Effects of Melody and Technique on Acoustical and Musical Features of Western Operatic Singing Voices

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Summary: Objective. The operatic singing technique is frequently used in classical music. Several acoustical parameters of this specific technique have been studied but how these parameters combine remains unclear. This study aims to further characterize the Western operatic singing technique by observing the effects of melody and technique on acoustical and musical parameters of the singing voice.

Methods. Fifty professional singers performed two contrasting melodies (popular song and romantic melody) with two vocal techniques (with and without operatic singing technique). The common quality parameters (energy distribution, vibrato rate, and extent), perturbation parameters (standard deviation of the fundamental frequency, signal-to-noise ratio, jitter, and shimmer), and musical features (fundamental frequency of the starting note, average tempo, and sound pressure level) of the 200 sung performances were analyzed.

Results. The results regarding the effect of melody and technique on the acoustical and musical parameters show that the choice of melody had a limited impact on the parameters observed, whereas a particular vocal profile appeared depending on the vocal technique used.

Conclusions. This study confirms that vocal technique affects most of the parameters examined. In addition, the observation of quality, perturbation, and musical parameters contributes to a better understanding of the Western operatic singing technique.

Key Words: Operatic technique–Singing–Acoustical analysis–Vibrato–Energy distribution–Vocal perturbation.

INTRODUCTION

The vocal technique used in singing differs depending on musical style. The Western operatic singing technique is used by classically trained singers. Such singing requires a highly refined use of physiological components such as the laryngeal, respiratory, and articulatory muscles.[1–6] These components lead to a complex combination of acoustical parameters,[7] which differs from natural or untrained singing.[8–10]

The concept of good vocal quality is naturally very difficult to define as it consists of various components. Among the acoustical parameters observed in the operatic singing technique, particular attention has been paid to vibrato and energy distribution.

Vocal vibrato has been the subject of several acoustical and perceptual studies since the beginning of the 20th century and is highly correlated with overall vocal beauty.[11,12] It can be defined as a slightly tremulous effect imparted to vocal tone and corresponds to a quasiperiodic modulation of the frequency of a tone. Vibrato is mainly characterized by two parameters: rate and extent. Vibrato rate (VR) specifies the number of frequency fluctuations per second and ranges between 5 and 7 Hz depending on the singer.[13] Observing the variability in VRs across 10 prominent artists singing in the western classical music tradition, Prame[13] found an average rate of 6 Hz, with a mean variation from the singer's average of 8%. More recently, the values were defined between 4.55 and 6.25 Hz for classical voices[14] and between 6.28 and 7.14 Hz for operatic singing voices.[15] However, other authors found a mean VR of 5.7 Hz with this particular technique, slower than for the Broadway style of singing (6.1 Hz).[16] Note that mean VR is considered to be a constant for a singer.[17] It does not depend on the context of solo or choir performance[18] but can be slightly modified deliberately[19] or by musical training[20] or warming up.[21] Vibrato extent (VE) describes how far the frequency fluctuates around the pitch of the tone. Unlike VR, VE varies considerably for individual singers[22] and between singers.[23] The variability pointed out by Seashore[24] has been confirmed since then, with, for example, a mean extent of 71 cents[22] and a variation of between 0.38 and 3.26 semitones[25] or between 0.54 and 1.66 semitones.[14] Mean VE has been found to be greater for the operatic singing style (±98 cents) than the Broadway style (±78 cents).[16]

The long-term average spectrum (LTAS) provides information on the spectral distribution of the sound. Operatic singing is associated with an increase of energy of between 2 and 4 kHz.[6,26,27] This frequency range has been identified as being of primary importance for opera soloists' vocal projection and is often associated with good quality, as it allows the audibility of the voice to be optimized against an orchestra.[28,29] Note that energy distribution can be developed with training[8,27,30] and depends on the sound level of the performance[31,32] as well as on the vocal technique used.[16,33] Several parameters, such as the singing power ratio,[27] the energy ratio,[6] the α coefficient,[32] and the difference in energy between different frequency bands, have been proposed to quantify the spectral balance from

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an LTAS. Although these measurements are not intended to provide information about the singer's formant, they illustrate differences in energy distribution.

In addition to these acoustical parameters describing the operatic singing technique (ie, VR, VE, and spectral distribution), one can apply perturbation analysis to these voices. By comparing 26 recordings of different singers and singing styles, some authors have observed that the operatic performances had "normal" jitter and "high median" shimmer values (but still in the "normal" range).[34] Despite the limitations regarding the control of the musical samples, these results suggest that perturbation analysis (ie, parameters such as jitter, shimmer, and signal-to-noise ratio [SNR]), which is commonly used for evaluating voice disorders,[3] is relevant for operatic voices.[35–37]

As well as investigating the vocal and quality parameters of the operatic singing technique (ie, VR and VE, spectral distribution, and vocal perturbation), this study examined some musical characteristics such as the loudness of the voice and fundamental frequency (F_0) of the starting note and tempo. In a comparison of the performance of a popular song with and without an operatic singing technique, a particularly slow tempo was observed when the song was performed with an operatic singing technique.[38] To observe the operatic singing technique, the present study investigated the effect of technique on the commonly examined acoustical parameters but also on vocal perturbation and the musical parameters mentioned above, as well as the relationship between the various parameters.

Previous studies had compared the physiological and acoustical parameters of different vocal techniques. They applied three kinds of methods: the comparison of a single professional singer in different musical styles[5,16,33,39–42]; the comparison of different groups specializing in one particular musical style[14,43–45]; or the examination of one melody performed by one group of participants with two different vocal techniques.[46–48] However, all these experimental designs have their limitations. First, an investigation that focuses on a single subject makes it difficult to generalize the effect of vocal technique and calls into question the general validity of the findings. Second, the use of different musical material, representing different musical styles, does not allow one to control for the effect of melody on the acoustical parameters of the vocal performances. Third, when the same musical material is performed by a group of participants, with different styles, only one melody is considered and the replicability of the findings for other melodies cannot be examined. To sum up, previous studies provided useful information on the Western operatic singing technique but further investigations, with more participants, the observation of several parameters, and the control of melodic effects, would allow for a better understanding of this particular singing technique.

The present study examined the effects of melody and technique on quality, perturbation, and musical parameters among a large panel of Western professional singers. For this purpose, we analyzed the sung performances of singers performing two different melodies (a popular song and a romantic melody from the participants' musical repertory), with and without an operatic singing technique. This experimental design allows one to observe which features are attributable to the musical material used and which to the technique used. One can then develop a theoretical model clarifying this particular singing technique.

METHOD

Participants

Fifty singers (38 women and 12 men) aged between 19 and 66 years ($M = 36.94$ years) participated in the study. They had all received a classical music education in higher institutions such as music conservatories and regularly engaged in classical solo vocal performances. They began their singing lessons between 6 and 49 years of age ($M = 20.18$ years) and they had between 5 and 51 years of singing experience ($M = 19.86$ years). They reported practicing with their vocal instrument for 13.68 h/wk on average.

Material and procedure

The sound recordings were made in a quiet room (background level < 30 dB(A)), using a head-worn microphone (Sennheiser HS2; Sennheiser, Wedemark, Germany) positioned at a constant distance of 2 cm from the right corner of the subjects' lips and a Marantz Professional Solid State PMD67 Recorder (Marantz, Kanagawa, Japan). Note that the recording equipment was never removed during each participant's recording session to keep a constant distance between the mouth and the microphone and limit potential bias due to differences in the recording environments.

Before taping, participants were asked to produce two glissandi to warm up their vocal organs and encourage a lack of inhibition in front of the experimenter and the recording equipment. Then, each one produced four vocal performances: the popular song "Happy Birthday" without any particular technique, for example, while imagining a festive and friendly context (birthday); a romantic melody of their choice without any particular technique (romantic); the same melody with a Western operatic singing technique (ROMANTIC); and finally, the birthday song with a Western operatic singing technique (BIRTHDAY). Concerning the romantic melody, the participants had to choose a melody in their musical repertory (eg, Lieder of Schubert or Schumann). Except for the chosen melody, no particular starting note was given so each participant could perform in his/her comfortable range. The performances were sung a cappella to avoid altering the auditory signal with musical instrumentation and recorded with a sampling frequency of 44.1 kHz and a 16-bit resolution (ie, sufficient to extract normal vocal perturbation measurements).

Acoustical analysis

For the 200 performances (birthday, romantic, ROMANTIC, BIRTHDAY from the 50 participants), 10 variables were observed, grouped into quality, perturbation, and musical parameters. All the acoustical analyses were run on a Macintosh (Mac OS X, Version 10.6.8, Apple, Cupertino, CA).

Quality parameters. For the acoustic analyses, we extracted the longest note of each melody ($M = 0.93$ seconds; standard error $= 0.034$). The selected note was the last note of "Happy Birthday" and the longest note of the romantic melody.

The variable known as *Energy distribution* allows one to observe the spectral balance and thus the energy in the band containing the singer's formant. This measurement was computed in two steps, using *AudioSculpt* and *OpenMusic* software (IRCAM, Paris, France). First, we separated the total frequency range into two bands following the procedure used in several studies of trained singers.[6,31,49,50] However, we adapted the frequency range according to the participants' gender, considering that the female formant pattern is scaled upward about 20% compared with the average male formant pattern. The two bands were 0–2 kHz and 2–4.5 kHz for the male participants and 0–2.4 kHz and 2.4–5.4 kHz for the female ones. The energy of the second band was then divided by the energy of the first band. Note that a high score for the energy distribution variable shows a strong reinforcement of the band containing the singer's formant.

The VR and VE were also measured with *AudioSculpt* and *OpenMusic* software (IRCAM). These measurements were supported by the fact that vibrato is defined as a quasiperiodic modulation of F_0, which is generally found to be closely sinusoidal.[13,22] For VR, the number of quasiperiodic modulations of the F_0 per second was reported in Hertz. For VE (ie, amplitude of the F_0 variations within the same tone), extreme F_0 values were measured from the F_0 curve. The difference between the minimum and maximum was reported in Cents.

Perturbation parameters. Perturbation analysis was performed on the same selected note using *Praat* software (Version 5.1.44 University of Amsterdam, The Netherlands).[51] We measured the *Standard Deviation of the Fundamental Frequency* (SDF_0) across the duration of the note, as an indication of the F_0 variations over a short period (in Hz). The *signal-to-noise ratio* (SNR) is commonly defined as the ratio of signal intensity to noise intensity. On the assumption that the notes analyzed were periodic, the SNR was estimated with the harmonic-to-noise measurement (in dB). The local *Jitter* (a measurement of period perturbation computed by dividing the average absolute difference between consecutive periods by the average period) and *Shimmer* (a measurement of amplitude perturbation computed by dividing the average absolute difference between the amplitudes of consecutive periods by average amplitude) were reported as percentages.

Note that for SDF_0, Jitter %, and Shimmer %, a high score shows a high perturbation of the auditory signal and is associated with a low vocal quality.

Musical parameters. The F_0 of the starting note was extracted using *Praat* software (Version 5.1.44)[51] and was reported in Hertz (Hz). The average *tempo* of the performance was calculated on the basis of its length, by dividing the number of beats (observed from the metrical indication in the musical score) by the duration of the performance (beats per minute). The *Sound level* (in dB) was also observed for the longest note of each melody using *Praat* software (Version 5.1.44).[51]

Statistical analysis

Each variable was modeled separately by means of multiple regression models, with the type of melody and the technique as covariates. An interaction effect between the melody and the technique, as well as a main effect of gender, were also included in the initial model. Note that the normality of each response variable was assessed through Kolmogorov-Smirnov test. Several variables (such as jitter, shimmer, and tempo) were log-transformed to increase the adjustment to normality. Then, the model was simplified by removing all statistically nonsignificant tests, using the likelihood ratio test for nested models.[52] The significance level was set at 5%. The final model was retained and discussed for further investigation of statistically significant trends. Although the effect of gender might be significant, this factor was used mainly as a control variable and will not be further discussed in this study. *z*-Scores were extracted from the retained models to describe both the strength and the direction of the relationships between melody and technique, on one hand, and the variables under study, on the other hand.

In a complementary analysis, we attempted to observe the profile of the operatic singing technique by modeling it as the dependent variable and including all the acoustical and musical parameters as model covariates. Logistic regression modeling of the probability of making use of the Western operatic singing technique was done. The model included all acoustical and musical parameters as main effects only. The "strength" of the relationships between the parameters and the type of singing technique was summarized by the *z*-scores derived from the logistic regression model. Those *z*-scores were plotted in decreasing magnitude to focus on the most significant covariates that can "predict" the use of the Western operatic singing technique. Note that the variables related to the participants' age and musical experience were also included in the study. However, none of them exhibited statistically significant effects. Therefore, they were not further considered in the analysis of the results.

RESULTS

Table 1 displays the means and standard deviations of the 10 parameters analyzed for each of the four vocal performances (birthday, romantic, ROMANTIC, BIRTHDAY).

The Pearson correlation matrix of the 10 parameters was computed to observe the relationships between the acoustical and musical features observed for the 200 sung performances. As Table 2 shows, in addition to the significant correlations between the perturbation parameters (SDF_0, SNR, Jitter, Shimmer), several significant correlations were found between these parameters and the F_0, energy distribution, VE, and sound level parameters. Regarding the relationships between the musical and quality parameters, the energy of the band containing the singer's formant increased with the sound level and the

TABLE 1.
Means and SD of the 10 Parameters Analyzed for Each of the Four Vocal Performances (ie, the Birthday and Romantic Melodies Performed Without and With an Operatic Singing Technique)

Parameters	Descriptive Statistics	Sung Performance			
		Birthday	BIRTHDAY	Romantic	ROMANTIC
Singing					
F_0 (Hz)	Mean	303	339	318	317
	SD	87.50	98.50	90.22	89.13
Tempo (beats per min)	Mean	93	76	80	73
	SD	20.39	16.31	33.50	31.28
Sound level (dB)	Mean	68.41	71.07	71.24	73.45
	SD	10.43	8.62	9.49	7.38
Quality					
Energy distribution (ratio)	Mean	1.88	1.60	2.20	1.95
	SD	0.37	0.35	0.65	0.60
VR (Hz)	Mean	5.87	5.95	5.75	5.95
	SD	1.23	0.83	0.72	0.82
VE (cents)	Mean	96.84	161.36	117.56	178.92
	SD	59.68	65.46	62.37	69.72
Perturbation					
SDF_0 (Hz)	Mean	5.22	9.37	7.30	10.39
	SD	3.70	4.74	6.94	5.17
SNR (dB)	Mean	24.76	21.35	27.29	21.82
	SD	3.93	5.59	5.55	5.29
Jitter (%)	Mean	0.31	0.38	0.27	0.43
	SD	0.19	0.19	0.16	0.24
Shimmer (%)	Mean	1.97	2.83	2.01	2.78
	SD	0.91	2.54	1.53	1.83

Abbreviation: SD, standard deviation.

F_0 of the starting note, whereas the VR increased with the tempo.

Effect of melody and technique on the singing parameters

Table 3 displays an overview of the effects of melody and technique on the acoustical and musical parameters, reporting F values, degrees of freedom, and P-values for both main effects. Note that the interaction between melody and technique never reached statistical significance and is, therefore, omitted from this table. Recall as well that gender was considered as a control factor but is not discussed here as it is outside the scope of the study.

The effect of melody is statistically significant for SNR, SDF_0, tempo, sound level, energy distribution, and VE. The final models reveal that singing the popular song with or without an operatic singing technique led to a smaller SNR ($P = 0.033$), a smaller SDF_0 ($P = 0.022$), a slower tempo ($P = 0.001$), a lower sound level ($P = 0.043$), a smaller energy distribution ($P < 0.001$), and a smaller VE ($P = 0.037$).

TABLE 2.
Observed Pearson Correlation Matrix of Musical and Acoustical Parameters for the 200 Sung Performances (*$P < 0.05$,$P < 0.01$)**

	Parameters	1	2	3	4	5	6	7	8	9	10
1	F_0	—									
2	Tempo	−0.06	—								
3	Sound level	0.07	0.09	—							
4	Energy	0.14*	−0.05	0.59**	—						
5	VR	0.10	0.22**	−0.11	−0.11	—					
6	VE	0.03	−0.10	0.08	−0.14*	−0.16*	—				
7	SDF_0	0.47**	−0.12	0.07	−0.04	−0.09	0.72**	—			
8	SNR	0.35**	−0.02	0.23*	0.54**	−0.05	−0.61**	−0.26**	—		
9	Jitter	−0.32**	0.01	−0.02	−0.25**	−0.03	0.59**	0.29**	−0.75**	—	
10	Shimmer	−0.28**	−0.11	−0.36**	−0.35**	−0.07	0.40**	0.18*	−0.73**	0.63**	—

TABLE 3.
***F*-Values, Degrees of Freedom, and *P*-Values of the Melody and Technique Effects for Each Parameters**

	Melody			Technique		
Parameters	*F*	df	*P*	*F*	df	*P*
F_0	0.106	1	0.745	3.263	1	0.072
Tempo	11.586	1	0.001	10.956	1	<0.001
Sound level	4.141	1	0.043	3.632	1	0.058
Energy distribution	18.783	1	<0.001	16.680	1	<0.001
VR	0.178	1	0.674	1.133	1	0.289
VE	4.430	1	0.037	47.904	1	<0.001
SDF_0	5.299	1	0.022	45.057	1	<0.001
SNR	4.637	1	0.033	40.717	1	<0.001
Jitter %	0.572	1	0.451	26.330	1	<0.001
Shimmer %	0.040	1	0.843	13.849	1	<0.001

The effect of technique, however, is significant for all variables but F_0, sound level, and VR. The response variables can be combined in two groups, as follows: the operatic singing technique yields an increase in SDF_0 ($P < 0.001$), Jitter % ($P < 0.001$), Shimmer % ($P < 0.001$), and VE ($P < 0.001$) compared with the performance without any particular singing technique. Conversely, the operatic singing technique results in a decrease in SNR ($P < 0.001$), tempo ($P < 0.001$), and energy distribution ($P < 0.001$) compared with the performance without any particular technique.

A visual representation of these results is given in Figure 1. The *z*-scores for the effects of melody (left panel) and technique (right panel) are displayed for the 10 parameters. In the left panel, positive *z*-scores indicate that larger values for the variables are obtained with the romantic melody. In the right panel, positive *z*-scores indicate that larger values for the variables are observed with the operatic singing technique. In both panels, significance levels are shown by horizontal dashed lines. The findings from this figure are in agreement with the results shown in Table 3.

As illustrated in Figure 1, the choice of melody ("Happy Birthday" vs romantic melody) had fewer consequences for the parameters observed than the choice of technique (with vs without an operatic singing technique). Regarding the quality parameters usually observed (energy distribution, VR, and VE), only VR was not affected by the effects of melody and technique. VE was larger with the romantic melody and with an operatic singing technique, whereas energy distribution was higher with a romantic melody (ie, strong reinforcement of the band containing the singer's formant) but lower with an operatic singing technique. The greatest differences were found with the perturbation parameters. The technique effect is clearly visible for all the parameters (SDF_0, SNR, Shimmer, and Jitter), which showed a high perturbation of the signal when the singers were asked to sing with an operatic singing technique. Otherwise, the perturbation parameters did not differ greatly depending on the melody. Concerning the musical parameters, the F_0 of the starting note did not differ significantly as a function of the melody performed or the technique used. However, the tempo was slower with the romantic melody and with the operatic singing technique. The sound level did not differ significantly depending on the technique but was higher with the romantic melody than with the birthday song.

Profile of the operatic singing technique

The results of the complementary analyses are displayed in Figure 2 as follows. The *z*-scores of statistical significance are displayed for each acoustical and musical parameter in decreasing order of magnitude. Positive *z*-scores indicate that the larger the value of the variable, the greater the probability of use of the operatic singing technique. Conversely, negative *z*-scores indicate that the larger the value of the variable, the lower the probability of making use of Western operatic singing technique. As in Figure 1, horizontal dashed lines refer to the significance limits (at significance level 5%).

As Figure 2 shows, five of the 10 parameters observed (sound level, tempo, energy distribution, VR, and F_0) seemed particularly important in the operatic singing technique profile. Note that *z*-scores of the SNR and the VE parameters were not significant but borderline, which can be interpreted as indicating that they are moderately important in the operatic singing profile. Conversely, the other parameters (Jitter, Shimmer, and SDF_0) do not appear to be significant predictors of this particular vocal technique.

DISCUSSION

The analysis of 50 singers performing two different melodies, with and without an operatic singing technique, provides a better understanding of this singing technique. Indeed, the experimental design of the present study allows us to observe the effects of melody and technique on acoustical and musical parameters. The correlation matrix confirms the relationships between the perturbation parameters and the link between musical and acoustical parameters. However, a closer examination of these parameters in a logistic regression model reveals the relevance of several specific parameters in explaining the Western operatic singing technique.

Effects of melody and technique

Quality parameters. The observation of the VR in the four kinds of performances (two melodies with two vocal techniques) confirms its consistency for a given singer.[17] With a mean of 5.88 undulations per second, the VR observed here is similar to that in several previous studies[13,14,16] but lower than others.[15] The results show that the melody or technique used by the singer did not affect the VR, which confirms the participants' training level and the consistency of this parameter regardless of the melody performed or the singing technique used by the singer.[13,20] The values for VE, on the other hand, depended on the melody (higher in the romantic melody) and the technique (higher with the operatic singing technique) used by the singer. Ranging between 14 and 370 cents ($M = 139$ cents), these values confirm the considerable variability of VE.[14,22,24,25]

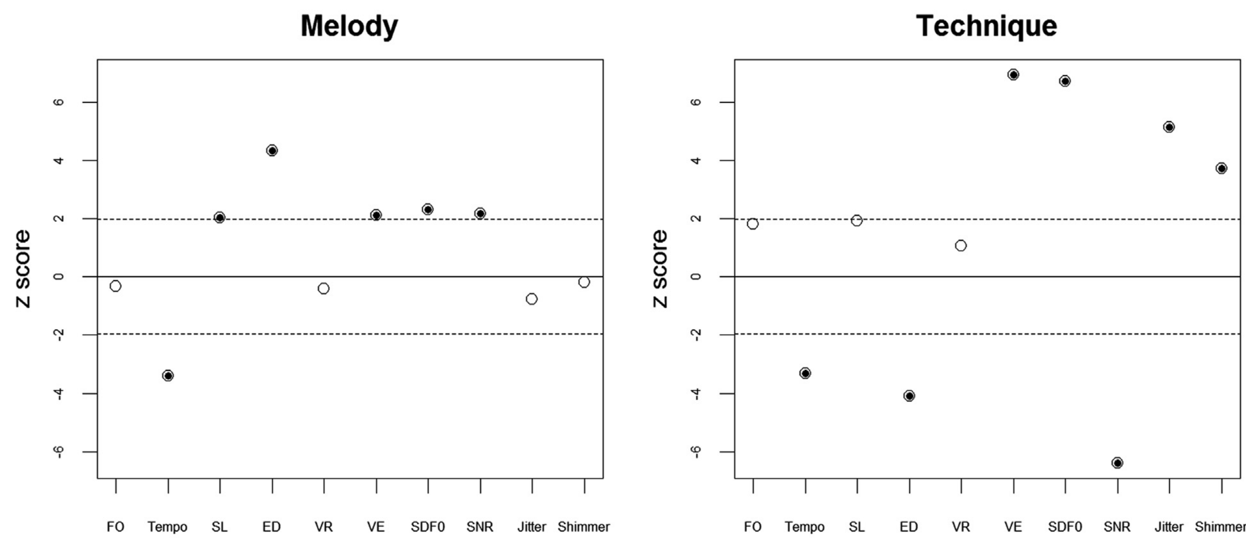

FIGURE 1. *z*-Scores for significant and nonsignificant effects of melody (left) and technique (right) on the 10 parameters observed: fundamental frequency of the starting note (F_0), tempo, sound level (SL), energy distribution (ED), vibrato rate (VR), vibrato extent (VE), standard deviation of the fundamental frequency (SDF_0), signal-to-noise ratio (SNR), Jitter, and Shimmer. Positive *z*-scores for melody indicate a positive effect of the covariate on the romantic melody. Positive z-scores for technique indicate a positive effect of the covariate on the operatic technique. Dashed horizontal lines refer to the 5% significance levels for *z*-scores.

The melodic effect highlights the relevance of selecting melodies that are specific to the singing technique investigated to observe acoustical parameters in future studies. The melodic effect observed for the energy distribution variable also points to the necessity of focusing on appropriate melodic material for observing the spectral balance of trained singers. Indeed, our result shows that the band containing the singer's formant is strongly reinforced when he or she performs a romantic melody. However, despite the participants' training level, we observed considerable variation in spectral balance. Other

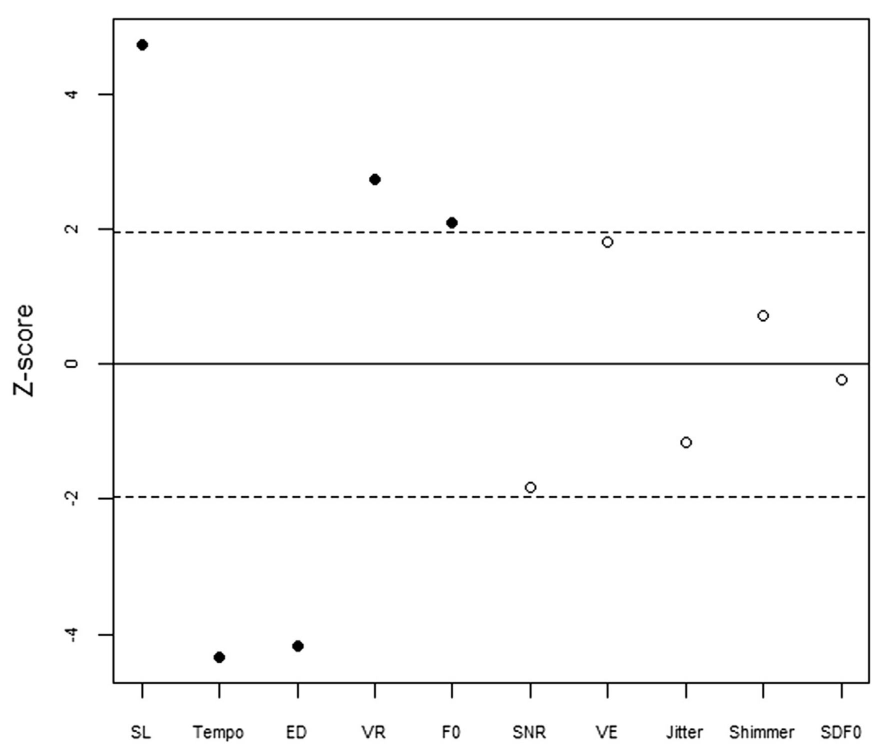

FIGURE 2. *z*-Scores for significant and nonsignificant effects of the 10 acoustical and musical parameters to clarify the operatic singing technique. Positive *z*-scores indicate positive effects of the covariates on the operatic technique. Dashed horizontal lines refer to the 5% significance levels for *z*-scores.

measurements, such as the singing power ratio,[27] energy ratio,[6] and α coefficient[32] could provide more information about this variability, as could controlling the sound pressure level.

Perturbation parameters. As expected, the jitter and shimmer measurements were particularly high with the operatic singing technique.[34] The other two perturbation parameters examined (SNR and SDF_0) generated similar results and support the hypothesis that the operatic singing technique leads to a high perturbation in intensity, amplitude, and frequency. Note that there was a limited effect of melody and the perturbation parameters were rather sensitive to the technique used. However, these findings should be compared with perceptual judgments. In fact, parameters such as jitter, shimmer, and SNR have been shown to be relevant for complex acoustical signals,[35–37] but the analytical tools may be limited; for example, a strong perturbation may lead to a failed F_0 extraction in perturbation analysis and thus provide irrelevant information.[53] Regarding the significant correlations between VE and the perturbation parameters, our results suggest the need to control for VE in future research on the aperiodicity of operatic singing voices.

Musical parameters. The F_0 of the starting note of the performance was not affected by melody or technique. Note that the participants had the opportunity to perform the two different melodies in their comfortable range (no starting note was given for "Happy Birthday" and the romantic melody was chosen by the participant), which explains the absence of melody effect. For the popular song, the F_0 seemed higher when the participants performed with an operatic singing technique (Table 1). However, the technique effect is not shown in the statistical analyses (Table 3), as they included the chosen melody, for which the starting note was controlled. Conversely, we observed a different tempo depending on the melody (slower for the romantic melody) and the technique used (slower with an operatic singing technique). Slow melodies thus seem to be representative of the romantic music era according to the participants, who chose the songs. Note that songs were sung more slowly with an operatic singing technique despite the tempo indication in the musical score.

Because vibrato is relevant in the operatic singing technique and takes place on vowels, trained singers may extend the duration of the vowels. It is, therefore, not surprising that the duration of the performance was longer with an operatic singing technique and when performing the romantic melody (ie, representative of the classical repertory). The technique effect observed confirms previous findings with a larger panel of professional singers.[38] In this study, the authors also found a relationship between tempo and singing voice accuracy when professional singers performed with an operatic singing technique (the faster they sang, the more accurate they were). As the present study highlights the effect of melody on the tempo, it seems relevant to observe similar melodies (in a singing research or music evaluation context) to control for this musical parameter and its consequences for the quality of the sung performance.

As for the loudness of the voice, the results show an effect of melody (louder with the romantic melody) but no effect of technique. The experimental design (each singer performed both melodies with both singing techniques, without removing the recording equipment) allows us to observe the correlation between this parameter and the energy of the band containing the singer's formant, as expected.[31,32] However, this variable should be controlled to accurately define the energy distribution of the operatic singing technique.

Profile of the operatic singing technique

The results clearly show the effect of technique on several parameters. However, the analysis of the 10 parameters in the logistic model identifies five parameters that explain the operatic singing technique: sound level, tempo, energy distribution, VR, and F_0 of the starting note. Note that two parameters were marginally significant (VE and SNR). These findings have pedagogical implications and provide some guidelines for singing teachers. The relationships between these acoustical parameters and physiological components have been examined[1–6] and music teachers could focus on the components linked to the parameters highlighted by the logistic model in this study (Figure 2). They could, for instance, focus on subglottal pressure to improve vocal projection and increase the energy in the band containing the singer's formant as well as the sound level of the performance. Because VR can be somewhat modified deliberately, by musical training or by warming up,[19–21] this parameter could be to the subject of specific training so singers can learn to reach a frequency around 5.95 Hz. In addition, although the tempo and the F_0 of the starting note are given by the musical score, prolonging the vowels (ie, slowing down the tempo) and choosing melodies in the high part of the singer's range would enhance the operatic character of a performance.

Still, this model needs to be developed and expanded before it can provide a precise definition of the operatic singing technique. First, the present study has the advantage of observing "typical" performances by Western operatic singers, but it also has some limitations regarding the number of notes that could be analyzed in each performance and the duration of the analyzed notes. Future studies with less typical musical material that is better adapted for acoustical analyses would be valuable to confirm these findings. Second, a larger number of participants would refine the present results. Third, this study focused on semiprofessional or professional singers and the number of years of musical training was shown to have no significance in the model. However, this pattern could vary as a function of other characteristics such as singing level or vocal ability. It would, therefore, be interesting to compare different singing levels, defined on the basis of Bunch and Chapman's taxonomy of singers or the phonetogram for singers.[54,55] Furthermore, the parameters examined in the present study are not exhaustive. Additional parameters such as the variation in VR and VE along the note,[56] articulation,[4] text intelligibility,[57] vocal accuracy,[38] formant tuning,[58] or other measurements of spectral distribution[31] could complete this framework. Finally, the statistically significant parameters describing the operatic singing voice could be observed to assess this singing technique objectively. However, this model would have to be compared with the perceptual judgment of expert judges to confirm the relevance of these parameters in classical music.

CONCLUSION

Several parameters (quality, perturbation, and musical) were examined in two different melodies sung with and without an operatic singing technique. The results confirm the effect of technique on the VE, energy distribution, perturbation parameters, and tempo of the performance. By examining these parameters in a theoretical model, this study highlights the relevance of sound level, tempo, energy distribution, VR, and F_0 of the starting note in describing the Western operatic singing technique. Although this model needs to be further developed in future research, it has already generated some implications for research and teaching.

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