Voice Quality in Low and High Registers in Two Different Styles of Singing

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Abstract

This paper compares the voice quality of low (C3-D#4[1]: 131-311 Hz) and high registers (E4-Bb4: 330-466 Hz) of singing, in order to investigate whether there are differences in voice quality regarding (i) the note register (low x high) and (ii) musical accentuation (unaccented x accented). These registers are respectively associated in the voice literature with the activity of the thyroarytenoid and cricothyroid muscles.

Two songs with a range from C3 to Bb4 were selected for analysis. Four professional singers sang and read the lyrics of these two songs. Thirteen voice quality parameters were automatically extracted in Voice Sauce software.

Our results support the idea that the action of different muscles may be correlated with different voice quality configurations in contemporary singing. The main results also show that thirteen voice quality parameters varied between low and high notes (low to high, accented low to accented high), and between unaccented and accented notes (low to accented low, high to accented high).

Index Terms: singing, voice quality, MPB, Grunge, acoustic analysis

1. Introduction

The range of a singer's voice in classical singing is composed most of the time of two basic voice registers: chest voice at the lower voice range, and head voice/falsetto at the higher voice range [1,2]. The low and high notes in this paper can be loosely associated, respectively, with these two voice types. It is important to highlight, nevertheless, that this classical terminology is not convenient for use in contemporary singing due to the complex laryngeal and supra-laryngeal settings used by singers, not allowing us to hypothesize a unique laryngeal/supra-laryngeal scheme for either the low and the high notes. As Titze [3] points out, "multiple sound sources can be engaged, including the ventricular folds, the aryepiglottic folds, and the velum, to produce inharmonicity in the spectrum", and different "singing styles make use of desynchronization of coupled vocal oscillators to enrich the frequency spectrum of the voice". We can, for example, have during phonation a low note with the vocal folds quite apart, and a high note with the vocal folds shut together. Yet, as the main references in the literature are related to classical singing, we base in these studies to investigate what are the laryngeal and supralaryngeal settings for singing in the region from C3 to B4 (131-494 Hz). We should be reminded though that distorted voices[2] are very common in the accented low and accented high notes of Grunge[3] [4] and MPB[4] [5] singing genres [6, 7], but not expected to occur in traditional classical singing [1].

The study of the distorted voices [3, 8, 9] has shown that, despite its successful use in classical singing, the traditional notion of voice registers in music such as chest, head, mixed voice, and falsetto is not useful in contemporary popular singing pedagogy. Also, the strict separation of classical singing voice within two octaves is too limiting in popular music, since it is possible with the use of the microphone, and by training certain muscles, to achieve notes in a much wider scope. The vocal coach and singer Brett Manning is one good example of this huge f0 range in popular singing[5]. Another famous example is Freddie Mercury who sang from F#2 (about 92.2 Hz) to G5 (about 784 Hz) [10]. Therefore, it is known by recent vocal pedagogy that male and female voices are very malleable in order to produce a great variety of voice qualities. Consider, for example, the distorted voice of Arch Enemy's singer Alissa White-Gluz[6], who can sing in a very low distorted register not expected by female singers.

2. Muscle activity in singing production

There are some studies that analyze the muscle activity in singing production. The EMG analysis by Hirano [11] has shown that the cricothyroid muscle (CT) stretches and elongates the vocal folds, works to control f0 production, and influences vocal registers significantly; thyroarytenoid (vocalis) (TA) adducts the vocal folds and is responsible for the control of f0, intensity, and register; the lateral cricoarytenoid muscle (LCA) adducts the vocal folds and is also responsible for the control of f0, intensity, and register; inter-arytenoid muscle (IA) adducts the vocal folds at their posterior portion; the posterior cricoarytenoid muscle (PCA) abducts the vocal folds. According to Hirano [11], it is usually inactive, but "contracts to some extent for high tones in heavy registers (pressed phonations) to brace the arytenoid cartilage against the anterior pull". Conversely, Choi et al. [12] reported that the stimulation of IA resulted in the increase of subglottal pressure, intensity and f0. This observation agrees with the findings of Coelho et al. [13] for extremely high notes. In another paper, Choi et al. [14] comment that the PCA works to control the glottal width. Also, Vennard and Hirano [15] showed that CT activity is greater for the head voice in

[1] We consider here C4 (262 Hz) as the middle C in a piano keyboard.

2 Distorted voices are defined here as sound sources that produce inharmonicity in the spectrum, such as the use of ventricular folds, aryepiglottic folds, and strain in the vocal folds [3].

3 https://www.youtube.com/watch?v=TAqZb52sgpU (at 1:05)

4 https://www.youtube.com/watch?v=2qqN4cEpPCw (at 0:54)

[5] See his performance in https://www.youtube.com/watch?v=Lx-BpQFbLrg

[6]Check the voice at 1:00.
https://www.youtube.com/watch?v=mjF1rmSV1dM

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comparison to the chest voice; TA (vocalis) activity follows the following pattern: chest voice > head voice > falsetto.

As the data in the literature suggest different muscle activities and/or vocal effort for specific groups of notes (see table 1), we decided to investigate whether the voice quality also changes according to the variation of low to high notes and from unaccented to accented notes.

Table 1: *Note range and the related muscular activity* [13]

Note Range	Hz (round)	Main (secondary) muscles
G#2-D#3	104-156	TA
E3-D#4	165-311	TA (CT)
E4-B4	330-494	CT (TA)

3. The definition of voice quality

Laver [16] describes the voice qualities in speech that are closely related to the use of voice in the contemporary styles of singing. He describes 15 different types of laryngeal settings[7] in voice production. There are four basic phonation types: 1-whisper, 2-creak, 3-modal voice, and 4-falsetto; and 11 compound types: 1-whispery creak, 2-whispery voice, 3-whispery falsetto, 4-creaky voice, 5-creaky falsetto, 6-whispery creak voice, 7-whispery creak falsetto, 8-breathy voice, 9-harsh voice, 10-harsh falsetto, and 11-harsh whispery voice.

Although Laver's description of phonation types is very useful for description of the voice qualities in speech, it is important to highlight that it is incomplete, since the phonation types are linked to certain areas of the voice range. Creak/Creaky voice is located at the extreme low range of the f0 range, modal voice in the middle, and falsetto at the top of the range. In singing, it is not necessarily like this, since we can produce a creaky voice in any note that we want, produce higher notes (above E4 = 330 Hz with a modal-voice-like quality), and also lower notes with a falsetto-like quality. In addition, there are other voice qualities possible in singing: 1-notes produced with the ventricular folds at 1/2 or 1/3 of f0 [10]; 2- ventricular folds to add distortion to speech (e.g. harsh voice); 3- use of aryepiglottic folds; 4- use of the vocal tract to create certain animal-like sounds[8].

As in our previous studies [17, 18, 19], voice production is understood here as stated by Laver [19], who defines voice quality as all the vocal characteristics that are related to speech, including laryngeal, supra-laryngeal, and muscular tension and voice dynamical features (see [18] for a review). In this paper we will only focus on the acoustic analysis of certain laryngeal and supra-laryngeal aspects of the voice qualities in singing, and not develop a full description of the voice quality as we did perceptually in Meireles and Cavalcante [17], and Meireles [18].

4. Methods

Two songs with an f0 range from C3 to Bb4 (131-466 Hz) were selected for analysis: Man in the Box (Layne Staley and Jerry Cantrell, Alice in Chains, Grunge style, henceforth MIB), and Como Nossos Pais (Belchior, performed by Elis Regina, MPB style, henceforth CNP). These two songs were sung by four professional male singers (two from Minas Gerais state and two from Espírito Santo state), and then the lyrics were read by the same subjects. As it was a song with short lyrics, all of the vocal notes in MIB were used in the analysis. For CNP, we selected seven stretches of the song for analysis. The notes (low range: 131-311 Hz, high range: 330-466 Hz) were divided in four types for both songs: "H" (high note), "Ha" (accented high note"), "L" (low note), and "La" (accented low note). At this stage we selected, based on the notes in the scores, the f0 floor and ceiling for the songs (100-500 Hz), and did not include the song parts with creaky voice that could cause wrong detection of f0 in VoiceSauce. By listening to the songs, we can perceive that the singers used different vocal strategies, which are reflected in the acoustics of their voice qualities.

The audios were recorded using a Shure Beta 58a microphone at a sampling rate of 96 kHz, converted to WAV (mono) in Praat [20], the notes were annotated as "H, L, Ha, or La" in Praat, and then the audio was down-sampled to 16 kHz in VoiceSauce. To avoid errors related to the recording methods, before calculating the acoustic measures, the audios were normalized to the maximum amplitude in the software Audacity. For the acoustic analysis we used the software VoiceSauce [21, 22] that automatically extracted thirteen parameters of short-term measures (H1*[9]: relative amplitude of the first harmonic; H1*H2*: difference in amplitude between the first and the second harmonic; H1*A3*: difference between the first harmonic amplitude and the amplitude of the peak harmonic in the F3 region; CPP: cepstral peak prominence; Energy: measure of voice intensity; HNR5, HNR15, HNR25, and HNR35: harmonics-to-noise ratios from 0-500 Hz, 0-1500 Hz, 0-2500 Hz, and 0-3500Hz; F1: peak frequency of the first formant; F2: peak frequency of the second formant; B1: bandwidth of F1; B2: bandwidth of F2). For f0 extraction we used VoiceSauce' Straight measure (strF0), and for formant extraction we used the Snack method [23]. The settings for calculating the formants and bandwidths were: window length of 25 ms, steps of 1 ms, LPC order of 12, and pre-emphasis of 0.98.

As the voice quality measurements in VoiceSauce are dependent on correct f0 values, we also checked whether they matched the expected values for the notes in the songs. We confirmed the measurements were robust by visualizing the boxplots and descriptive statistics of f0 and checking the notes on the score. The mean notes (in Hz) for the songs were as follows: MIB: L = 241; La = 243[10]; H = 387; Ha = 437; CNP: L = 244, La = 255, H = 339, Ha = 351.

The term "accent" in this paper refers to its use in music composition, in which it implies a greater emphasis on certain notes marked by the symbol ">". The music software Sibelius, for example, increases the note intensity by 50% in the accented notes (see figure 1).

Figure 1: *Example of accented (La, Ha) and unaccented notes (L,*

[6]https://www.phonetik.uni-muenchen.de/studium/skripten/languagedemos/Demos/laver.html

[7] In his course "Vocal drives: access memories", Prof. Ariel Coelho demonstrates many of these possibilities in contemporary singing. See https://www.hotmart.com/product/drives-vocais-memorias-de-acesso/V5564914P

[8] The asterisks mean that the spectral magnitudes were corrected to remove the influences of the vocal tract transfer function, resulting in a measure more related to the voice source.

[10] L and La in CNP is musically perceived as the same note, meaning this song had similar notes in the excerpts.

H) in the low (L) and high regions (H). The low region is represented by the C note (262 Hz) and the high note is represented by the E note (333 Hz).

Higher values of H1* are usually associated in the literature with breathy voice [24, 25], i.e., the presence of a certain air escape (breath) through the vocal folds during phonation (modal voice). In singing, due to the difficulty of holding the folds together for a more intense sound without breaking into the falsetto phonation, we hypothesize greater air escape in high notes, and, therefore higher values for high notes and accented notes.

According to Keating and colleagues [26], higher values of H1*H2* are associated with breathy and lax phonations [see also 24, 25, 27, 28, 29], and lower values with creaky and tense phonations. We hypothesize a decrease of this value from low to high notes due to the greater vocal tension in the latter, and a decrease of this value from the unaccented to the accented note for the same reason.

According to Gordon and Ladefoged [30], spectral tilt [H1*A3*] is "the degree to which intensity drops off as frequency increases" (p. 15) and "characteristically most steeply positive for creaky vowels and most steeply negative for breathy vowels" (p. 15). Many studies have associated this measure as a correlate for stress [31, 32], and according to Shue [21, p. 19], "words with more stress or emphasis will lead to tenser vocal folds which contain more high spectral frequency components during phonation". We hypothesize, therefore, a decrease of this measure from the low to the high notes, and from the unaccented to the accented notes.

According to Hillenbrand and colleagues [25, p. 772], "the idea behind the CPP measure is that a highly periodic signal should show a well defined harmonic structure and, consequently, a more prominent cepstral peak than a less periodic signal". Also, Shue [21] states that it "should be larger for modal phonations and smaller for breathy phonations", and "smaller for creaky voices if the phonation is aperiodic". Our hypothesis is then that CPP should be higher for the lower notes in comparison to the higher notes, and higher for the accented notes in comparison to the unaccented notes.

Energy, according to Shue [21, p. 61-62], may be correlated with vocal effort. So, as greater vocal effort is expected for the high notes and the accented notes, we hypothesize a greater value of this parameter for these notes in comparison to their lower and unaccented counterpart.

Yumoto and Gould [33] found that the HNR for a healthy group varied between 7.0 and 17.0 dB with a mean of 11.9 dB. They also considered values below 7.4 dB to be pathological. As HNR can be correlated to noise in the spectrum, we hypothesize higher values for the low notes in comparison to the high notes, and higher values for the unaccented notes in comparison to the accented notes.

F1 and F2 are correlated with vowel height and frontness. The higher the F1, the lower is the tongue position; and the higher the F2, the more anterior is the vowel. As a common strategy of singers for reaching vowels with high fundamental frequencies is to widen the vocal tract [see, for example, 1], we hypothesize higher F1s and F2 for high and accented notes.

Due to the increase of vocal fold tension, and a possible greater air escape, what may disturb the bandwidth measurements, we hypothesize greater bandwidths of B1 and B2 for high and accented notes.

The hypotheses of this study are summarized in Table 2.

Table 2: Sentences and measures used for the analysis of CNP. inc = increasing pattern, and dec = decreasing pattern.

Pattern	H1*	H1*H2*	H1*A3*	CPP	Energy	HNR	F1	F2	B1	B2
L-H, La-Ha	inc	dec	dec	dec	inc	dec	inc	inc	inc	inc
L-La, H-Ha	inc	dec	dec	inc	inc	dec	inc	inc	inc	inc

5. Results

All statistical analyses were run in RStudio (version 1.0.153). First we checked the histograms of the four different note types to observe whether they exhibit a normal distribution, and then ran a Shapiro test for statistical significance. The analyses were run at every 1 ms resulting in a large amount of data[11] (N[12]: **CNP**: Subject FES: L = 19380, La = 15107, H = 3739, Ha = 11593; Subject FMG: L = 12422, La = 14915, H = 3961, Ha = 8838; Subject MES: L = 16932, La = 13292, H = 4283, Ha = 10851; Subject MMG: L = 11516, La = 14692, H = 3098, Ha = 11939. **MIB**: Subject FES: L = 5199, La = 49661, H = 2736, Ha = 36896; Subject FMG: L = 4357, La = 45509, H = 2147, Ha = 39410; Subject MES: L = 5621, La = 40988, H = 5712, Ha = 21711; Subject MMG: L = 4041, La = 42546, H = 1737, Ha = 38231). As no data passed the normality test, we ran a Kruskal-Wallis test with the voice quality parameter (e.g. H1*) as a function of the note type (L, La, H, Ha), and then a Dunn's test for multiple comparisons with Bonferroni correction. Statistical significance was found for all parameters regarding the Kruskal-Wallis test. As the song performances were different between singers, we analyzed each subject individually based on boxplots and descriptive statistics and then tried to identify some general patterns as a function of the note types.

Table 3 shows the hypotheses were partly or strongly corroborated in the following conditions: i) L to H pattern: H1*H2*, H1*A3*, CPP, F1, F2, and B1; ii) unaccented to accented pattern: CPP, F2, B2. Also, the hypotheses were weakly corroborated for the following patterns: i) L to H: H1*, Energy, F2, B2; ii) unaccented to accented: H1*, H1*H2*, H1*A3*, Energy, F1, B1, B1.

Regarding HNR, after comparing the data between HNR5, HNR15, HNR25, and HNR35 we analyzed them together as HNR group. We also ran a Pearson correlation on the data that showed these measurements are strongly correlated among each other. The results greatly support our hypothesis of higher values for low notes and unaccented notes. With the exception of three non-statistical differences between L-H (FES, MIB), L-H (FMG, CNP), and La-Ha (MES, CNP) for the HNR5 parameter, 61 out 64 measurements had a downward pattern from the low note to the high note. For the pattern from L to La, we had in all cases a upward movement from the unaccented notes to the accented notes. For H to Ha, seven results out of 32 were according to our hypothesis. Four results were non-statistically significant: MES (MIB: HNR15, HNR25, HNR35), and MMG (MIB: HNR15).

[11] The data was unbalanced for two reasons: 1- the exclusion of notes with irregularities such as creaky voice in the spectrogram analysis in Praat; 2- the unbalanced proportion of high and low notes in the songs.

[12] N refers to sample size, the number of observations.

Table 3: Results compared to our hypotheses. Bold letters mean agreement with the hypothesis, and the signal "-", corresponds to non-significant results. The four measurements for each parameters corresponds to FES, FMG, MES, and MMG. (1) is CNP, and (2) is MIB.

Pattern	H1*	H1*H2*	H1*A3*	CPP	Energy	HNR	F1	F2	B1	B2
L-H (1)	ddd**i**	**dddd**	**dddd**	**dddd**	d**iii**	**dddd**	**iiii**	-**i**d**i**	d**iii**	d**i**dd
(2)	dddd	**dd**i**d**	**dddd**	**dddd**	ddd**i**	**dddd**	**iiii**	dd**i**d	**iii**d	dd**i**d
La-Ha (1)	dddd	i**ddd**	**d**i**dd**	**dd**i**d**	d**iii**	**dddd**	**iiii**	-d**i**d	dd**ii**	dddd
(2)	dddd	**d**ii**d**	**dddd**	**dddd**	d**ii**d	**dddd**	**iiii**	d**ii**d	**ii**d**i**	**i**d**ii**
L-La (1)	ddd**i**	ii**d**i	i**dd**i	**iiii**	-**ii**d	iiii	**iiii**	**ii**d**i**	**i**d**i**d	**i**ddd
(2)	**i**dd**i**	i**d**ii	**dd**ii	**iiii**	dddd	iiii	**i**d**ii**	-**ii**-	dd-**i**	d**ii**d
H-Ha (1)	**i**ddd	ii**d**i	**d**iii	**iiii**	**iii**d	iiii	**iiii**	**iii**-	**i**d**ii**	**i**d**ii**
(2)	dd--	**d**iii	**d**iii	**iii**d	d**ii**d	**dd**i**d**	**iiii**	**iiii**	**i**-d**i**	**ii**d**i**

^{o} = same minor differences found for HNR are explained in the text.

6. Discussion

Based on our findings and the acoustic data from the literature, and the descriptive statistics of this study, we suggest the voice qualities have changed as follows: as all three parameters (H1*, H1*H2*, H1*A3*) decreased from the low notes to the high notes (L to H, La to Ha) for all singers in both songs (CNP, MIB), we infer they used some sort of modal voice even in higher note registers. Although apparently controversial, Herbst et al. [34] demonstrated that a note such as D4 (294 Hz) above the primo passaggio of the tenor voice (between 196-293.66 Hz, [35]) can be produced as a chest-like (modal) voice. They explain this possibility by the actuation of the posterior glottal adduction muscle in addition to the TA muscle. In another study, Amarante [35] have also found a chest-like voice in the region above the primo passaggio (H, Ha in our study). He describes that this was possible by changing the TA muscle contraction from isotonic (no change in muscle length) to isometric (change in muscle length). For the relation between the accentuation of the notes (L to La, and H to Ha) and the expected voice register, it was not possible to make a good inference since there was a lot of variation in the parameters for all subjects. Therefore, we need further physiological experiments to find a specific pattern when analyzing the correlation of these parameters.

Heinrich et al. [36] in a study of classical singing found a positive correlation between intensity and glottal contact in chest voice and negative correlation between intensity and f0 in the "falsetto" (high) register. This may be valid for classical singing, since the singers are not allowed to break into the falsetto register, but it is more complex in contemporary singing. In addition, Shue [21, p. 61-62] show that voice intensity may be positively correlated to vocal effort. Our results have shown that this negative correlation between intensity and f0 was only true for subject FES, who has years of formal training in classical singing. The other subjects, on the contrary, basically increased intensity when moving from the low to the high notes (L to H, La to Ha) and from the unaccented to the accented notes (L to La, H to Ha).

For singing and emotional data, we cannot make the HNR assumption of Yumoto and Gould [33], since we are able to manipulate our voice to add distortions without being pathological. In our data, all subjects in the two songs showed decreases from the low notes to the high notes, suggesting addition of noise and/or creak in the signal. Nevertheless, from the unaccented to the accented notes, the opposing pattern occurred, suggesting a more modal-like phonation in accented syllables.

Dmitriev [37] has observed a stable larynx position in a two-octave range for classical singers, but with some gender variation. The larynx position was higher than the rest position for sopranos and lower for basses/baritones. In popular singing, it is known that this fixed larynx position is not used for singing, allowing a lot more freedom to sing, and to sound different from each other. Nevertheless, as in classical singing, there is usually an increase in the vocal tract dimensions to facilitate the access to higher voice registers (see, for example, [18] and [38]). Our F1 and F2 results support this claim for there was supposedly a more-open jaw position (higher F1) and a more-anterior articulation[13] (higher F2) when singing higher notes and when singing accented notes.

The weak corroboration of our hypothesis on the bandwidth of F1 and F2 may be related to the ultra stretching of the vocal folds, that can cause a rigid vibration movement, and, therefore explain the decrease of B1 and B2 in some high registers of speech. This explanation must nevertheless be checked with a proper physiological investigation of the vocal folds.

The next steps of this work will be twofold: i) run physiological and/or articulatory experiments to observe the glottal contact area and correlate with acoustic parameters of voice quality; ii) run perceptual experiments to observe whether the perception of trained voice scientists correlates with the inferences based on the audio signal.

7. Conclusions

Although preliminary, our acoustic results support the idea that the action of different muscles results in different voice quality configurations in contemporary singing. The main results have shown that thirteen voice quality parameters varied from low to high notes (L to H, La to Ha), and from unaccented to accented notes (L to La, H to Ha).

The next steps of research are to gather physiological and perceptual data to examine whether the related voice qualities for singing in two completely different music styles correlate to the data and findings here presented.

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