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Adapting the Voice Range Profile for Singers to Include Duration of Voicing

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INTRODUCTION

The Voice Range Profile (VRP) has long been recognized as a clinical voice assessment tool. It provides an overview of the physiologic range of vocal intensity (measured in dB SPL at a specified distance from the mouth) as a function of fundamental frequency range.[1] The VRP was recommended early as a voice classification tool for singers.[2] For general clinical applications, Gramming offered a study of male-female differences of the VRP, as well as differences with respect to the vowel used.[3] Pabon and Plomp added some voice quality parameters.[4] Titze offered an acoustic interpretation of the VRP in terms of energy distribution across harmonics at high and low f_o.[5]

Recent studies have brought the VRP to the forefront again for professional and amateur vocal performers. Normative voice range profiles of male and female professional voice users (teachers) were reported by Heylen et al.[6] Lamarche et al. have included some additional variables, including the voice area above a dynamic threshold level and the dynamic range independent of fundamental frequency, as well as the singer's own perception of vocal challenges.[7] Pabon et al. added a Fourier descriptor analysis and a unification approach to VRPs.[8] Herbst et al. addressed the quantitative voice class assessment of amateur choir singers.[9] The VRP continues to be a standard tool in voice clinics to assess vocal capability in trained and untrained speakers.[10]

Recent investigations on vocal dosimetry in school teachers have shown that duration of voicing is a key variable in the establishment of a damage risk criterion for overexposure to vibration from vocalization, along with fundamental frequency and vocal intensity. For equal-energy-dissipation in vibrating tissues, a 10 dB reduction in vocal intensity allows a doubling of voicing duration.[11] Duration of voicing and voice intensity appear to be inversely related if voice preservation is a concern.[12] This goes along with the inverse relation between maximum voluntary muscle force and maximum duration of muscle contraction.[13] Many singers struggle with the combination of high, loud, and long notes in a song, or an entire performance of songs. This is especially the case if a singer is not electronically amplified.[14] For practical applications, Schloneger, Schloneger, et al., and Patinka et al. are using combination measures for assessment of singing ability in the school systems.[15]

Tessitura, an Italian descriptor of where a song lies in mean pitch and timbral texture, has been quantified acoustically in conjunction with the VRP.[16] In Titze's study, the tenor aria "Il mio tesoro intanto" from Mozart's opera *Don Giovanni* was analyzed with a series of histograms of the notes sung. First, the number of occurrences of each note (D_3 to A_4) was quantified, followed by the equivalent number of full note durations represented by each note in the piece, followed by the number of cycles of vocal fold vibration that occurred on each note. This approach built on the early introduction of a *tessiturogram* by Thurmer, who documented the frequency of note occurrence within each composition or piece.[17] In Titze's approach, the three histograms were compared, note by note, to the VRP of the singer. The combination of the histograms and the VRP was called a *tessituragram*, a one letter name change to distinguish it from the Thurmer graphic. An example was given from a trained amateur tenor who was capable of singing the Mozart aria. The analysis showed, however, that the singer (a 74 year old bari-tenor) had a limited dynamic range in the region where most of the vocalization took place. In other words, the tessitura of the song did not match the tessitura of the singer. The analysis would have been even more revealing if note duration had also been available on the VRP. To our knowledge, however, duration has not been routinely used as a third variable in the VRP. Voice quality has been more prevalent.

The purpose of the current investigation was to quantify the duration with which a vocalist can comfortably produce both soft and loud notes along the entire f_o range. In the traditional VRP acquisition, subjects produce the loudest and the softest intensities possible for each pitch, with a duration of voicing long enough to capture the signal for accurate analysis of f_o and SPL. The process often begins in the middle of the pitch range and descends until the lowest pitch possible is found. This process is then repeated for ascending pitches until the highest pitch possible is found. In most reports, no deliberate effort is made to sustain phonation for any specific amount of time. In the current investigation, maximum comfortable duration is the target, which the singer determines on the basis of avoidance of injury or note insecurity.

METHODS

Subjects

Twelve males, 14 females, and one male-to-female transgendered subject participated in this study (27 total) as part of a classroom assignment in one of two graduate level courses, Principles of Voice Production and Voice for Performers. The first class was taught at both the University of Iowa (Fall 2015) and the University of Utah (Summer 2016), while the second course was taught only at the University of Utah (Summer 2016). The first author was an instructor in both courses. He also participated as a subject in order to relate this study to a previous pilot study on *tessitura* in which he was the only participant.[18] The second author was an instructor in the second course. Subjects ranged in age from 25 to 45 (with one exception, the classroom teacher, age 74) and all but one self-reported as having normal, healthy speaking voices and having had at least four years of formal singing training. One female subject (F14) self-reported a history of vocal tremor, for which she had sought and received treatment.

Equipment and Environment

Recordings were made in two locations. Seven subjects were recorded in the official voice therapy room at the Department of Communication Sciences and Disorders at the University of Iowa, while an additional 20 subjects were recorded in the research therapy room at the National Center for Voice and Speech at the University of Utah. Both rooms had minimal sound reduction measures, but this was not considered an issue because the focus of the study was not on exact SPL measures or acoustic spectra, but rather on the duration of voicing. A noise floor at or below 45 dBC was noted for each recording in each room, ensuring that the lowest intensity recorded (above 50 dBC) for each subject was not influenced by environmental noise. SPL was recorded 30 cm from the subject's mouth using a Brüel & Kjær (2238 Mediator) sound level meter. An experimenter observed the digital readout of the SL meter over the course of the vocalization and judged the mean SPL value over the utterance. Pitches were cued to the subject using either an acoustic piano (U. Iowa) or an electronic keyboard (NCVS). Voicing duration was recorded with a stop

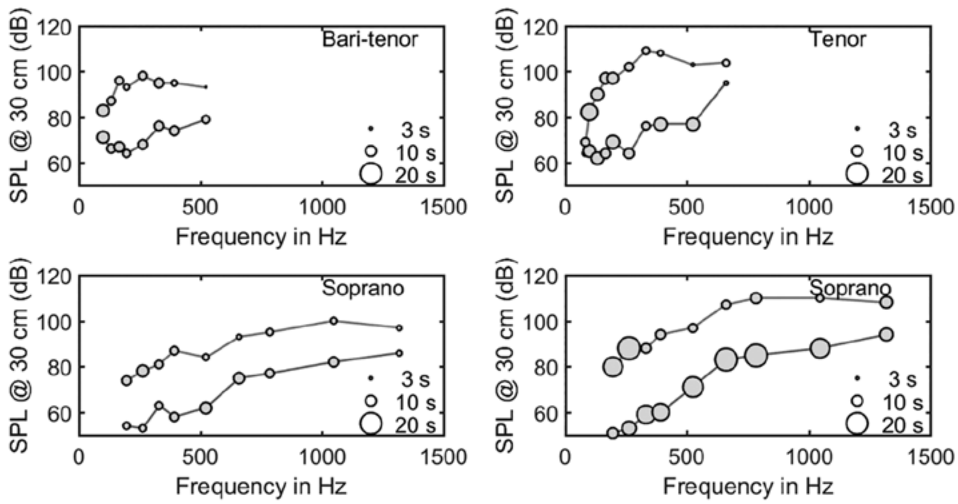

Figure 1. Voice range profiles with duration (diameter of circle) for two tenors and two sopranos.

watch by the experimenter in the room, who judged voice onset and offset.

Procedure and Instructions

Subjects were instructed to prepare for each phonation with a "full" breath and sustain each phonation for as long as possible, ending either when they ran out of breath or they could no longer maintain a steady intensity or tone quality. The following range of notes was cued, but the subjects chose only the notes they wished to sing: C_2 (65 Hz), E_2 (82 Hz), G_2 (98 Hz), C_3 (131 Hz), E_3 (165 Hz), G_3 (196 Hz), C_4 (262 Hz), E_4 (330 Hz), G_4 (392 Hz), C_5 (523 Hz), E_5 (659 Hz), G_5 (784 Hz), C_6 (1047 Hz), E_6 (1318 Hz), G_6 (1568 Hz). Pitch cues were varied in a quasi-random fashion, avoiding repeated phonations in either extreme of the subject's voice range. Doing so avoided fatiguing the subjects in any one area of the pitch range, which could have resulted in artificially low duration limits at the extremes of the physiologic range. A pitch was cued by the researcher and the subject produced the softest phonation possible for as long as possible at that pitch. The same pitch was cued again and the subject produced the loudest phonation possible for as long as possible. This process was repeated in the previously described quasi-random order until the physiologic pitch range had been exhausted.

RESULTS

The voice range profiles (VRPs) of four subjects (2 males and 2 females) from the Iowa group are shown in Figure 1. Their self-determined voice categories are shown in the upper right legend. The duration for each note produced is coded with the radius of the circle, with a duration scale given in the lower right of each figure. Note that the soprano in the lower right panel was able to sustain low SPL notes for nearly 20 s well into the mid-frequency range. High SPL notes were also sustainable for nearly 20 s, but only for the lowest 20 % of the f_o range. At this stage of research, no standards of comparison are available for duration, but this singer appears to be exceptional. It is interesting to note that she was able to sustain her highest loud note (G_5) about the same length as her softest note at the same pitch, just above 10 s. Intermediate pitches (500—1000 Hz) had smaller durations, on the order of 5–8 s for high SPL.

In comparison, another soprano from the Iowa group (lower left panel of Figure 1) displayed overall lower durations across her SPL—f_o range. Maximum durations were on the order of 10 s, and the 500–1300 Hz range for high SPL had the lowest durations, on the order of 5 s. With regard to the two males in Figure 1, a bari-tenor student (baritone turned tenor) had the smallest SPL-f_o range, but his durations were only slightly lower than those of the tenor, on the order of 8–10 s. The bari-tenor

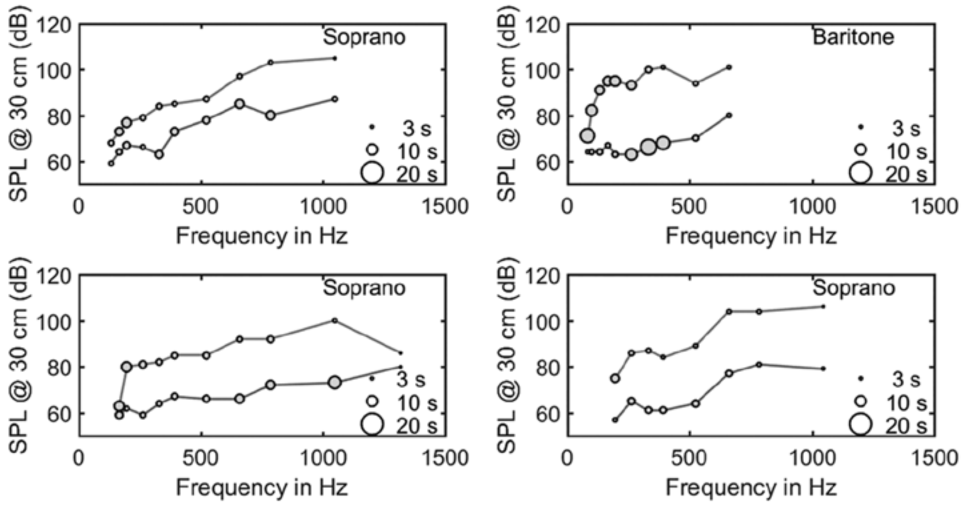

Figure 2. Voice range profiles with duration (diameter of circle) for three sopranos and one baritone.

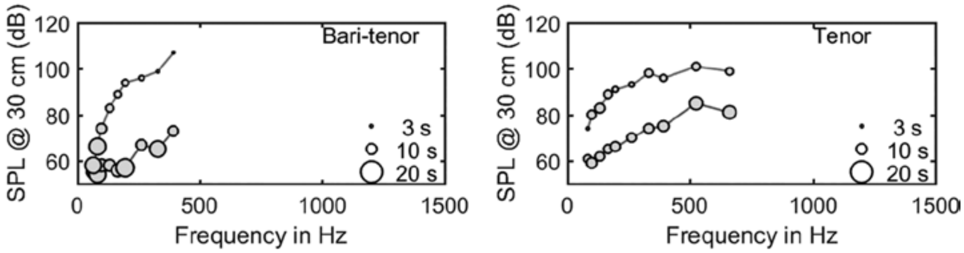

Figure 3. Voice range profiles with duration (diameter of circle) for a bari-tenor and a tenor.

did not attempt notes above C_5 (523 Hz), where durations for the tenor were 3–5 s. For loud phonation, the bari-tenor sustained C_5 for only a second.

Figure 2 shows VRPs for three more sopranos and one baritone. The sopranos have similar SPL-f_o ranges to the soprano in the lower left of Figure 1. None had the durations of the exceptional case in the lower right of Figure 1. Only one of 58 phonations for the three sopranos had a duration greater than 10 s. The baritone did have several durations greater than 10 s over the bottom half of his f_o range, similar to the bari-tenor and the tenor in Figure 1.

Two more VRPs of interest are shown in Figure 3. A second self-classified bari-tenor, the 74 year old teacher of the class, demonstrated a systematic decrease in duration with f_o at high SPL. His highest loud note was on the order of 1 s in duration. There apparently was no respiratory weakness, however, given that his low SPL notes were between 10–15 s. In comparison, the right panel in Figure 3 shows the VRP for a 40 year old tenor (also claiming to be a bari-tenor but singing mostly operatic literature as a tenor) has a relatively constant duration across f_o. It is on the order of 10 s for low SPL and on the order of 5–7 s on higher SPL.

Tables 1 and 2 present all durations, separately for males and females, at each pitch and loudness. On average, across all notes and both genders, durations were 14.6 s for soft notes (SD 6.7 s) and 12.8 s for loud notes (SD 6.0 s). For females alone, durations for soft notes averaged 13.1 s (SD 5.8 s) and for loud notes 11.2 s (SD 4.7 s). For males alone, durations for soft notes averaged 16.1 s (SD 7.2 s) and for loud notes 14.5 s (SD 6.9 s). Across the f_o spectrum (low notes to high notes), durations for males on soft notes peaked at E_4 (18.5 s,

TABLE 1. Trained Females: duration of phonation time at each pitch and duration range for each subject.

Subject Number	C_3 (131Hz)		E_3 (165Hz)		G_3 (196Hz)		C_4 (262Hz)		E_4 (330Hz)		G_4 (392Hz)		C_5 (523Hz)		E_5 (659Hz)		G_5 (784Hz)		C_6 (1047Hz)		E_6 (1318Hz)		G_6 (1568Hz)		Max Duration	Min Duration	Max-Min (duration range)
	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud			
F01	9	11	11	15	14	18	9	11	15	11	15	9	14	11	17	10	17	8	10	5					18	5	13
F02			14	18	9	19	11	14	11	12	12	12	13	13	17	11	17	13	23	8	5	5			23	5	18
F03					8	15	13	10	12	9	12	7	13	8	12	8	8	8	6	4					15	4	11
F04					14	18	14	22	15	13	17	16	22	13	21	10	17	14	19	13	11	10			22	10	12
F05					10	18	13	21	17	9	16	9	19	8	21	8	21	10	18	7	12	11			21	7	14
F06			11	10	12	15	8	12	9	10	9	9	10	9	12	11	10	9	7	7	5	4			15	4	11
F07			11	9	10	15	15	11	24	10	24	11	13	10	28	14	29	13	26	7	6	2			29	2	27
F08			8	16	9	15	8	11	11	16	13	11	15	11	14	10	15	10	26	8	3				26	3	23
F09					15	14	12	13	13	13	14	8	17	12	16	10	19	9	15	10	7	7			19	7	12
F10	15	17	14	26	11	24	11	27	11	9	16	23	17	10	20	10	29	14	27	18	15	13			29	9	20
F11	3	3	15	17	16	23	11	17	12	17	26	7	19	11	22	13	27	18	29	19	9	10	8	6	29	3	26
F12			8	8	13	16	15	16	16	15	13	9	7	8	10	7	7	6	5	3					16	3	13
F13			10	9	12	14	20	14	11	12	10	10	9	11	6	8	13	9	3	5					20	3	17
F14					7	8	9	8	9	8	16	9	14	8	6	7	9	3							16.0	3.0	13
F15	7	9	9	8	9	9	7	6	7	8	8	9	4	9	5	6	7	6							9.0	4.0	5.0
Average	8.5	10	11	14	11	16	12	14	13	11	15	11	14	10	15	9.5	16	10	16	8.8	8.1	7.8	8	6	20.5	4.8	15.7
SD	5	5.8	2.5	5.9	2.7	4.3	3.4	5.6	4.1	2.9	5	4.1	4.8	1.8	6.7	2.2	7.6	3.8	9.4	5	3.9	3.8			6.0	2.4	6.1

TABLE 2. Trained Males: duration of phonation time at each pitch and duration range for each subject.

Subject Number	C_2 (65Hz)		E_2 (82Hz)		G_2 (98Hz)		C_3 (131Hz)		E_3 (165Hz)		G_3 (196Hz)		C_4 (262Hz)		E_4 (330Hz)		G_4 (392Hz)		C_5 (523Hz)		E_5 (659Hz)		G_5 (784Hz)		Max Duration	Min Duration	Max-Min (duration range)
	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud	soft	loud			
M01			7	26	10	21	11	16	10	18	11	19	21	17	29	12	24	7	11	9	8	7			29	7	22
M02	25	30	31	31	23	19	22	15	24	13	33	13	20	10	30	6	19	5							33	5	28
M03			15	6	20	17	17	18	17	16	18	11	17	10	18	15	20	13	24	15	24	14			24	6	18
M04					22	22	17	16	19	15	15	12	18	16	18	18	18	12	15	4					22	4	18
M05			11	16	23	31	23	23	19	21	25	21	19	16	15	14	24	11	24	6	8	13			31	6	25
M06			10	26	14	27	19	32	23	24	12	29	14	20	29	19	29	12	35	27	21	17	24		35	10	25
M08					6	6	12	13	16	21	14	13	16	13	14	12	14	8	14	10	10	12	7	7	21	6	15
M09			7	19	8	19	12	17	8	15	7	13	9	11	9	8	9	8	7	10					19	7	12
M11	33	37	25	19	21	17	17	12	17	11	22	8	20	7	21	6	17	3	7	6					37	3	34
M12			18	22	14	20	17	21	13	19	17	17	18	10	16	12	11	6	40	7	21	3			40	3	37
M13					6	9	13	10	15	12	11	9	17	13	12	7	10	6	8	9	7	8	6	9	17	6	11
M14					7	7	10	24	15	21	14	21	14	12	19	17	16	14	12	9	10	8	3	6	24	3	21
M15							5	23	9	19	10	15	13	19	10	18	24	10	18	14	14	4			24	4	20
Average	29	34	16	21	15	18	15	18	16	17	16	15	17	13	18	13	18	8.8	18	11	14	9.6	10	7.3	27.4	5.4	22
SD	5.7	4.9	8.7	7.6	7	7.6	5.1	6	4.9	4	7.1	5.8	3.4	3.9	7.1	4.7	6.1	3.4	11	6.1	6.6	4.7	9.5	1.5	7.3	2.0	7.8

SD 12.7 s) and on loud notes at C_3 (18.5 s, SD 6.0 s). For females, durations peaked on soft notes at C_6 (16.5 s, SD 8.8 s) and on loud notes at G_3 (16.1 s, SD 4.3 s).

The range of duration (maximum duration time minus minimum duration time) for each subject was also tabulated. On average, males had a larger range between their maximum duration and their minimum duration than females (21.08 s for males versus 15.67 s for females). Most of this difference is a result of the average maximum duration for males being nearly 6 seconds longer than the average maximum duration for females. Average minimum duration times were less than a second apart for males versus females, suggesting that the maximum duration time is primarily an effect of lung volume, while minimum duration time (usually exhibited at the frequency extremes) is likely primarily influenced by the degree of muscle contraction for pitch control.

DISCUSSION

The ability to sustain a musical note, especially a high note, is a requirement in many styles of vocal music. Physiologically, it involves the ability to maintain a controlled lung pressure and steady contractions of a variety of muscle that maintain vocal fold length and adduction.

The duration for maximum contraction of skeletal muscles (e.g., the biceps or quadriceps) is inversely related to the maximum voluntary contractile force.[19] For example, at 100% voluntary contractile force, the duration is on the order of 5 s, while at 85% contractile force, the duration increases to about 20 s. At 70 % voluntary contractile force, the duration is 40 s, which exceeds the typical maximum phonation time determined by expiratory lung capacity. Thus, if any production in the VRP involves muscle contractile forces less than 70% of voluntary maximum, the singers should be limited only by respiratory capability. Assume that the thyroarytenoid (TA) muscle fibers were to provide all the tension for vibration of the vocal fold (as opposed to the vocal ligament), the maximum fiber stress would dictate f_o. Using the simple string formula

$$f_o = (2L)^{-1} (\sigma/\rho)^{0.5} ,$$

where L is the vocal fold length (≈ 1 cm), σ is the maximum fiber stress (≈ 200 kPa in striated muscle like the biceps or quadriceps), and ρ is the fiber density (≈ 1 g/cm^3), a maximum f_o of about 700 Hz would be attainable. This assumes that the thyroarytenoid muscle fibers can produce the same maximum stress as the biceps or quadriceps. Alipour-Haghighi et al. measured a maximum stress of 120 kPa on a canine thyroarytenoid muscle *in vitro*, which may have been a slight underestimation of a human *in vivo* stress.[20] Regardless of the exact value (100 kPa or 200 kPa), the maximum active stress in muscle fibers is simply not sufficient to produce very high notes with long durations. The 700 Hz f_o could be supported for only about 5 s according to Edwards.[21] For higher f_o with longer duration, a vocal ligament has evolved in humans and other species, which develops during maturation.

Two factors are critical in the ability to produce a wide f_o range with the vocal ligament, a high collagen density and a wide range of vocal fold length change.[22] The high collagen density provides a steep stress-strain curve, and the range of elongation (on the order of a factor 2:1 for longest to shortest length) allows the ligament stress to vary over several factors of 10 (up to 10 MPa for collagen fibers instead of 200 kPa for muscle fibers). Titze et al. predicted a 4-octave f_o range based on human vocal ligament stress-strain curves.[23] The cricothyroid muscle can deliver this stress only if its cross-sectional area is much larger than the cross-sectional area of the ligament (for a given force, stress is inversely related to cross-sectional area).

Another factor may limit the duration of high notes. All biological tissue, and specifically vocal fold tissue, tends to relax its stress after a sudden (step) elongation has been applied.[24] This can happen in a fraction of a second and continue over several seconds. To overcome this relaxation, more fiber elongation is needed. If rotation and gliding between the cricoid and thyroid cartilages cannot provide this further elongation, the note will become flat and the singer will choose not to sustain it. Vibrato will also be difficult to sustain because an upward swing in f_o is needed to balance a downward swing.

Based on a brief preliminary report, a new analysis of the aria "Il mio tesoro intanto" from the opera *Don Giovanni* by Wolfgang A. Mozart is given here to assess the match between the tessitura of a song and the tessitura of a singer.[25] The current analysis is based on the singer's VRP with duration, plotted directly above the keyboard in Figure 4. The singer is the 74 year old baritenor in the current data set.

The aria is written *andante* in 4/4 meter, meaning that each measure or whole note is approximately 2 s in duration. Figure 4 illustrates the analysis by way of a tessituragram. On top is a histogram of occurrences of notes throughout the aria, assuming that it is performed in its original key of B♭. There are 66 occurrences of B♭$_3$ and 70 occurences of C_4, but only one occurrence each of D_3 and A_4. Second from the top is a histogram of the equivalent number of whole note duration on these notes. Clearly, the note F_4 dominates in accumulated duration. It dominates even more in terms of the number of vocal fold vibration cycles produced on a note, as indicated in the third histogram from the top. Not plotted is the *fermata* duration of any single note. For this measure, F_4 is again the dominant note. In one instance in the score, it is held for three measures with a two measure cadenza, and in another it is held for three measures with a fermata. In either case, the duration on F_4 is on the order of 5 measures, or 10 s at the tempo indicated above. The tenor (who claims to be a baritenor) is barely capable of sustaining these durations

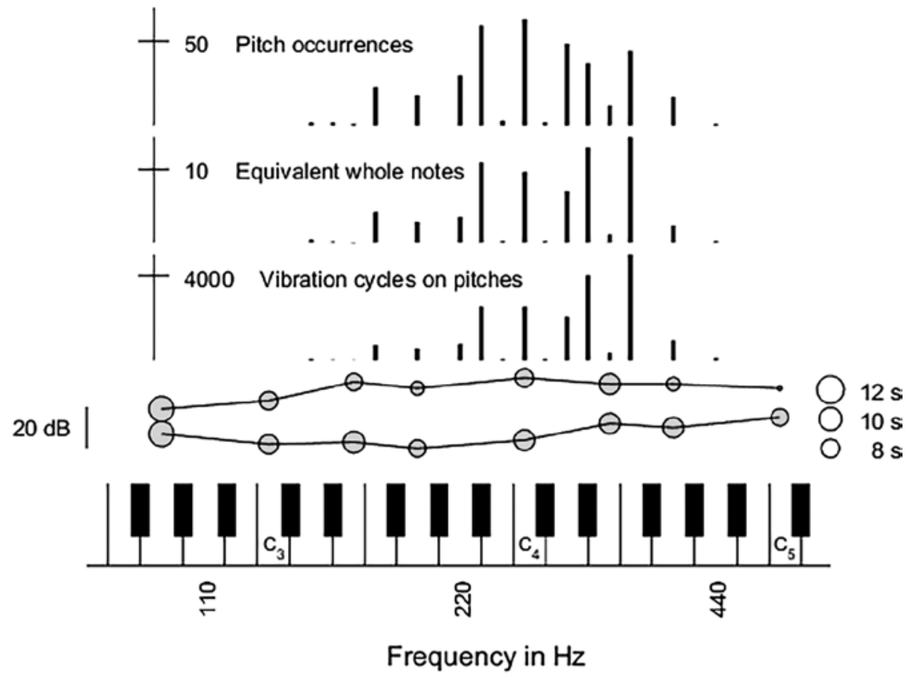

Figure 4. Tessituragram for a bari-tenor singing "Il mio tesoro intanto" from *Don Giovanni* by W. A. Mozart.

on F_4, as the VRP circle diameters show (see legends to the right). If the aria had been written one note higher (in the key of C), the same durations on G_4 would be an immense struggle for this tenor.

Other tenors in our data pool would appear to have less difficulty with this aria on the basis of duration. For example, male singer M06 in Table 2 was able to produce durations well above 10 s on all notes between C_4 to C_5, both soft and loud.

CONCLUSIONS

This study was not exhaustive in terms of the number of subjects studied, but there was sufficient variety in the durational characteristics of the voice range profiles to propose its possible use in voice classification and selection of repertoire. While the f_0 and intensity range information supplied by the traditional VRP is likely sufficient to classify singers into the standard categories of bass, baritone, tenor, alto, mezzo soprano, or soprano, the additional element of duration could be highly beneficial in finding a singer's place in a subcategory, or *Fach*, commonly used to identify appropriate roles and repertoire. As has been clearly shown in the example of the Mozart aria, some singers simply will not be able to sustain notes for the durations required by a song or aria, even if their traditional VRP indicates that they are able to perform those notes with a significant range of intensities.

Additionally, by identifying how long a singer can sustain a note, the singing teacher or vocal coach could gain valuable insight into the degree of muscular contraction being used to produce that note. This is particularly true as the durations approach or drop below 5 s, which was identified by Edwards as the maximum contraction time when skeletal muscles are 100% contracted.[26] This degree of contraction, particularly of the pitch control muscles, could also affect other elements of the singer's performance ability, such as their ability to quickly and easily change pitch or the acoustic tone quality of the pitches produced in that frequency range. While these elements may be symptomatic of physical limitations of the singer, they may also be related to technical issues that can be addressed by the singer and teacher/coach.

NOTES

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