	22.9	18.5	4.3	41.4	4.5
S04	64.6	−42.7	−71.5	−85.0	28.8	13.5	15.3	42.3	3.5
S05	64.5	−45.2	−67.8	−85.8	22.6	18.0	4.6	40.6	5.6
S06	69.6	−39.1	−63.2	−83.8	24.1	20.6	3.5	44.7	5.4
S07	76.5	−32.1	−54.6	−68.4	22.6	13.7	8.8	36.3	6.7
S08	79.8	−29.0	−51.8	−67.6	22.7	15.9	6.9	38.6	4.9
S09	71.8	−39.0	−62.7	−81.3	23.8	18.5	5.3	42.3	5.9
S10	69.5	−39.3	−62.7	−77.9	23.4	15.1	8.3	38.6	7.8
S11	68.9	−41.4	−67.4	−76.9	26.0	9.5	16.4	35.5	3.9
S12	70.9	−36.0	−63.7	−76.5	27.7	12.8	14.9	40.5	2.6
S13	72.0	−37.3	−58.6	−82.4	21.2	23.8	−2.6	45.0	8.2
S14	73.5	−36.2	−59.3	−75.0	23.1	15.8	7.3	38.8	5.6
S15	66.9	−40.4	−66.5	−82.4	26.0	15.9	10.1	42.0	5.8
S16	72.8	−34.8	−55.5	−79.6	20.7	24.2	−3.5	44.8	5.8
M	70.8	−37.9	−62.0	−78.8	24.1	16.7	7.4	40.9	5.3
SD	3.8	3.8	5.0	5.1	2.2	3.9	5.6	2.9	1.5

TABLE 4.
Mean difference (*MD*) and standard deviations (*SD*) between singing and reading the lyrics of the Fado-Canção *Saudades de Coimbra*, with the results of a Paired Sample *t*-test (n = 16). Definitions of symbols are given in Figure 1.

Acoustical parameters	*MD* [dB]	*SD* [dB]	Paired *t*-test	*P*-value
$L_{eq@30cm}$	15.6	6.8	$t(15) = 9.146$	< 0.001*
ΔL_1	−6.7	5.1	$t(15) = -5.246$	< 0.001*
ΔL_2	1.0	5.2	$t(15) = 0.793$	0.440
ΔL_3	−7.7	9.58	$t(15) = -3.225$	0.006*
ΔL_4	−5.6	3.9	$t(15) = -5.684$	< 0.001*
FCP	4.6	2.7	$t(15) = 6.697$	< 0.001*

* Paired Sample *t*-test, statistical significance ($P < 0.05$).

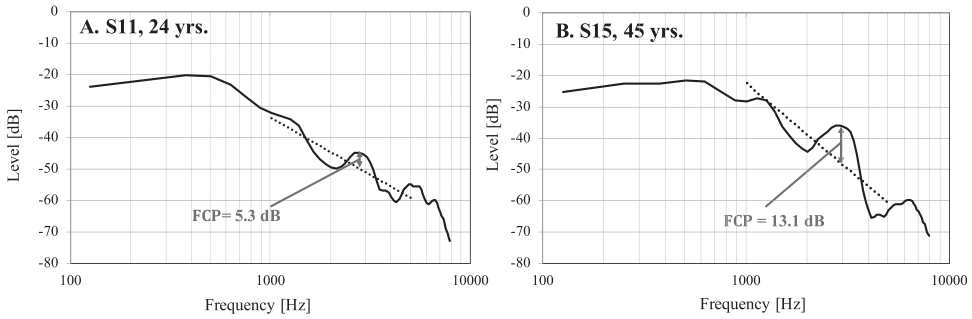

FIGURE 3. Long-term average spectra (LTAS) for the song Fado-Canção *Saudades de Coimbra* displaying the Formant Cluster Prominence (FCP) for an younger and an older tenor (panels A and B, respectively).

These results indicate that, as compared with reading, Fado-Canção singing has a higher spectral peak near the region of the singer's formant cluster. This finding is in accordance with the dips near 2 and 4 kHz surrounding the peak; if two formants approach each other in frequency, dips are likely to occur in the LTAS at their original frequencies.[15] Thus, the dips are in accordance with the assumption that the peak is the result of formant clustering. Moreover, the lower value of ΔL_4 in singing indicates that the peak between 5 and 8 kHz was significantly stronger than in reading. The missing significance for ΔL_2 may be the result of the presence of a singer's formant combined with a reduced spectral slope with increasing loudness in singing.

Regarding comparisons with other vocal styles, the prominence of the singer's formant cluster, the mean FCP was 9.7 dB for Fado-Canção singers and 14.8 and 20 dB for the two international opera singers. However, it might be mentioned that the 9.7 dB, (or 10 dB when calculated from the averaged FCP values extracted from the 16 individual LTAS), is extracted from an average LTAS across 16 singers, thus containing the extremes 3.7 and 14.3 dB. The plateau for singing between 2 and 3.5 kHz is the result of the differing centre frequency of the cluster between the 16

TABLE 5.
Pearson's correlations between singer's age and L_{eq}, ΔL_1, ΔL_2, ΔL_3, ΔL_4 and FCP, for the Fado-Canção song *Saudades de Coimbra*.

	Correlation Coefficient	*P*-value
$L_{eq@30cm}$	0.090	0.739
ΔL_1	-0.406	0.119
ΔL_2	0.664	0.005*
ΔL_3	-0.558	0.025*
ΔL_4	0.532	0.034*
FCP	0.153	0.571

* Pearson's correlation test statistical significance ($P < .05$).

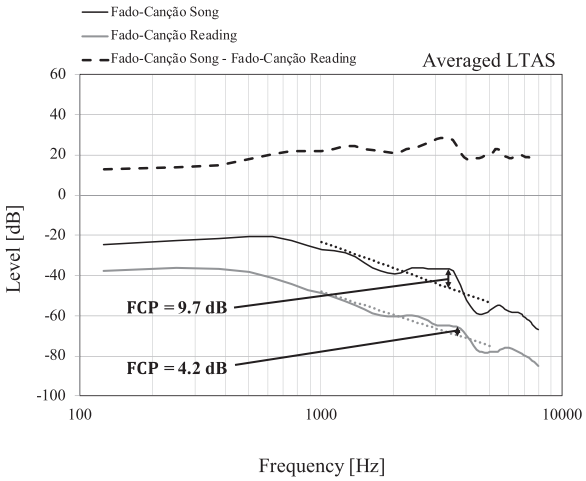

FIGURE 4. LTAS curves, averaged across the 16 singers, for singing and reading the lyrics of the Fado-Canção *Saudades de Coimbra* (black and grey solid lines, respectively), the dashed black line showing the difference. Formant cluster prominence (FCP) is also displayed.

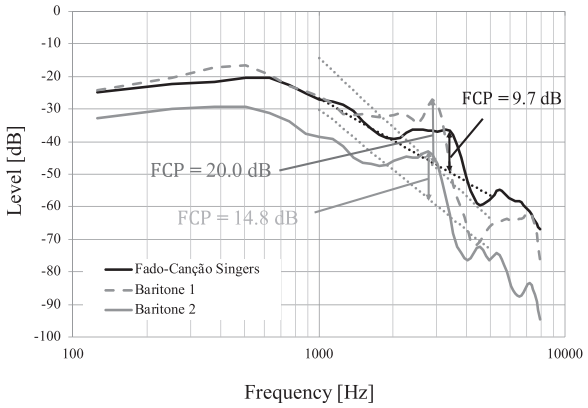

FIGURE 5. Averaged LTAS across all 16 Fado-Canção singers while singing the Fado-Canção song (black solid curve) and LTAS for two professional classically trained baritones while singing an operatic aria and a *lied* (dashed and solid grey curves, respectively). The three dotted lines represent the trendlines between 1 and 5 kHz drawn to quantify the formant cluster prominence (FCP).

singers; the centre frequency of the singer's formant cluster varies with voice classification, being high for tenors and low for baritones.[29] The higher FCP of classical singers may reflect a closer clustering of $R_3 - R_5$, a question left to a future investigation.

Although visual inspections of the individual LTAS of the Fado-Canção song seemed to suggest that FCP in singing could be related to age, the Fado-Canção singers' age showed a significant correlation, neither with FCP nor with ΔL_1 . However, age correlated with ΔL_2, ΔL_3 and ΔL_4; older singers had less energy between 5 and 8 kHz than younger ones. This invites to the speculation that the style of Fado-Canção is presently drifting away from classical singing, as currently claimed by Fado-Canção experts. Possibly, younger singers sing with a stronger glottal adduction, a type of phonation frequently heard in e.g., rock and pop styles.[30–32]

The significantly higher value of the 5–8 kHz energy may seem perceptually irrelevant, considering masking and frequency range. However, first, the LTAS peaks near 3 and 5.5 kHz are located in separate critical bands, thus reducing the risk of masking. Second, even small differences within the 5 to 8 kHz frequency range have been shown to be perceptually relevant to normal-hearing people.[18] Third, for certain recording and amplification systems, high energy in this frequency band seems to be relevant.[17,33]

The study of levels at high frequencies can be difficult for at least three reasons. One could be the sensitivity to electronic noise, the other the sensitivity to microphone positioning and the third the requirement to remove fricatives. In our study, fricatives were removed by running a script in Sopran. However, a possible limitation was that microphone positions were different for different singers during the recordings of the singing tasks because of the overloading of the audio signal. This may have introduced variability in frequency levels in the high frequency range, but within the magnitude of only few decibels. In future studies, the use of microphone and electronics that can handle the high sound pressure levels that occur close to the mouth is recommended.[22]

In the current study we suggest FCP as a new LTAS measure to quantify formant clustering in the region of the singer's formant. This quantification seems needed; the *Hammarberg index* is insufficient for this purpose, as it is affected by both vowels and overall LTAS slope.[11] The deviation of the LTAS peak from the trendline between 1 and 5 kHz seems to solve these limitations. However, it should be noted that FCP still varies with ΔL_1 .

The difference between SPL and the level in the 2.2–3.6 kHz 1/3 octave band was proposed as another measure of the level of the singer's formant (L_{sf}) (Bloothooft & Plomp, 1986). Like ΔL_1, L_{sf} is sensitive to overall spectral slope. As a definition of a singer's formant, these authors further proposed the criterion that "the relative level of the high-frequency spectral peak exceeds a threshold of about -20 dB". This threshold has the limitation of depending on vocal loudness and vowel.

It should be noted that FCP is an LTAS measure, thus not applicable to sustained vowels. It appears to be attractive for quantifying clustering of vocal tract resonances in the region of the singer's formant. It is a continuous rather than binary measure, thus facilitating comparisons between singers and styles of singing. Its quantitative relationship to the degree of formant cluster, analysed by, e.g., inverse-filtering, would be a worthwhile topic for future research.

CONCLUSIONS

The vocal style used in Fado-Canção differs from speech with regard to loudness, prominence of LTAS peaks in the region of the singer's formant, and in the region 5–8 kHz. A high L_{eq} and a prominent peak near 3 kHz seems to meet the conditions of outdoors singing for large audiences. The method here proposed for quantifying the formant clustering underlying the singer's formant LTAS peak suggests that Fado-Canção has absorbed some acoustical characteristics of classical singing. However, younger singers seem to drift away from the classical singing tradition by producing more energy in the 5–8 kHz band.

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