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Perturbation and Nonlinear Dynamic Analysis of Different Singing Styles

Caitlin J. Butte^{*}, Yu Zhang^{*}, Huangqiang Song[†], and Jack J. Jiang^{*}

^{*}Department of Surgery, Division of Otolaryngology Head and Neck Surgery, University of Wisconsin Medical School, Madison, Wisconsin

[†]Hosting Arts School of Shanghai Theatre Academy, Shanghai, China

Summary

Previous research has used perturbation analysis methods to study the singing voice. Using perturbation and nonlinear dynamic analysis (NDA) methods in conjunction may provide more accurate information on the singing voice and may distinguish vocal usage in different styles. Acoustic samples from different styles of singing were compared using nonlinear dynamic and perturbation measures. Twenty-six songs from different musical styles were obtained from an online music database (Rhapsody, RealNetworks, Inc., Seattle, WA). One-second samples were selected from each song for analysis. Perturbation analyses of jitter, shimmer, and signal-to-noise ratio and NDA of correlation dimension (D_2) were performed on samples from each singing style. Percent jitter and shimmer median values were low normal for country (0.32% and 3.82%), musical theater (MT) (0.280% and 2.80%), jazz (0.440% and 2.34%), and soul (0.430% and 6.42%). The popular style had slightly higher median jitter and shimmer values (1.13% and 6.78%) than other singing styles, although this was not statistically significant. The opera singing style had median jitter of 0.520%, and yielded significantly high shimmer ($P = 0.001$) of 7.72%. All six singing styles were measured reliably using NDA, indicating that operatic singing is notably more chaotic than other singing styles. Median correlation dimension values were low to normal, compared to healthy voices, in country (median $D_2 = 2.14$), jazz (median $D_2 = 2.24$), pop (median $D_2 = 2.60$), MT (median $D_2 = 2.73$), and soul (mean $D_2 = 3.26$). Correlation dimension was significantly higher in opera ($P < 0.001$) with median $D_2 = 6.19$. In this study, acoustic analysis in opera singing gave significantly high values for shimmer and D_2 , suggesting that it is more irregular than other singing styles; a previously unknown quality of opera singing. Perturbation analysis also suggested significant differences in vocal output in different singing styles. This preliminary study using acoustic analysis with nonlinear dynamic measures and perturbation measures may represent a valuable procedure in quantitatively describing the properties of the singing voice. Further research with human test subjects may allow us to characterize singing styles and diagnose vocal dysfunction in the singing voice.

Keywords

Perturbation analysis; Nonlinear dynamic analysis; Singing voice; Singing styles

INTRODUCTION

The singing voice is often described in subjective terms based on the individual singer's perceptions. Individual singers attempt to explain different styles of singing based on the physical changes they experience and the different sounds they produce, but it is difficult to rely on these because individuals are rarely proficient in all styles. Opinions and terms accompanying perceptual descriptions are usually not scientific and can vary significantly even among experts. Previous research identifies this inconsistency, and attempts to characterize the voice in different styles through both qualitative and quantitative measures. Aerodynamic measurements of subglottal pressure and glottal compliance are taken. Singers are classified by vocal register, vocal classification, types of vocal vibration, and presence of the singer's formant. Other acoustic measurements, such as fundamental frequency, are acquired through perturbation analysis.¹

Previous research indicates that vocal technique in singing differs greatly depending on musical style.²⁻⁴ In a study by Thalén and Sundberg describing different styles of singing, subglottal pressure, glottal adduction, and glottal compliance were obtained for one voice while performing in four different singing styles.² Glottal compliance, the ratio between the air volume displaced in the voice pulse and subglottal pressure, decreases with increasing glottal adduction. Their findings demonstrated that by varying the degree of glottal adduction, singers can change their styles of phonation within a wide range. Aerodynamic measurements found the highest subglottal pressure values and lowest glottal compliance values in blues singing, resembling a pressed phonation and characterized by hyperfunctional phonation. In contrast, classical singing produced the highest glottal compliance values and most nearly resembled a flow phonation and is characterized as a resonant voice. An additional, breathy phonation style was characterized by hypofunctional phonation. These results confirm that the voice is used differently for various styles of singing.

In addition to these measurements, perturbation analysis is another common method of analyzing voice, and applies parameters such as jitter, shimmer, and noise-to-harmonic ratio to objectively assess laryngeal function and voice quality in periodic voices.⁵⁻⁷ Brown et al used perturbation parameters to assess both spoken and sung voice segments.⁸ Buder and Wolf assessed spoken and sung samples of two related singers; one with vocal injury and the other with normal voice. Although perceptual judges were not able to detect a difference between the singers, perturbation analysis found the injured voice to have much higher parameters than the normal voice, suggesting that vocal differences that cannot be heard by the human ear are detectable via perturbation analysis.⁹

Another vocal measurement that has been applied to the singing voice is nonlinear dynamic analysis (NDA), which has been used to assess pathological voices in subjects with vocal fold pathologies, such as polyps and nodules, due to the amount of irregular and aperiodic phenomena that occur in such voices.¹⁰⁻¹² NDA has also been applied to study nonpathological vocal signals such as infant cries to detect the presence of chaotic phonation.^{13,14} Recently, nonlinear dynamic methods have been applied to the singing voice. Lee et al assessed differences in the amount of chaotic behavior found in traditional Korean and Western singing.¹⁵ Zangger Borch et al found aperiodic vibration in the supraglottal mucosa of distorted singing, a loud tone produced primarily in rock music,³ and Neubauer et al detected various forms of nonlinear phenomena in modern contemporary singing.¹⁶ These investigations into the singing voice suggest that nonlinear phenomena are found in the singing voices of healthy individuals and that such phenomena are present in a range depending on the style of singing being performed.

Much of the previous research on singing has focused on the classical style. Perturbation analysis has traditionally been used to assess voice quality, but is limited to the analysis of periodic voices. Nonlinear dynamic methods have identified chaotic properties in many voice types, but these methods have been used infrequently to analyze styles of singing. Furthermore, methodological differences in studies using NDA make them incomparable. Zhang et al suggest that the joint application of perturbation analysis and NDA can provide complementary information that may enhance our understanding of the voice.⁷ This study attempts to quantify the dynamics of the singing voice and is the first to use NDA to make a distinction between different styles of singing. Perturbation analysis and NDA are used to characterize the voice in multiple singing styles, including jazz, opera, soul, country, musical theater (MT), and pop.

METHODS

Singing Voice Samples

Samples of music from six different singing styles were compiled from RealNetworks Rhapsody (Seattle, WA) online music database. Twenty-six songs were selected from the styles of opera, pop, MT, country, jazz, and soul. Some songs yielded multiple samples, giving a total of 59 samples available for analysis. All samples had a sampling frequency of 44.1 kHz and a bit resolution of 16, which are sufficient to extract normal voice jitter and shimmer.¹⁷ Similar to the study by Thalén and Sundberg, songs were chosen on the basis of representative singers for each style, which are archetypical examples of the singing style to which they pertain (Table 1).²

Criteria for inclusion of data samples used in the experiment were the following: the song is characteristic of a specific phonation style, based on representative singers, and the segments used contain only the acoustic signal of a single, sustained vowel in the singing voice, termed a *cappella*. Samples were cut to exclude musical instrumentation or vocalization of consonants; such background noise could potentially lead to skewed results and appear as stochastic noise or other chaotic behavior.¹⁵ In addition, central segments of the singing voice samples were selected, and voice onset and offset were not included for analysis.

These criteria for inclusion of musical samples limited the number of samples that could be used in each style. The “rock” music style, although commonly observed in popular music, is absent from this study because very few representative rock songs do not contain instruments or some other form of turbulent background noise. This disqualified the rock style. Additionally, multiple representative songs of the selected styles were disqualified due to background noise.

Each music sample was extracted from the original song so as to only contain the acoustic signal of a single human voice. Ideal sample length was 1 second (1000 ms) to provide the most accurate results and shortest time of analysis; average sample length was 911.7 ± 286.2 milliseconds.

Perturbation Analysis

Perturbation analysis was performed on the samples using *CSpeech* software, version 4.0 (Milenkovic and Read, Madison, WI). Percent jitter, percent shimmer, and signal-to-noise ratio (SNR) were measured. Jitter is a measure of cycle-to-cycle frequency variation. Shimmer is a measure of cycle-to-cycle amplitude variation. SNR indicates the amount of noise present in the speech waveform.

Error in perturbation measurement (err) was calculated by the *CSpeech* program to determine reliability. Err tallies the number of times the analysis algorithm overlooks a pitch period consistent with the peak of the autocorrelation function used to calculate jitter, shimmer, and SNR values.¹⁸ The err value therefore acts as a reliability measurement for all three parameters. Algorithm failure to compute parameters is generally due to inaccurate pitch estimation or a failed attempt to analyze a highly aperiodic waveform.¹⁸ In accordance with the *CSpeech* user manual, an error count greater than 10 indicates that analysis via perturbation analysis methods is unreliable.¹⁸ In the perturbation analysis of this study, 15 outliers of the 59 samples were eliminated due to high err values, 11 of which came from the opera singing style. The loss of pitch tracking associated with high err can be caused by deviation from periodic sustained phonation, including breathiness, pitch variability, or noise.

Nonlinear Dynamic Analysis

Correlation dimensions are used frequently due to their applicability for analysis of aperiodic voices, and were applied to describe the nonlinear dynamic characteristics of all samples.^{12,19–22} Correlation dimension (D_2) is a quantitative measure specifying the number of degrees of freedom necessary to describe a dynamic system; a more complex system has higher dimension, and greater degrees of freedom may be needed to describe its dynamic state.^{10,23} D_2 is based on the comparison of pair-wise distances between points, accounting for the density of the points and providing an estimate of the operational degrees of freedom of the dynamics.²⁴ Correlation dimension measurements were calculated using *Nonlinear Dynamic Analysis* software developed by our lab, derived from previously described numerical algorithms.^{19,21,22}

Statistical Analysis

Jitter, shimmer, SNR, and correlation dimensions were compared for the six groups (jazz, opera, soul, country, MT, and pop). Because it could not be predefined whether or not the tested groups were from normally distributed populations, we applied the Kruskal-Wallis one-way analysis of variance on ranks. Percent jitter, percent shimmer, SNR, and correlation dimensions were the dependent variables, and the subject groups (jazz, opera, soul, country, MT, and pop) were the independent variables. Statistical significance level was set at $P = 0.05$. *SigmaStat* 3.0 (Jandel Scientific, San Rafael, CA) software was used for statistical analysis.

RESULTS

The results of perturbation analysis and NDA can be found in Figure 2. Results obtained from most styles in this study nearly matched previously obtained values for normal speaking voices, which had normative jitter and shimmer ranges of 0.3–1.6% and 0.7–6.0%, respectively.²⁵ The popular style had perturbation values slightly higher than normal, with a median jitter of 1.13% and shimmer of 6.78%. Jazz, soul, MT, and country had values within the normal range (Table 2). The opera style had normal jitter (0.52%) and significantly high median shimmer values ($P = 0.001$) of 7.07%.

SNR was calculated for each style. Previous studies have shown the normal range of SNR in the human voice to be 9–30 dB.²⁵ The SNR values for all singing styles fell into the normal range. The pop style yielded significantly low median SNR (12.3 dB, $P = 0.021$) in comparison with opera, soul, country, jazz, and MT (17.1–24.4 dB).

Median D_2 was low in jazz, country, MT, pop, all of which were on the upper range of sustained vowel, healthy speaking voice D_2 values, which have median 2.02.²⁶ Soul D_2

values were slightly higher, approaching the range of pathological sustained vowels, which have median 3.38.²⁶ The correlation dimension was significantly higher ($P < 0.001$) in the opera style (median $D_2 = 6.19$) indicating that singing in the operatic style exhibits more chaos than other styles of singing.

DISCUSSION

Our results were based on a limited number of samples for each singing style, so generalizations must be made with caution. The use of representative singers, however, ensured that each song depicted characteristics of the singing style under which it was classified. This methodology was also used by Thalén and Sundberg to clarify the designation of each genre.²

Previous research using jitter, shimmer, and SNR to study the singing voice made comparisons between the singing and speaking voice. Their results suggested that differences between healthy and unhealthy voices may be less perceptibly different in singing than in speaking; however, perturbation analysis was able to detect differences in both styles of vocal output that were not detectable by the human ear.⁸ These results are mostly applicable in assessing differences among a limited sample size.

Similarly, perturbation measurements detected significant differences among singing styles. Soul, pop, and opera displayed significantly higher shimmer than MT, country, and jazz ($P < 0.001$). Similarly, significant variance was seen in SNR values ($P = 0.021$). However, many samples analyzed via perturbation methods had unreliable error estimates ($\text{err} > 10$). Approximately, 25% of analyzed samples were excluded from the results due to high error, and 73% of excluded samples were from the opera singing style.

Strong presences of pitch and intensity vibrato, which vary during the course of individual tones in a song, may lead to a failed pitch extraction in perturbation analysis. Vibrato has been compared to vocal tremor, which exhibits high jitter and shimmer values.²⁷ When all samples are included, regardless of error, the operatic singing style has high median values for both jitter and shimmer, 1.03% and 13.03%, respectively. When samples with $\text{err} > 10$ are removed, jitter = 0.52% and shimmer = 7.72%. The extent of pitch variability found in opera due to vibrato is most likely the reason for high perturbation values.

Vibrato measurement, as magnitude and rate of fundamental frequency (F0) modulation, has been used to classify opera.²⁷ This measurement may be applicable for nearly periodic voices; however, it cannot fully describe the aperiodicity in the singing voice. For some aperiodic opera voices in this study, the magnitude and rate of F0 modulation may not be reliably obtained because that pitch extraction is difficult and the magnitude and rate of F0 modulation become unstable (Figure 1). However, NDA has no such limitations and can be applied for the analysis of both periodic and aperiodic singing voices. Thus, NDA may be valuable in this particular application.

Perturbation analysis is sensitive to aperiodicity as well as to error that can be created by environmental noise and measurement noise from recording, sampling, and analysis systems. Zhang et al found that NDA is not only more reliable for aperiodic samples, but also for samples of shorter signal lengths, lower sampling rates, and larger noise levels.⁷ NDA is less easily influenced by environmental factors and is proficient to analyze more chaotic samples. NDA was performed on all samples in our study; those considered unreliable due to high error counts in perturbation analysis were analyzed reliably by NDA. For example, a country sample with $\text{err} = 513$ had mean jitter = 2.01% and shimmer = 13.48%. The sample had $D_2 = 1.688$. Another soul sample with $\text{err} = 224$ had mean jitter = 1.46% and shimmer = 9.97%, and its correlation dimension was estimated as $D_2 = 2.389$. In

both cases, perturbation analysis cannot be reliably obtained; however, NDA provides effect descriptions for the single samples.

Unlike other musical styles, which showed less aperiodicity through NDA, operatic singing presented more chaotic results. In Table 2, the median value D_2 for the opera style was 6.19, and D_2 was significantly higher than other singing styles ($P = <0.001$). High D_2 indicates that the opera singing style is more aperiodic than other styles of singing. Articular changes in operatic singing create a very intense vibrato that is not as noticeable in other singing styles. From nonlinear dynamic point of view, Titze has classified voices into three types: type 1 signals are nearly periodic, type 2 signals contain strong subharmonics and low-frequency modulation, and the type 3 signals show strong aperiodic or chaotic characteristics.²⁸ Zhang and colleagues have shown that NDA represents a valuable quantitative scheme in classifying these three typical signals of human voices.^{20,29} As seen in Figure 1, the waveforms of country, soul, jazz, MT, and pop show the typical properties of type 1 signals. However, the opera voice in Figure 1 illustrates noticeable amplitude modulation, which is associated with type 2 vocal signals. In addition, some opera voices illustrate the typical properties of type 3 signals. Thus, opera voice is much more chaotic than other waveforms, characterized by the higher D_2 . Nonlinear dynamic methods provide effective description for the strong aperiodicity in opera voices.

CONCLUSIONS

In this study, we applied nonlinear dynamic and perturbation analyses to measure acoustic samples from different styles of singing, including jazz, opera, soul, country, MT, and pop. Median values in acoustic analysis were given for six different singing styles (Figure 2). These ranges may play a role in the clinical assessment of singers' health. Singers who produce acoustic parameters outside of the normal range for a particular style may indicate vocal dysfunction. More information from a larger number of human recordings is needed to assess the applicability of these methods on singing-related injuries. In addition, the opera style yielded percent jitter and shimmer values that were significantly higher than other singing styles. NDA also yielded significantly high differences and indicated that operatic singing is highly chaotic in comparison to other singing genres. However, small sample size prevented statistically sound inferences from being made among the other singing styles. This was mostly due to the limited samples available in the Rhapsody Online music database that fit the criteria for inclusion. Future investigations would ideally include larger sample sizes, which could be made possible with human subjects proficient in each singing style. Acoustic analysis including nonlinear dynamic measures and perturbation measures may represent a valuable procedure in quantitatively describing the properties of singing voice.

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FIGURE 1.

The typical waveforms of the six singing modes including country, MT, soul, pop, jazz, and opera.

FIGURE 2.

The distribution of jitter, shimmer, SNR, and D_2 for six singing styles including country, MT, soul, pop, jazz, and opera, where the error bars represent ± 1 SE.

TABLE 1

Songs Used in the Study, Obtained From the Rhapsody Online Music Database

Track Information		
Mode	Song	Artist
Opera	Un giuramento atroce mi constringe	John Alldis, Russell Burgess
	Perduta la battaglia	Birgit Nilsson
	Core 'ngrato	Luciano Pavarotti
	'O sole mia	Luciano Pavarotti
	Carmen	Maria Callas
Pop	Oops! I Did It Again	Britney Spears
	It's Gonna Be Me	N'Sync
Musical theater	Go Into Your Dance	Myllinda Hull
	Sunny Side to Every Situation	Myllinda Hull
	Lullaby of Broadway	Michael Cumpsty
	42nd Street	Kate Levering
	I Only Have Eyes For You	Christine Ebersole
Country	Courtesy of the Red, White, and Blue	Toby Keith
	Make the World Go Away	Martina McBride
	Stronger	Faith Hill
	Not Ready to Make Nice	Dixie Chicks
Jazz	Misty	Ella Fitzgerald
	Loverman	Billie Holiday
	I Got a Woman	Ray Charles
	Nobody Cares	Ray Charles
Soul	Fallin'	Alicia Keys
	I Turn to You	Christina Aguilera
	Mercy on Me	Christina Aguilera
	Afterwhile	Kirk Franklin

Each song had fit the criteria for inclusion: (1) it is characteristic of a specific singing mode and (2) it contains segments with the acoustic signal of a single vowel from one voice.

TABLE 2

Comparisons of Modes for Difference in Acoustic Analysis Values

Parameter	Median (25–75% Range)						Kruskal-Wallis H ($df = 5$)
	Country ($n = 5$)	MT ($n = 5$)	Soul ($n = 9$)	Pop ($n = 5$)	Jazz ($n = 3$)	Opera ($n = 27$)	
Jitter	0.320 (0.27–0.44)	0.280 (0.21–0.70)	0.430 (0.34–0.58)	1.13 (0.81–1.99)	0.440 (0.22–0.65)	0.520 (0.37–1.01)	9.807
Shimmer	3.82 (2.76–4.27)	2.80 (2.53–4.58)	6.42 (3.82–8.52)	6.78 (4.67–8.47)	2.335 (1.07–2.98)	7.72 (6.88–12.99)	25.803*
SNR	19.75 (17.45–22.0)	23.3 (16.85–24.8)	17.1 (15.9–18.3)	12.3 (9.75–16.53)	24.4 (19.7–28.7)	18.5 (10.28–20.4)	11.880*
D_2	2.14 (1.75–2.69)	2.73 (1.93–3.29)	3.26 (2.65–3.49)	2.60 (2.343–3.66)	2.24 (1.73–2.47)	6.19 (4.77–7.84)	33.796*
Err	0.5 (0–2.5)	0 (0–0.25)	0.5 (0–1)	2 (0–4)	0 (0–0)	3 (0.75–4.25)	11.614*

* Significance level $P < 0.05$.