The singing voice: rediscovering a diamond with many facets

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Resumo
Um dos acontecimentos que mais significativamente contribuiu para a evolução da espécie humana resultou da aquisição de uma eficiente capacidade de comunicação. Esta culminou na criação de um instrumento musical único. É pois a singularidade da voz humana, como instrumento musical refletor de facetas multidisciplinares, que aqui se abordará. Serão discutidos resultados de estudos que realçam a verdadeira natureza interdisciplinar da voz, nomeadamente: (i) a importância e aplicabilidade da tecnologia no ensino do canto; (ii) aspetos aerodinâmicos e fisiológicos de avaliação e classificação vocal; (iii) aspetos bioquímicos que podem condicionar ou afetar o desempenho vocal artístico; (iv) o canto como elemento unificador e diferenciador de diferentes estilos e culturas musicais.

Palavras-chave: interdisciplinaridade da voz cantada, tecnologia, educação, física, química, biologia, cultura, arte.

Abstract
One of the most contributing events for human's evolution was the possibility for effective communication, which eventually has lead to the development of a unique musical instrument. The underlying complexity of the singing voice, reflected in its multidisciplinary nature, constitutes the focus of this presentation, shedding light into: (i) technology and singing education; (ii) aerodynamic and physiological aspects of voice evaluation and classification; (iii) biochemical aspects affecting vocal performance; and (iv) aspects of the singing voice in different musical and cultural backgrounds.

Keywords: interdisciplinary of the singing voice, technology, education, physics, chemistry, biology, culture, art.

1 Introduction

The survival of all animal species strongly depends on oral communication. Additionally, communication has a significant influence on human's quality of life as more than about 30% of the entire working population depends on a functional voice [1]. However, the singing voice has not yet received as much attention as it should in today's society; its value in the public understanding of education in science, arts and culture still remains under-estimated. Thus, it seems relevant to highlight the true interdisciplinary value of the singing voice, focusing on some recent studies, namely: (i) technology applied to the teaching of singing; (ii) aerodynamic and physiological aspects of voice evaluation and classification; (iii) biochemical features affecting vocal performance; and (iv) singing as a bond between different cultures.

2 The voice as a musical instrument: rediscovering multiple disciplines

2.1 Technology in the singing studio

The technological development occurred over the past 30 years transformed vocal pedagogy into an interdisciplinary model of artistic education. Currently, singing teachers use real-time feedback to display particular aspects of the student's voice. For example, William Vennard (1909-1971) was one of the first singing teachers acknowledging the importance of transporting sound from the aural to the visual realm by implementing acoustical analysis in the singing studio [2]. As the voice is a hidden instrument, "(...) a*nything that can assist the learning process in the provision of more robust, less ambiguous and easily understandable feedback to both teacher and student would seem to be worthwhile*" (in Welch et al., 2005: 227). Real-time feedback has been found to improve the singing teaching/learning process. As the student receives quantitative feedback during his/her vocal behaviour, subsequent responses are almost immediately influenced, leading to the completion of more learning cycles [3]. Real-time feedback also contributes to promote attention, interest and emotional expressivity in performance [4], further assisting the development of a musical identity [5]. Some useful examples of software which can be used in teaching and learning singing are: *WaveSurfer (*Kåre Sjölander and Jonas Beskow, KTH), *SpeechStudio* (Adrian Fourcin, Laryngograph®) and *Madde* (Svante Granqvist, KTH).

WaveSurfer is a free available software (http://www.speech.kth.se/wavesurfer/), which allows the display of both spectrograms and spectrums. Using a wide band spectrogram, both teacher and student can visualise formant frequency regions: the dark coloured horizontal lines (or simply black, for cases of black and white spectrograms) indicate the vicinity of a certain formant. These change according to vocal tract configurations. For example, a constriction in the front of the vocal tract (e.g. palatal moving of the tongue for the production of the vowel /i/) lowers the first formant (F1) and raises the second one (F2); a constriction in the back of the vocal tract (e.g. pharyngeal movement of the tongue for the production of the vowel /a/) raises F1 and lowers F2. Figure 1 displays a wide band spectrogram of different vowels, showing F1 and F2 regions in red and green, respectively.

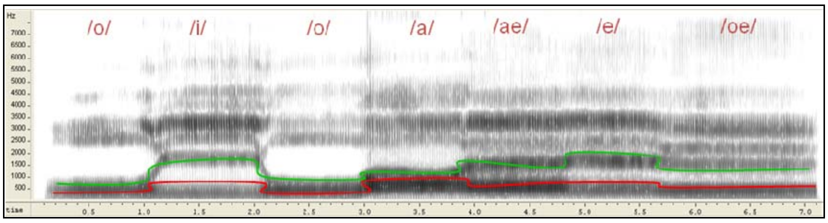

Figure 1 – Wide band spectrogram displaying formant frequency regions for different vowels. Red and green lines correspond to F1 and F2 for the different sung vowels, respectively. The horizontal axis displays time [6] and the vertical axis frequency [Hz].

Modifications of the vocal tract also have a direct impact on the singer's voice quality, as the voice is the only musical instrument in which articulation also affects resonance [7]. For example, lengthening of the vocal tract lowers uniformly all formant frequencies, whereas by shortening the vocal tract raises all frequencies uniformly. For example, by lowering the larynx and protruding the lips, one might achieve a 10% increase in vocal tract length [8], and by raising the larynx and spreading the lips one decreases it [7]. Classically trained singers master these resonance modification strategies. With increasing pitch, sopranos increase larynx height; as pitch continuous to rise, they further shorten the vocal tract by lowering the jaw. This is needed to avoid cases in which the fundamental frequency (F0) is higher than F1, as this situation would lead to vocal vibratory instabilities [9]. Male singers lower the larynx, and widen the pharyngeal wall, the laryngeal ventricle and the *sinus piriformes* to cluster F3, F4 and F5. This physiological effect is known as the *singer's formant cluster*. Acoustically, it allows a boost in the spectrum energy around 2500-3000Hz [9], precisely in the middle of the region where the human ear is most sensible (1KHz-4KHz) [8]. Figure 2 displays the wide band spectrum of the sung vowel /u/. The energy displayed in the region of about 2000Hz to 3600Hz is significantly decdreased when the singer does not apply the appropriated resonance strategy.

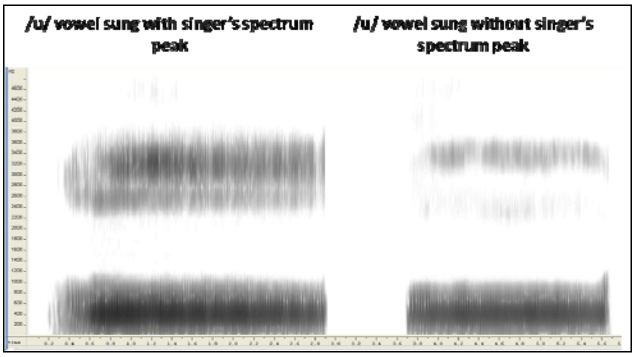

Figure 2 – Wide band spectrogram of a baritone singing a sustained /u/, applying (left) and not applying (right) the fine art of clustering F3, F4 and F5. The horizontal axis displays time [s] and the vertical axis frequency [Hz].

According to the source-filter theory of voice production [10], the spectrum of the resulting sound is the spectrum of the glottal source filtered by the vocal tract. Thus, phonation types can also be monitored through the analysis of wide band spectrograms. Depending on subglottal pressure (Psub), defined as "*the overpressure of air in the lungs*" (in Sundberg, 1987, pp. 16), and the strength of vocal adduction, the amplitude of F0 will be different (because the amplitude of the flow glottogram will be different). Thus, two extreme types of phonation can be produced: **pressed** and **breathy**. The first occurs when there is a combination between high Psub and high adductory forces in the larynx, resulting in low amplitude of F0; the second is originated with lower Psub combined with weak adduction; the result is a high amplitude of F0. In between these two extreme types of phonation, there is a continuous of possibilities of different levels of pressedness and breathiness. **Flow phonation** is one possibility. It is characterised by a lower Psub and a moderate adductory force. This type of phonation seems to be associated with more efficient voice: this combination of physiological parameters lead to an increase in acoustic output without increasing vocal effort [9]. Figure 3 illustrates these types of phonation. On the upper panel, a song is sung by a male pop singer, using both pressed and breathy phonation types (marked with number 1 and 2, respectively). The lower panel displays a wide band spectrogram of the same exact song, but now sung by a classically male trained singer. The singer uses mostly flow phonation, allowing the identification of the singer's formant cluster [9], a region of added acoustical energy between 2000Hz-3000Hz (number 3), and a clear .

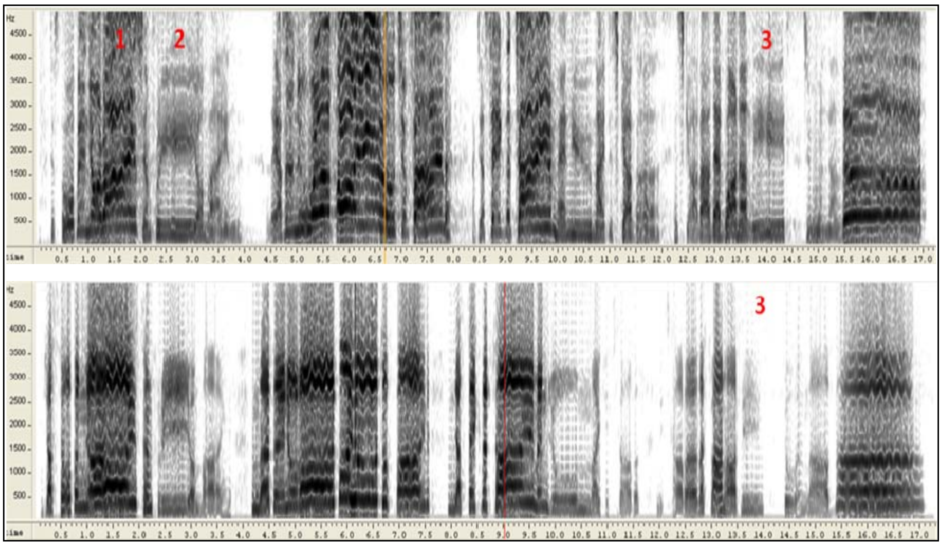

Figure 3 – Wide band spectrogram of the same song sung by two male singers in two different styles: pop (upper panel) and classical (lower panel). The horizontal axis displays time [s] and the vertical axis frequency [Hz].

A narrow band spectrogram displays particular voice events in time clearly as compared to wide band spectrogram displays: the well defined horizontal lines correspond to single harmonic partials which have been energized by vocal tract resonances. Thus, aspects such as voice onset and vibrato can be monitored. Voice onset much depends on the existence of synchronization between three main events: Psub, vocal fold adduction and vocal fold vibration. Thus, there are three possible onsets: (i) **coordinated (or staccato)**, when these three events are synchronised in time; (ii) **breathy (or aspirated)**, if the adduction and vibration of the vocal folds follow the increase of Psub; and (iii) **hard (or glottal)**, if adduction occurs first, followed by the vibration of the vocal folds caused by an increase in Psub [9]. For a breathy onset, non-harmonic components (i.e. noise) appear first than the harmonic components of the vowel; the hard vocal onset reveals a long time in the spectrum before the phonation quality stabilises; the coordinated onset presents all harmonic partials at same time, but their maximum intensity does not occur synchronised (see Figure 4). Voice onset has an impact on the quality of the sustained vowel: the coordinated version produces a more efficient sound, as observed by the created energy intensity of higher harmonic partials; the hard onset has been associated with long term development of vocal disorders, associated with the fast intensity rise-time created by an increased vocal fold impact force [11].

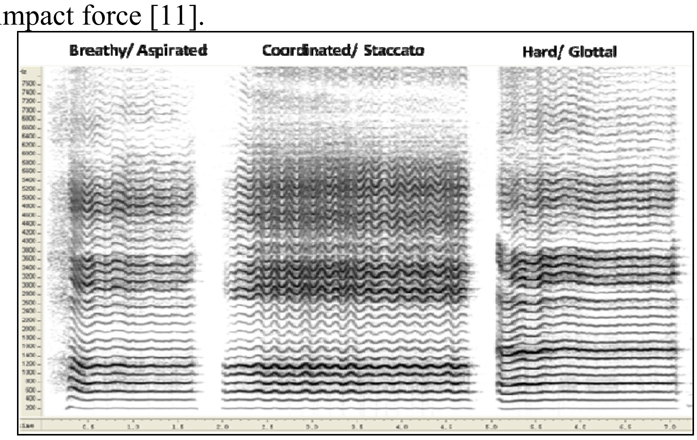

Figure 4 - Narrow band spectrograms displaying the three types of vocal onset for the sung vowel /a/. These examples correspond to the same pitch, produced by the same tenor. The horizontal axis displays time [s] and the vertical axis F0 distribution [Hz].

This type of display also allows the visualization of other important contributing factors to voice quality, namely vibrato. Depending on cultural aspects, vibrato can be quite different. In Western singing tradition, vibrato is the regular moderate modulation of F0 rate and extent, for which the perceived pitch corresponds to the mean F0 variation. Its regularity is associated with skilful singing in this style singing [9].

Intonation is another relevant aspect to the quality of singing, varying depending on the music genre. It involves the activation of a number of different mechanisms, which can be improved with training: (i) prephonatory tuning, to achieve the desired pitch (setting of pitch by setting the regulating muscles, i.e. laryngeal, oropharyngeal and respiratory muscles); (ii) auditory feedback, to monitor the produced pitch; and (iii) kinaesthetic feedback which, based on a "neuromuscular memory", leads to laryngeal adjustments [12, 13]. As for the acquisition of any singing skill, trial and error is the most common method to improve the student's ability to singing in tune [14]. *WaveSurfer* also allows the display of pitch track, so that a comparison can be made between the reference tone and the one produced by the student, or even between different attempts of the student. In Figure 5, the student's attempt (right example) is slightly below the reference tone provided by the singing teacher (left example). Other significant differences between teacher's and student's F0 patterns include the onset of the tone, which starts and finishes below the intended F0 for the student's case.

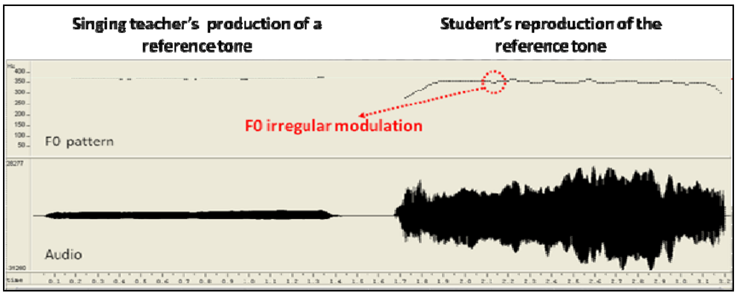

Figure 5 – Comparison of F0 pattern between a reference tone (sustain vowel /u/, sung on F#$_4$ - approximately 370 Hz) given by the singing teacher (left) and the student's attempt of reproduction of the same tone (right). The horizontal axis displays time [s] and the vertical axis F0 distribution [Hz].

SpeechStudio software allows the recording and display of four signals which reflect the most influencing physiological factors affecting voice source (or transglottal airflow), and thus the quality of the final singing output. These signals are: air flow, Psub, vocal fold oscillatory patterns and audio (see Figure 6). Other applications exist in this software allowing, for example, the display of wide and narrow band spectrograms.

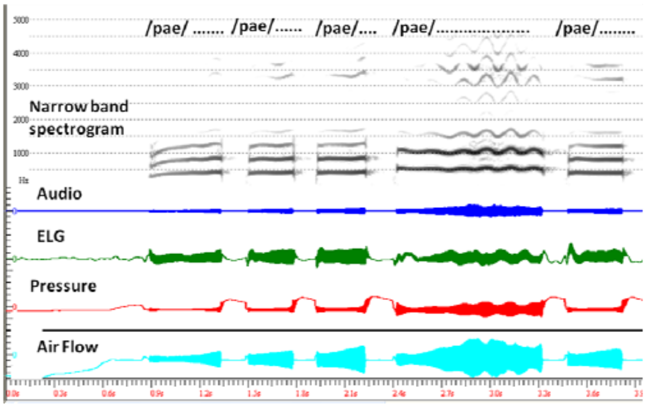

Figure 6 – *SeepchStudio* display of four simultaneously recorded channels during the performance of the first bars of the aria *"O mio babbino caro"*, from Gianni Schicchi, by G. Puccini, sung as the syllable /pae/: audio – dark blue, electrolgaryngograph (ELG) - green, pressure - red and air flow – light blue. The display is also showing a narrow band spectrogram of this excerpt of the aria.

The red peaks in the display correspond to intraoral pressure during the /p/ occlusion, constituting an estimate of Psub values. Psub plays an important role in voice pedagogy as it constitutes a direct way of controlling vocal loudness and thus dynamic changes. It also constitutes a parameter related to vocal efficiency, vocal health and fine intonation [15]. In voice pedagogy, Psub is also relevant for expressive purposes, e.g. phrasing. For an arpeggio sung in legato, phrasing is highly dependent on using the highest Psub not to sing the highest note, but the one immediately following (which has a slightly lower F0). Finally, the advantage of real-time display of four simultaneous channels dwells on the fact that the student can understand quicker what physiological parameters during the performance of a diminuendo on the same pitch. This is a difficult vocal task to accomplish, which has been associated with fine singing skills [16]: it is achieved by ceasing vocal fold collision whereas maintaining air flow and decreasing Psub (see Figure 7). Singers might perceive different acoustic pressures at different locations in the vocal tract [8]; thus, it is possible that, by visualizing these relations, the singer will be able to control these parameters quicker and in a more systematic way. Several kinds of learners have been identified, stressing the idiosyncratic nature of the teaching/learning process [2]. Those students who need to feel and to have a visual input associated with that feeling, would clearly benefit from this type of display.

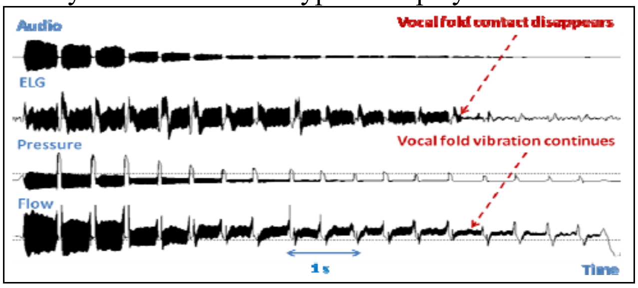

Figure 7 - SoundSwell work station software display of an E4 (≅329Hz) sung by a baritone as a diminuendo, using the syllable [pae]. It is demonstrated that soft phonation requires vibration of the vocal folds (as evidenced by the existing flow signal for soft notes) but not necessary vocal fold collision (as shown by the absence of ELG signal in softer notes).

In voice science *Madde* voice synthesiser has been applied to, for example, verify formant frequencies obtained from inverse filtering [17]. Its applications in singing pedagogy are endless. The synthesiser sound quality can be step by step transformed and approximated to the quality of a singer's voice, male, female or a child, by changing some of the available parameters at each time. Examples of such parameters are (see Figure 8): (1) F0 randomisation factor; (ii) vibrato, a common feature in adult singing, changeable in frequency and in extent; (iii) formant frequencies. By changing values of F1 to F6, a great impact on voice timbre and vowel modification can be heard; (iv) source spectrum tilt. When increasing it, vocal loudness is increased, being therefore physiologically related with changing Psub; (v) the amplitude of F0 in the source spectrum will significantly affect phonation type, and thus voice timbre.

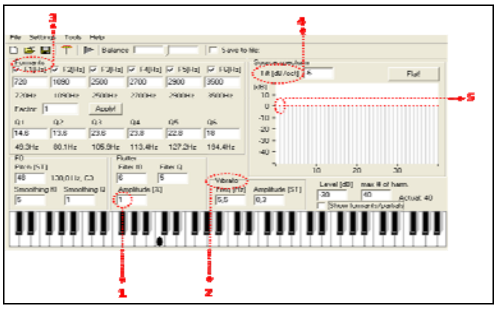

Figure 8 – Madde synthethizer (Svante Granqvist) showing the parameters that can be changed in order to approximate the sound to the voice of a singer. 1- F0 randomized factor; 2 – vibrato (changeable in rate and in amplitude); 3 - formant frequencies; 4 – Source spectrum tilt; 5 – amplitude of F0 in the source spectrum.

2.2 Aerodynamic aspects of voice evaluation and classification

The minimum Psub required to set the vocal folds into vibration (without necessary involving collision) - phonation threshold pressure (PTP) - has been reported to be related to physiological properties of the vocal folds and to acoustical features of the vocal tract. Vocal fold thickness and supraglottal vocal tract inertance decrease PTP, whereas vocal fold abduction, glottal convergence, supraglottal resistance, tissue viscosity and mucosal wave velocity are all contributing factors to raise PTP values [18]. For a given degree of vocal loudness, high mobility may be associated with less phonatory effort; thus, PTP comparisons may assist on the diagnose of some voice disturbances [19].

Although PTP applications in vocal health have been, to some extent, explored, its applications in singing are still unexplored. For example, previous studies have found significant differences in Psub related to female voice classification in Western classical singing tradition. Dramatic sopranos were found to possess significant higher Psub as compared to lyric sopranos (Sundberg, 2012 - Personal Communication). Thus, one might extrapolate that PTP will also be significant different between different soprano types. Voice classification constitutes a crucial element for the development of proficiency in classical singing [16]. However, several competing systems of voice classification exist, partially because voice classification is based on multifactorial analysis of perceptual evaluations, which may include subjective parameters (e.g. personality and voice timbre). Thus, although extremely relevant to healthy vocal development of a classical singer, it constitutes a rather complex phenomenon which singing teachers have to face; any contributing clarifying and objective evaluation would therefore constitute an important aid. In this section, the hypothesis that PTP can constitute a parameter for voice classification will be tested. This is an ongoing Master study by Sara Cláudio, at the University of Aveiro.

Method

Eleven sopranos (age range between 19 and 49 years old), with different levels of vocal proficiency (five final year students, two Master students at University of Aveiro, and four professional singers who are also teachers) were recorded using a hybrid system, i.e. a combination of a Digital Laryngograph Microprocessor and the Glottal Enterprises MS-110 computer interface. This equipment was used in order to allow simultaneous recordings of four signals: (1) audio and (2) electrolaryngograph signals, recorded by the Laryngograph device; and (3) oral pressure and (4) flow signals, recorded by the Glottal Enterprises unit. The latter was collected by means of a Rothenberg flow mask. Psub was determined as an estimate of intraoral pressure during /p/ occlusion, using a pressure transducer attached to a thin plastic tube inserted into the flow mask, such that its end was located inside the subject's lip opening at the corner of the mouth. The four signals were digitized and sent over a USB contact into a PC provided with the SpeechStudio software; thus, audio, ELG, Psub and airflow signals were obtained as separate tracks of wav computer files. Each signal was previously calibrated for each recording session. Singers were asked to perform two different vocal tasks: (i) sing the operatic aria "*O mio babbino caro*", from Gianni Schicchi, by G. Pucini, while listening to the respective piano accompaniment in one headphone; and (ii) perform six renderings of a set of repetitions of the syllable /pae/ sung as diminuendos at pitches D4 (≅ 293,7Hz), F4 (≅ 349,2Hz), Ab4 (≅ 415,3Hz), B4 (≅ 493,9Hz), D5 (≅587,3Hz), F5 (≅ 698,5Hz) and Ab5 (≅ 830,6Hz). When all recordings were made, a perceptual evaluation was undertaken with 19 singing teachers, in order to obtain a voice classification for each participant. The evaluators were asked to classify, along 100 mm long visual-analogue scales (VAS), the type of soprano, the extremes ranging from "Soubrette" to "Dramatic". In this way, quantitative estimates were obtained of how typical the example was with regard to voice subcategory.

Data Analysis

The listening test contained 22 stimuli (repeated stimuli for each of the 11 sopranos). The excerpt of the operatic aria "(...) *mi struggo e mi tormento o Dio, vorrei morrir* (...)", lasting approximately 19s, was presented in a blind randomised order to each evaluator, using the *Glue* option of SoundSwell work station programme. At the end, the listening code for stimuli order was broken, and consistency for each evaluator was verified using a Person's correlation test.

Long-term average spectrogram (LTAS) analysis of the aria was carried out, using a bandwidth of 300Hz, allowing calculations of the alpha ratio (α), i.e. the ratio between the energy below and above 1kHz. This ratio reflects the mean strengths of the higher as compared to the lower spectrum partials [20]. The equivalent sound level (Leq), in dB, was also calculated. It corresponds to the time average of sound energy in the audio signal [20]. In addition, the difference in mean LTAS level was determined over the filter bands surrounding mean F0 and those surrounding two times mean F0. This parameter, expressed in dB, was assumed to be related to the level difference between the first and the second voice source spectrum partials $(H1\text{-}H2)_{LTAS}$. This measure should thus vary with type of phonation [21].

The diminuendos sung using the syllable /pae/ provided data for PTP calculations. Figure 9 is an example of such calculation: for each rendering, PTP is calculated as the mean of the lowest pressure that caused vibration, as evidenced by the ELG signal, and the highest pressure that failed to produce vibration, as evidenced by the flow signal. At the end, the values obtained for the six renderings of the task were averaged for each of the seven pitches.

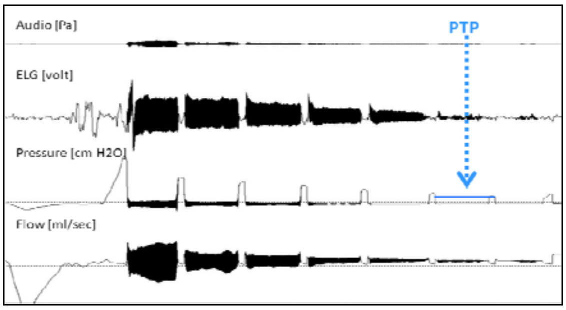

Figure 9 – SoundSwell work station software display of an E4 (≅329Hz) sung as a diminuendo of the /pae/ syllable by a baritone. The display shows four signals: audio, ELG, Psub measured as an estimate of intraoral pressure during the /p/ occlusion, and airflow. PTP is calculated as the mean between the lowest pressure that caused vocal fold vibration (evidenced by the ELG signal) and the first pressure that failed to cause vocal fold vibration (evidenced by the flow signal).

Results

The results of Pearson's Correlations revealed that only four evaluators failed to be consistent, thus being excluded from analysis. Figure 10 presents the results of the listening tests. A mean percentage rating of the 15 consistent evaluators is given for each soprano (11 in total).

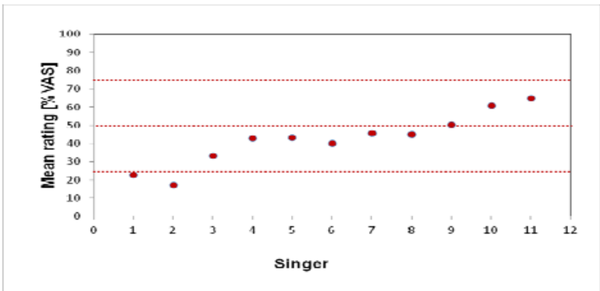

Figure 10 – Results of the listening test given as a mean percentage of VAS.

As it can be observed, data can be divided into percentiles: two singers fall below the first quartile, six are in between the first and second quartiles, five of which are rated closely to 50% VAS, and three are located between the second and the third quartiles (50% - 75%). No sopranos were rated above the 75th percentile. Thus, results suggest that the majority of sopranos were classified as towards more "Lyric/Soubrette" type of voices, whereas only three could fall into the category of more "Lyric/Dramatic" sopranos, considering that 50% is regarded as a "Lyric" sub-classification. Table 1 displays the results of perceptual evaluations (listening tests), acoustical (LTAS measures) and physiological (PTP) evaluations for all singers.

Table 1 – Summary results of perceptual, acoustical and physiological evaluations

Singer's Id	Perceptual evaluations	Acoustical evaluations			Physiological evaluation (PTP ratio of obtained values and those predicted from Titze's equation) and others						
	Mean VAS Ratings	Alpha Ratio	Leq	H1-H2(LTAS)	PTP D4 (293,7Hz)	PTP F4 (349,2Hz)	PTP Ab4 (415,3Hz)	PTP B4 (493,9Hz)	PTP D5 (587,3Hz)	PTP F5 (698,5Hz)	PTP Ab5 (830,6Hz)
1	22,9	-6,90	94,3	5,035	0,79	1,59	1,97	1,83	2,73	3,84	4,02
2	17,3	-2,95	93	2,777	0,79	0,94	1,16	1,62	1,73	1,01	1,95
3	33,2	-6,73	99,47	3,563	0,00	1,07	1,41	1,46	2,24	2,51	4,08
4	42,9	-10,09	94,57	6,74	1,70	1,60	1,91	2,11	2,26	2,70	2,66
5	43,4	-6,04	96,29	3,745	1,44	1,86	1,70	2,47	3,49	5,45	7,85
6	40,1	-5,56	100,4	1,984	1,30	1,57	1,46	1,08	0,82	1,33	1,34
7	45,8	-5,95	97,69	4,689	1,70	1,42	1,66	1,51	2,90	5,16	6,65
8	45,2	-7,47	96,37	5,398	1,32	1,62	1,93	2,49	3,33	3,28	4,60
9	50,5	-4,08	98,25	1,691	2,82	2,44	2,61	3,47	3,56	5,41	4,90
10	60,9	-9,34	99,9	5,13	1,62	1,84	2,15	3,14	3,86	4,81	5,62
11	64,9	-3,06	102,1	0,978	0,76	0,62	1,48	1,94	2,10	2,32	4,56

Running a multiple regression analysis, the results suggest that both Leq and PTP for B4 are highly correlated to perceptual voice classification (R^2 = 0,735 and R^2 = 0,495, respectively). Perception of voice classification can be predicted by a model constituted by these two parameters ($F_{(2)}$ = 13,045; p = 0,03; R^2 = 0,765). A prediction can also be made using only Leq, although the significance for this model with one single predictor is lower ($F_{(1)}$ = 10,54; p = 0,10; R^2 = 0,54).

Discussion

The model which provided a better prediction of voice classification was the one including PTP and Leq parameters, suggesting that both physiological and acoustical features can constitute a further valid aid to voice classification. These results corroborate previous studies indicating that size of both vocal folds and vocal tract accounts for voice classification [22, 23]. Nevertheless, it is important to mention the fact that PTP constituted a good predictor for soprano's voice classification only for B4. Possibly, there are important mucosal events in the vicinity of this F0 that should be revised.

It is important to mention that the model constituted by Leq analysis alone also provided a good prediction of perceived voice type, suggesting that, even with a simple recording (although carefully planned in terms of procedure and microphone selection [24]), Leq analysis can be assessable to all teachers, and thus be included in the parameters commonly used to evaluate the student's vocal classification.

2.3 Biochemical aspects affecting vocal performance

Professional voice users are more sensitive to questions related to voice quality and healthy voice than other professionals [25]. Bearing in mind that the efficacy of communication is reduced by all types of voice disorders, for those who have highly developed vocal skills, even minor vocal difficulties can be extremely distressful [26]. Previous studies have shown that 15% of vocal disorders are related to endocrine causes [27]. Hormones are biochemical mediators of the human body, executing the orders given by the neural central system in response to external stimuli [28]. From all organic systems which potentially might interfere with voice quality, there is evidence that the endocrine system is one of the most influential, making the voice a psyco-acoustic-biological phenomenon of hormonal influence. The following section provides a summary of such evidence, namely discussing the effects of hormones on the voice as a musical instrument. The voice of (i) Castrati; (ii) pubertal girls and boys; (iii) female singers during the menstrual cycle and when taking an oral combined contraceptive pill (OCP); and (iV) pregnant western classical singers constitute the focus of this section.

The voice of the Castrati

Historically, evidence that the voice could be an organ of hormonal influence goes back to the 16th century, when castration was also used to preserve a child's voice in an adult male body [29]. At this time, castration was done commonly to fulfil the requirements of having masculine voices singing high parts in polyphonic compositions [30]. The castrato voice was described as: "*clear and penetrating as that of choirboys, but a great deal louder with something dry and sour about it yet brilliant, light, full of impact*" (in De Brosses, C. (1799) Lettres historiques et critiques sur l'Italie. 3 vols. Paris: 3, 246). The castrati were extremely skilful singers, which made them very popular, and sing the majority of operatic roles of their time [30]. Their speaking voice would be very similar to the female's speaking voice [29]. These singular vocal characteristics can be explained as a consequence of a remaining paediatric laryngeal structure (due to the removal of testes before puberty), vibrating in a female register but supported by the breathing power and with resonating characteristics of a male body [30]. With frequent singing lessons, a voice with a similar range to the a soprano was achieved, but with a completely different timbre and power [29]. The last castrato of the Sistine Chapel (until 1902) was Alessandro Moreschi (1858-1922) and his voice can be heard in a recent CD album released by Mambran Music Ltd.

Pubertal voices

Due to the study of the castrato voice and after the invention of the laryngoscope by the singing teacher Manuel Garcia (1854), pubertal vocal changes could be better understood and described. Commonly associated vocal symptoms are: loss of vocal power, descending vocal pitch and loss of vocal control. The production of sex steroid hormones (i.e. oestrogens, progesterone and testosterone) leads to complex modifications in all components of the voice apparatus. In the majority of cases, girls start to undergo pubertal changes earlier than boys. The time during which vocal symptoms persist vary between 3 and 6 months. Vocal alterations associated with sexual maturation which last more than one year should be considered as pathological cases. Significant endocrinal imbalances or functional disorders during puberty might be the cause for these pathological cases, such as a persistent falsetto voice, an incomplete mutation or an abnormally low voice [31]. Vocal changes during puberty are a result of a rapid increase in the size of the larynx: there is a rapid and disproportional growth in the thyroid cartilage and vocal fold length [32]. Physically, there is an increase in breathing capacity as a consequence of an enlargement of chest and expansion of the abdominal wall. The lengthening of the neck allows the descent of the larynx, which is more significant for boys, and especially for deeper voices [33]. Following these transformations, the gender of a person can be detected by pitch and timbre, whereas before pubertal changes, the identification of genre through voice is quite difficult to perceive [34]. Pubertal changes are commonly more noticeable in boys than in girls because the production of testosterone is greater and more abrupt for boys than for girls. A pubertal girl might speak or sing with a husky voice timbre, whereas a boy may produce sudden register breaks [33].

The menstrual cycle, oral combined contraception pill and the singer's ability to perform

Evidence that cyclical variations in sex steroid hormones occurring during the menstrual cycle affect the singer's ability to perform has not always being acknowledged. In the 1950s, and later in 1980s, evidence that both cervical and vocal fold's mucosa had similar histological responses to sex steroid hormones was found [35]. However, the effects of these relation in the singer's performance was only taken into account after reports of well established singers mentioning vocal symptoms associated with specific phases of the menstrual cycle were made public. For example, Dame Joan Sutherland (1926-2010) said: "*I don't think there's ever a moment when you are not aware of the next performance. Everything affects the voice, just being at all tired. And let's face it, at certain times of the month for a woman, cloudiness, fuzziness, gets on the voice*" (interview with Joan Sutherland, Life Magazine, 1970). The existence of premenstrual and menstrual vocal symptoms in 42 opera singers in the National Opera House in Prague was also confirmed. During the above mentioned phases of the menstrual cycle, these singers commonly reported loss of high notes, and uncertainty of pitch. A laryngological examination performed on one of the above mentioned singers showed a vocal haemorrhage and a small zone of oedema [36]. Further studies corroborated these findings, explaining that possibly vocal symptoms associated with the menstrual cycle could also dwell on cyclical hormonal variations [37, 38]. Thus, a hypothesis emerged: dampening cyclical hormonal variations by taking an oral combined contraceptive pill (OCP), singers might avoid vocal symptoms associated with the menstrual cycle.

To test this hypothesis, a double blind randomised placebo controlled trial was undertaken. Both voice recordings and hormonal samples were collected at the three phases of the menstrual cycle (i.e. menstrual, follicular and luteal) for the third month of placebo/OCP intake, with 9 singers (8 sopranos and 1 mezzo-soprano). Voice recordings were undertaken using an electrolaryngograph, i.e. a portable device that allows the collection of large amounts of data concerning the pattern of vibration of the vocal folds in a non-invasive way [39]. Thus, the regularity of amplitude of vibration of the vocal folds (expressed as a percentage - CAx) was measured when participants were singing a Lied while listening to the respective piano accompaniment in one head phone. This particular parameter was chosen as it has been suggested that it relates to roughness, a symptom commonly reported by singers to be associated with the menstrual cycle. At the end of the recording, a blood test was taken to allow the collection of concentrations of sex steroid hormones. Details of this study can be found elsewhere, so here only a summary of the most important results will be provided [40].

Differences between placebo and OCP use concerning vocal irregularity were found, but only for menstrual and follicular phases of the cycle - OCP use seems to decrease vocal fold irregularity related to amplitude of vibration. These phases showed a significantly reduction of concentrations of free testosterone; thus, variations in concentrations of testosterone seem to be the major cause for vocal changes in female singers, corroborating the suggestions made by an earlier study [41].

Singing during pregnancy

Considering that during pregnancy significant hormonal variations occur and that the voice is an organ of hormonal influence, it seems plausible to hypothesise that the voice might suffer great modifications during this reproductive period of a singer's life. To test this, a longitudinal study was carried out, involving weekly recordings of a professional singer, during the last trimester of pregnancy (*Prae* condition), 48h after birth (*At* condition), and the consequent consecutive 11 weeks after birth (Post condition). Recordings were carried out using the same hybrid system as described previously. The singer was asked to: (i) perform a set of repetitions of the syllable /pae/, sung as diminuendos, at pitches A3, E4, B4 and F5; and (ii) sing the Lied "Widmung" (Myrthen, Op. 25/1) by R. Schumann, while listening to the respective piano accompaniment in one head phone.

Data analysis included both vocal and perceptual analysis. **Voice analysis** included: (i) Subglottal pressure (Psub); (ii) Collision Threshold Pressure (CTP), or the minimum required pressure to cause collision, measured as the mean between the last pressure that caused collision and the first that failed to cause collision, as evidenced by the ELG signal; (iii) Phonation Threshold Pressure (PTP); (iii) Normalized Amplitude Quotient (NAQ), i.e. the ratio between the peak amplitude of the flow glottogram and the product of MFDR and the period (T0); (iv) Alpha ratio (α); and (v) the LTAS dominance of the voice source fundamental $(H1\text{-}H2)_{LTAS}$, i.e. the level difference between the first and second partials of the LTAS spectrum, which provides an estimate of the dominance of the fundamental frequency. **Perceptual evaluations** involved a panel of expert singing evaluators who, in a visual analogue scale (VAS), were asked to point out degree of vocal fatigue and vocal brightness for the last 10 bars of the Lied, at different phases of the study. Vocal fatigue and brightness were the chosen parameters because these were perceived by the singer as being modified with pregnancy. Detailed information on the study's method is available elsewhere [42].

The results showed that CTP and PTP were high during pregnancy and considerably lower at and after birth, thus suggesting that vocal fold motility is reduced during pregnancy, for pitches A3 ($\cong$ 220Hz) and E4 ($\cong$ 330Hz). NAQ was low during pregnancy and high after birth, α decreased during pregnancy and $(H1\text{-}H2)_{LTAS}$ decreased during pregnancy and increased after birth. These results might constitute evidence for an increased glottal adduction during pregnancy. Finally, there was a perceived decrease in brightness during pregnancy, which increased after birth; the effects on this singer's voice may be audible. All reported effects can be assumed to be related to an increase in water retention and tissue viscosity in the vocal folds' mucosa during pregnancy.

2.4 Particular aspects of singing in different musical and cultural backgrounds

The following section constitutes a first attempt to compare the singing voice in two complete different socio-cultural settings: one is the *Fado/Canção* from Coimbra, and the other the Croatia Traditional Folk Singing, *Klapa*. Although one might think that these styles cannot be compared, they share an important communality which may influence the physiological and acoustical aspects of voice production: both have their roots in traditional singing.

Like other urban rooted singing styles (e.g. Samba from Brasil, Tango from Argentina, Rebetika from Athens, *Chanson Realiste* in Paris*),* *Fado* appeared in the middle of 19th century, in economically deprived and socially marginalised neighbourhoods of the florescent industrial city of Lisbon [43]. Thus, *Fado* music was strongly influenced by a wide variety of oral inherited music, brought from the interior part of Portugal and from abroad. Living in a completely new and broader socio-cultural environment, these population found a need of identity and expression [43]. The *Fado/Canção* from Coimbra, although originated from *Fado* brought from Lisbon by students, has some singularities: it is sung outdoors only, and by male singers, with the guitars tuned one tone lower than the ones accompanying *Fado* from Lisbon. Also, its character is more romantic and erudite as compared to *Fado* from Lisbon. These particularities might be related to the intensive monastic and university cultural influences (the latter since the 13th century), and also to the fact that the city was (and still is) a meeting point for students coming from different interior parts of Portugal (geographically Coimbra is not in the coast). They naturally bring their own inherited musical cultures, making *Fado/Canção* from Coimbra a style of singing which results from a sum of a variety of traditional singing styles [43]. Nowadays, *Fado/Canção* from Coimbra evolved towards ballads and serenades describing the love and life of students, the lyrics concerning love and longing for the years of student's life. On the other hand, the subtype of Croatian Traditional Singing Style here presented, *Klapa* (meaning group of friends), originated in Dalmatia, a Mediterranean part of Croatia, also in the 19th century. It is typically performed *a cappella*, by both females and males. It uses a Western European musical scale and the lyrics concern generally love, so that it is usually performed soft and slow, resembling a serenade like love songs [44]. From historical and socio-cultural perspectives, one might argue that both *Fado/Canção* from Coimbra and *Klapa* share some communalities: nursed by singing tradition roots of the 19th century, describing love and friendship, in a serenade type of singing, sung outdoors.

Could these common links be reflected to some extent in the way the voice is being used? To shed some light on this question, a comparison was made between two *Fado/Canção* singers in Coimbra and two male *Klapa* singers. In the following section, a short description of this case study is presented. This constitutes a preliminary study, which is being further developed in collaboration with Bojan Pogrmilović and Johan Sundberg.

Method

Two singers of Fado/Canção from Coimbra and two Croatian Folk singers acquainted with the Klapa substyle of singing were recorded; the first two singers were recorded in a rehearsal room in Tuna Academica in Coimbra, Portugal, whereas the others were recorded in a rehearsal room of a traditional singing group in Zagreb, Croatia. The singers were asked to perform a representative song of each style, meaning a song commonly performed in the musical activities in which they are involved as singers. For the *Fado/Canção* from Coimbra, the song "*Oh Coimbra do Mondego*" (Mário Faria Fonseca and Edmundo Bettencourt) was chosen by both singers, whereas both *Klapa* singers chosen "*Polegala Trava Detela*" (Hr. Zagorje).

The same recording equipment as described previously (i.e. a hybrid system) was used. Data analysis consisted of both acoustical and voice source analysis: LTAS analysis of the audio signal and inverse filtering of the flow signal, respectively. The acoustical analyses included measures of: (i) Equivalent Sound Level (Leq), a measure of vocal intensity obtained by a logarithm of sound energy averaged over time [45]. Leq was normalized with respect to the level of the highest peak in the LTAS; (ii) Long-term Average Spectrum (LTAS), reflecting voice quality in terms of contributions of glottal source combined with vocal tract resonances [45]; (iii) alpha ratio (α) [46]; and (iv) estimate of F0 dominance from the LTAS curve $(H1\text{-}H2)_{LTAS}$. It corresponds to the difference between the mean LTAS level in the F0 range as well as one octave higher, since the fundamental and the second partial must have determined these mean levels [47]. The voice source analyses were carried out using the custom made *Decap* software (Svante Granqvist, KTH) for one singer in each of the two contrasting styles. A detailed description of this method can be found elsewhere [17]. Summarizing, it allows calculations of voice source parameters by analyzing the results of the inverse filter by the custom made software SNAQ (Svante Granqvist, KTH). The voice parameters analysed were: (i) maximum flow declination rate (MFDR), i.e. the negative peak amplitude of the differentiated flow glottogram; (ii) normalized amplitude quotient (NAQ); (iii) level difference between the first and second partials of the source spectrum *H1-H2;* and (iv) closed quotient (Qclosed), i.e. the ratio between the time duration of the closed phase and T0. These four last measures provide an estimation of phonation type [47].

Results

Figure 11 displays the results of the LTAS comparison between singers. The LTAS slope for *Fado/Canção* de Coimbra is steeper as compared to *Klapa* singing for the region above 1000Hz. This difference is confirmed by α, which is clearly lower for *Fado/Canção* from Coimbra (α_{Mean}= - 7,14) than for *Klapa* (α_{Mean}= - 1,52). This result suggests that for *Klapa*, the higher partials are much stronger, probably reflecting a stronger glottal adduction and a higher Psub. With respect to the lower portion of the spectrum, it seems that for both styles, the second harmonic is on average always dominant in relation for the first one: $H1\text{-}H2_{(LTAS)}$ = - 0,8 DB and $H1\text{-}H2_{(LTAS)}$ = - 5,5 dB for *Fado/Canção* from Coimbra and for *Klapa,* respectively. Nevertheless, it seems that dominance of the fundamental is more pronounced in the case of the *Fado/Canção* from Coimbra. Finally, both songs have similar equivalent sound levels (*Fado*/*Canção* from Coimbra Leq = 91,69 dB; *Klapa* Leq = 91,94 dB).

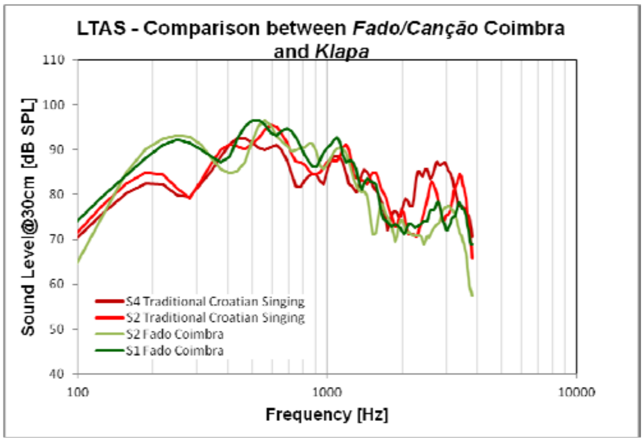

Figure 11 – LTAS comparison of *Fado/Canção* Coimbra and *Klapa* singing

Figure 12 displays a summary of the voice source parameters extracted from the results of inverse filtering different sustained vowels within each song, at similar F0, for two singers (S1 in *Fado/Canção* from Coimbra and S2 in *Klapa*).

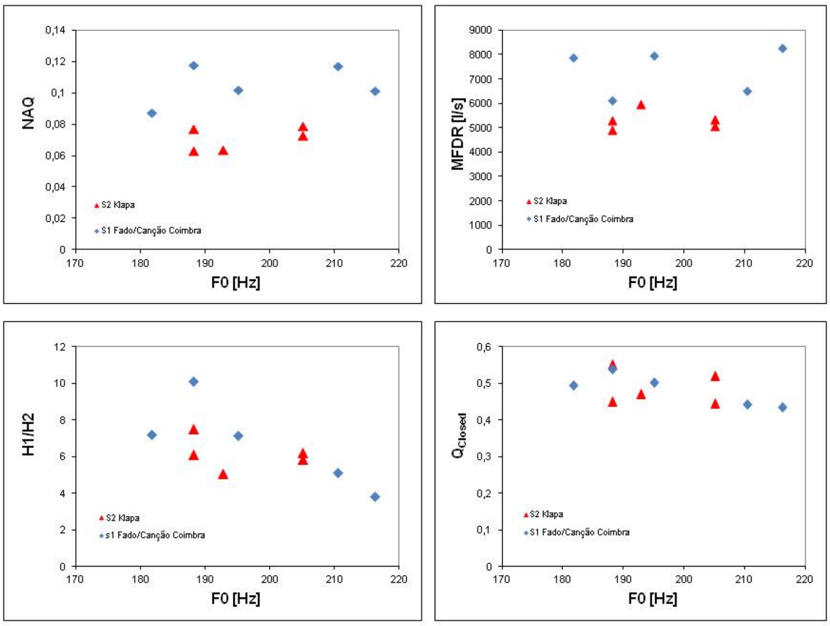

Figure 12 – Summary results of voice source parameters for two singers: *Fado/Canção* from Coimbra (blue) and *Klapa* (red).

The higher values of MFDR for *Fado/Canção* from Coimbra suggest that, for this style of singing, the vocal folds arrest the transglottal airflow more quickly than for *Klapa* style. As MFDR reflects vocal intensity in a form that it is unaffected by formants (as opposed to SPL, and thus Leq), it can provide reliable information on glottal characteristics [48]. Higher values of MFDR reflect a higher vocal tract excitation by the voice source, as the glottis closes faster. This phenomenon can be regarded as a sign of vocal efficiency [49]. NAQ values were also higher for the *Fado/Canção* from Coimbra. As this parameter inversely related to perceived level of pressedness, it seems that *Fado/Canção* from Coimbra can be perceived as less pressed than *Klapa* [49]. Similar values were found for both styles concerning H1/H2 and $Q_{Closed.}$

Returning to the earlier posed question, this preliminary study suggests that the most significant difference between these two styles concerns voice source efficiency. To some extent, the results suggest that, although both styles have similar Leq, it seems that for *Fado/Canção* from Coimbra there is a more efficient voice source use, with a quicker closure of the glottis. It would be interesting to assess whether similar results would be found when comparing other urban styles with other traditional singing styles. Possibly, urban styles evolved to a more efficient use of the voice over the past centuries.

3 Conclusion

The understanding of voice as a musical instrument relies on several areas of science, such as physics (particularly biophysics, aerodynamics, mechanics and acoustics), mathematics, biology and chemistry, as well as on sociology, on arts and on cultural studies. The human voice offers the possibility of both semantic and emotional communication, being therefore relevant to disciplines such as education, psychology, cognition, linguistics, phonetics and music. Like a diamond, reflecting light into many beautiful colours, the singing voice reflects a true interdisciplinary complexity by embracing multiple scientific, artistic and socio-cultural disciplines (see Figure 13).

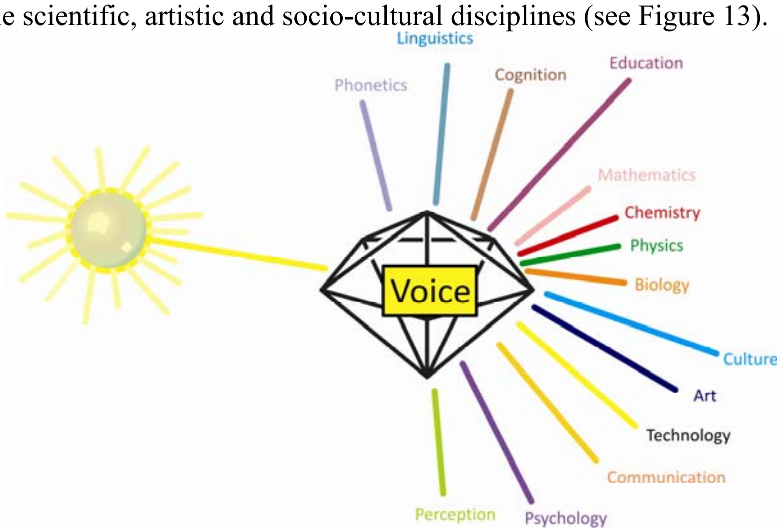

Figure 13 – Schematic representation of the interdisciplinary nature of the singing voice.

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4 References

[1] Titze, I.R., E.J. Hunter, and J.G. Švec, *Voicing and silence periods in daily and weekly vocalizations of teachers*. Journal of the Acoustical Society of America, 2007. **121**(1469-478).

[2] McCoy, S., *Your Voice: An Inside View - Multimedia Voice Science and Pedagogy*. 2004, Princeton: Inside View Press.

[3] Howard, D.M., et al., *WinSingad: a real-time display for the singing studio.* Logopedics Phoniatrics Vocology, 2004. **29**(3): p. 135-144.

[4] Juslin, P.N., et al., *Feedback learning of musical expressivity*, in *Musical excellence*, A. Williamon, Editor. 2004, Oxford University Press: Oxford. p. 247-270.

[5] Hargreaves, D.J., D. Miell, and R.A.R. MacDonald, *What are musical identities and why are they important?* , in *Musical Identities*, R. A. R. MacDonald, D. Hargreaves, and D. Miell, Editors. 2002, Oxford University Press: Oxford. p. 1-20.

[6] Abitbol, J., *Normal voice maturation: hormones and age*, in *The Performer's Voice*, M.S. Benninger and T. Murry, Editors. 2006, Plural Publishing, Inc.: San Diego. p. 33-50.

[7] Lindblom, B. and J. Sundberg, *The Human Voice in Speech and Singing,*, in *Springer Handbook of Acoustics*, T.D. Rossing, Editor. 2007, Springer: Stanford. p. 669-712.

[8] Titze, I.R., *Principles of Voice Production*. 2000, Iowa: National Center for Voice and Speech.

[9] Sundberg, J., *The science of the singing voice*. 1987, Northern Illinois University Press: Illinois.

[10] Fant, G., *Acoustic Theory of Speech Production*. 1960, The Hague, Netherlands: Mouton & Co.

[11] Shrivastav, R. and J. Wingate, *Perceptual attributes and assessment of the singer's voice*, in *The Singer's Voice*, M.S. Benninger and T. Murry, Editors. 2008, Plural Publishing Inc.: San Diego, California. p. 65-77.

[12] Larson, C.R., et al., *A proposal for the study of voice F0 control using the pitch shifting technique*, in *Vocal fold physiology: voice quality control*, O. Fujimura and M. Hirano, Editors. 1995, Singular: San Diego. p. 321-331.

[13] Mürbe, D., et al., *Effects of a professional solo singer education on auditory and kinesthetic feedback - a longitudinal study of singers' pitch contro.* Speech, Music and Hearing, Quarterly Progress and Status Report,, 2002. **43**: p. 81-87.

[14] Welch, G.F., D.M. Howard, and C. Rush, *Real-time Visual Feedback in the Development of Vocal Pitch Accuracy in Singing.* Psychology of Music, 1989. **17**(2): p. 146.157.

[15] Scherer, R.C., *Laryngeal Function During Phonation*, in *Vocal Health and Pedagogy: science and assessment*, R.T. Sataloff, Editor. 2006, Plural Publishing, Inc.: San Diego. p. 85-102.

[16] Miller, R., *Training Soprano Voices*. 2000, New York: Oxford University Press.

[17] Sundberg, J., F.M.B. Lã, and B.P. Gill, *Professional male singers' formant strategies for the vowel a.* Logopedics Phoniatrics Vocology, 2011. **36**(4): p. 156-167.

[18] Titze, I.R., *Phonation Threshold Pressure Measurement With a Semi-Occluded Vocal Tract.* . Journal of Speech, Language and Hearing Research, 2009. **53**: p. 1062-1072.

[19] Enflo, L. and J. Sundberg, *Vocal fold collision threshold pressure: an alternative to phonation threshold pressure?* Logopedics Phoniatrics Vocology, 2009. **34**: p. 210-217.

[20] Sundberg, J. and M. Nordenberg, *Effects of vocal loudness variation on spectrum balance as reflected by the alpha measure of long-term-average spectra of speech.* Journal of the aoustical Society of America, 2006. **120**(1): p. 453–457.

[21] Klatt, D.H. and L.C. Klatt, *Analysis, synthesis, and perception of voice quality variations among females and male talkers.* . Journal of the Acoustical Society of America, 1990. **8**: p. 820-857.

[22] Roers, F., D. Mürbe, and J. Sundberg, *Voice classification and vocal tract of singers: A study of x-ray images and morphology.* Journal of the Acoustical Society of America, 2009. **125** (1): p. 503 - 512.

[23] Roers, F., D. Mürbe, and J. Sundberg, *Predicted Singers'Vocal Fold Lengths and Voice Classification-A Study of X-Ray Morphological Measures.* Journal of Voice, 2009. **23**(4): p. 408-413.

[24] Svec, J. and S. Granqvist, *Guidelines for Selecting Microphones for Human Voice Production Research.* American Journal of Speech-Pathology, 2010. **19**: p. 356-368.

[25] Linville, S.E., *Vocal Aging*. 2001, San Diego: Singular Thomson Learning.

[26] Mathieson, L., *Greene and Mathieson's The Voice and Its Disorders*. 6th Ed ed. 2001, London: Whurr Publishers Ltd.

[27] Brodnitz, F.S., *Hormones and the human voice.* Bulletin of the New York Academy of Medicine, 1971. **47**: p. 183-191.

[28] Abitbol, J. and P. Abitbol, *Endocrine disorders of the larynx.*, in *Diseases of the Larynx.*, A. Ferlito, Editor. 2000, ARNOLD: London. p. 311-333.

[29] Jenkins, J.S., *The voice of the castrato.* Lancet, 1998(351): p. 1877-1880.

[30] Abitbol, J., P. Abitbol, and B. Abitbol, *Sex hormones and the female voice.* Journal of Voice,, 1999. **13**(424-446).

[31] Weiss, D.A., *Pubertal change of the human voice.* Pholia Phoniatrica, 1950. **2**: p. 126-159.

[32] Titze, I.R., *Critical periods of vocal change: puberty.* . The National Association Teachers of Singing Journal, 1993. **49**: p. 24.

[33] Cooksey, J.M. and G.F. Welch, *Adolescence, singing development and national curricula design.* British Journal of Music Education, 1998. **15**: p. 99-119.

[34] Welch, G.F. and D.M. Howard, *Gendered Voice in the Cathedral Choir.* Psychology of Music, 2002. **30**: p. 102-120.

[35] Abitbol, J., et al., *Does a hormonal vocal cord cycle exist in women? Study of vocal premenstrual syndrome in voice performers by videoscopy-glottography and citology on 38 women.* Journal of Voice, 1989. **3**: p. 157-162.

[36] Brodnitz, F.S., *Hormones and the human voice.* Bulletin of the New York Academy of Medicine, 1971. **47**(183-191).

[37] Amir, O. and L. Kishon-Rabin, *Association between birth control pills and voice quality.* Laryngoscope, (2004). **114**: p. 1021-1026.

[38] Lã, F. and J.W. Davidon, *Investigating the Relationship between Sexual Hormones and Female Western Classical Singing.* Journal of Research Studies in Music Education, 2005. **24**: p. 75-87.

[39] Fourcin, A., et al., *Laryngograph: speech pattern element tools for therapy, training and assessment.* European Journal of Disorders of Communication, 1995. **30**: p. 101-115.

[40] Lã, F., et al., *The effects of a third generation combined oral contraceptive pill on the classical singing voice.* . Journal of Voice. , 2007. **21** (6): p. 754-761.

[41] Isenberg, H., W.S. Brown, and H.B. Rothman, *Effects of menstruation on the singing voice; Part II: Further developments in research.*, in *Transcriptions of the twelfth symposium for the care of the professional voice. Part I.*, V. Laurence, Editor. 1983), The Voice Foundation: New York. p. 117-123.

[42] Lã, F.M.B. and J. Sundberg, *Pregnancy and the Singing Voice: Reports From a Case Study.* Journal of Voice, 2012. **26**(4).

[43] Carvalho, J.P.R., *História do Fado*. 2nd ed. 1984, Lisbon: Publicações D. Quixote.

[44] Boersma, P. and G. Kovacic, *Spectral characteristics of three styles of Croatian folk singing.* Journal of the Acoustical Society of America, 2006. **119** (3): p. 1805–1816.

[45] Nordenberg, M. and J. Sundberg, *Effect on LTAS of vocal loudness variation.* Logopedics Phoniatrics Vocology, 2004. **29**(4): p. 183-191.

[46] Sundberg, J. and M. Nordenberg, *Effects of vocal loudness variation on spectrum balance as reflected by the alpha measure of long-term-average spectra of speech.* Journal of the Acoustical Society of America, 2006. **120**(1): p. 453-457.

[47] Sundberg, J., E. Fahlstedt, and A. Morell, *Effects on the glottal voice source of vocal loudness variation in untrained female and male voices.* The Journal of the Acoustical Society of America, 2005. **117**(2): p. 879-885.

[48] Bjorkner, E., 2008. **22**(5): p. 533-540.

[49] Sundberg, J., M. Thalén, and L. Popeil, *Substyles of Belting: Phonatory and Resonatory Characteristics.* Journal of Voice, 2012. **26**(1): p. 44-50.