CPPS and Voice-Source Parameters: Objective Analysis of the Singing Voice

*Calvin P Baker, †Johan Sundberg, ‡Suzanne C Purdy, *Te Oti Rakena, and §Sylvia H de S Leão, *‡Auckland, and §Grafton, Auckland, New Zealand, and †Sweden

SUMMARY: Introduction. In recent years cepstral analysis and specific cepstrum-based measures such as smoothed cepstral peak prominence (CPPS) has become increasingly researched and utilized in attempts to determine the extent of overall dysphonia in voice signals. Yet, few studies have extensively examined how specific voice-source parameters affect CPPS values.

Objective. Using a range of synthesized tones, this exploratory study sought to systematically analyze the effect of fundamental frequency (f_o), vibrato extent, source-spectrum tilt, and the amplitude of the voice-source fundamental on CPPS values.

Materials and Methods. A series of scales were synthesised using the freeware *Madde*. Fundamental frequency, vibrato extent, source-spectrum tilt, and the amplitude of the voice-source fundamental were systematically and independently varied. The tones were analysed in *PRAAT*, and statistical analyses were conducted in *SPSS*.

Results. CPPS was significantly affected by both f_o and source-spectrum tilt, independently. A nonlinear association was seen between vibrato extent and CPPS, where CPPS values increased from 0 to 0.6 semitones (ST), then rapidly decreased approaching 1.0 ST. No relationship was seen between the amplitude of the voice-source fundamental and CPPS.

Conclusion. The large effect of f_o should be taken into account when analyzing the voice, particularly in singing-voice research, when comparing pre and posttreatment data, and when comparing inter-subject CPPS data.

Key Words: Cepstral analysis−CPPS−Singing−Voice−Voice analysis.

Abbreviations: CP, Cepstral peak−CPP, Cepstral peak prominence−CPPS, Smoothed cepstral peak prominence−f_o, Fundamental frequency−P_{sub}, Subglottal Pressure−SPL, Sound pressure level−ST, Semitones−VE, Vibrato extent−WCSV, Western classical singing voice.

INTRODUCTION

Smoothed cepstral peak prominence (CPPS) has been touted as a robust overall measure of dysphonic voice characteristics in single vowel and connected-speech tasks.[1−5] The ability of cepstral measures to operate without traditional pitch tracking methods, such as those used in jitter and shimmer, allows for their application to highly irregular signals (type II in Titze's model).[6]

The cepstrum has been defined as a spectrum of a spectrum, whereby an inverse Fast Fourier Transform of the natural log of a frequency-domain spectrum is applied, transforming the spectrum to the time domain.[7] The cepstral peak (CP) is a representation of the most dominant peak in the cepstrum − normally the fundamental frequency (f_o) in a type I signal. After its first applications to voice by Noll,[8,9] Hillenbrand et al[10] established the method of normalizing the amplitude of the overall cepstrum using a linear regression line. When applied to the cepstrum, the level difference (dB) between the cepstral peak and the regression line at the same quefrency provides the cepstral peak prominence (CPP). CPPS, as first described by Hillenbrand and Houde,[11] is derived when a smoothing factor is applied to the individual cepstra before extraction of the CPP. Figure 1 illustrates the relevant components of the smoothed cepstrum and CPPS. The harmonics in the spectrum translate to rahmonics in the cepstrum − another play on words originating from the inverted nature of the cepstrum.[12] Near-periodic signals (type I) with clear harmonic organization are expected to have distinct rahmonics and a clearly defined cepstral peak. As noisy or dysphonic signals (type II) show reduced harmonic organization and increased noise in the spectrum, rahmonic distinguishability is hindered and the CPP is lowered. In the case of completely aperiodic signals (type III) no CP would be present.

Hillenbrand et al [10,11] found a strong correlation between perceptual measures of breathiness in normophonic and dysphonic subjects and CPP magnitudes. Heman-Ackah et al[2,5] compared perceptual ratings of dysphonic voices to CPPS values in running speech and sustained /a/ vowel tasks. In both studies (2002 and 2003) the CPPS values obtained from speech and vowel tasks proved reliable in predicting overall grade of dysphonia as well as breathiness. Awan et al[13] saw similar results when testing the ability of

Accepted for publication December 13, 2021.

From the *Department of Voice, School of Music, University of Auckland, Auckland Central, Auckland, New Zealand; †Division of Speech, Music and Hearing, School of Electrical Engineering and Computer Science, KTH (Royal Institute of Technology), Stockholm, Sweden; Department of Linguistics, Stockholm University, Stockholm, Sweden; University College of Music Education Stockholm, Sweden; ‡-School of Psychology, University of Auckland, Auckland Central, Auckland, New Zealand; and the §Speech Science, School of Psychology, University of Auckland, Grafton, Auckland, New Zealand.

Address correspondence and reprint requests to Calvin P Baker, Department of Voice, School of Music, University of Auckland, Auckland Central, Building 250, 6 Symonds St, Auckland 1010, New Zealand E-mail: calvin.baker@auckland.ac.nz

Journal of Voice, Vol. ■■, No. ■■, pp. ■■−■■
0892-1997

https://doi.org/10.1016/j.jvoice.2021.12.010

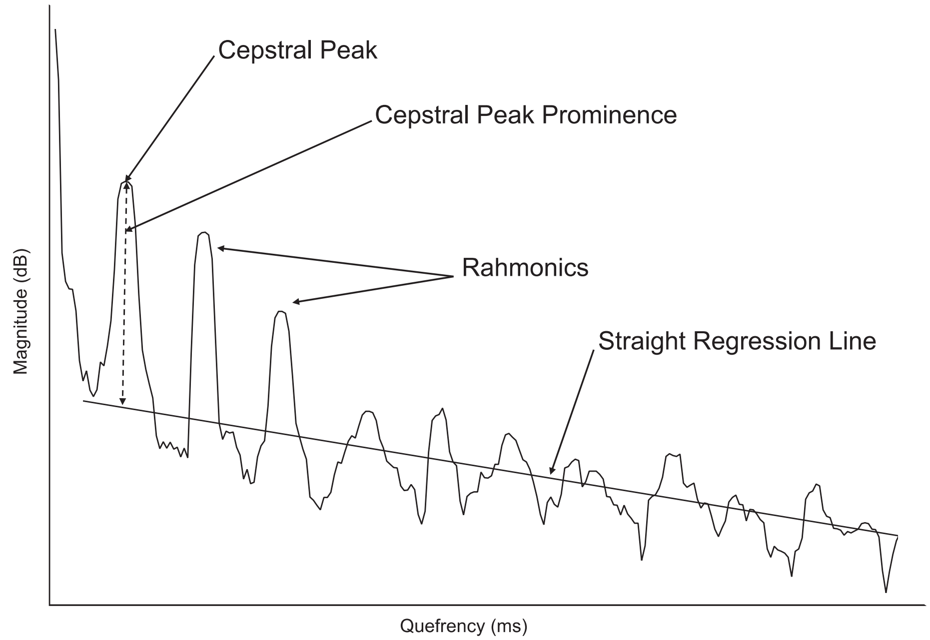

FIGURE 1. Schematic illustrating the components of the smoothed cepstrum and its regression line for determining the CPPS in a quasi-periodic signal (type I).

CPP to predict pre and posttreatment changes in dysphonic patients, independently and as a part of a composite spectral/cepstral model. Later, a meta-analysis of the literature considering the efficacy of various traditional and non-traditional acoustic voice measures to determine overall dysphonia severity led Maryn et al[14] to conclude that CPPS 'can be regarded as the most promising and perhaps robust acoustic measure of dysphonia severity.'

Although cepstral measures and in particular CPPS have proven utility in distinguishing normophonic and dysphonic voices, there are still very few published studies reporting how CPPS reacts to singing-voice variables such as extremes in f_o, vibrato extent (VE), source-spectrum tilt, and amplitude of the voice-source fundamental. Several studies have observed or directly explored the effects of f_o, sound pressure level (SPL), and formant frequencies on CPP and CPPS values using the speaking voice.[15−20] Such studies have exemplified the necessity of control and standardization of voice tasks and measurement procedures (particularly SPL), and many of the authors have called for further research to determine the effects of such variables on cepstrum-based measurement outputs. While these works have included a wide variety of subjects and voice types, they have not considered these variables in the context of the singing voice. Thus, a specific analysis of the effect of such variables on CPPS in the context of the singing voice appears warranted.

CPPS and the singing voice

In the clinical realm, CPPS has been used with sustained-vowel and connected-speech tasks,[1,2,10,11,21] however meagre information is available regarding its behavior in sung tasks. Singing elicits various physio-acoustic parameters that are in many ways different to speech,[22−27] hence the inclusion of singing tasks is crucial when working with a singer for determining underlying vocal issues. In Western classical vocal music, singers are trained to develop specific and highly nuanced control of variables such as pitch, intensity, and vibrato. Operatic *arie* generally contain singing ranges of well over one octave (consider the vocal works of Rossini, Rubini, and Donizetti, for example). Most *arie* have *tessiture* (the most frequently sung pitch within the aria) well above the normative ranges for adult speech.[28−30] While f_o and intensity typically increase together in speech, singers are trained to independently control these parameters − some vocal works require a high f_o and low sound intensity, and others the opposite, all for the sake of character portrayal and emotional expression.[31,32] Physiologically, these mechanisms are manifest in control of and interaction between subglottal pressure (P_{sub}), glottal adduction, and vocal-tract shaping (breath, voice source, and articulator coordination).

Cepstral measures are promising for the voice clinician and researcher due to their robustness to environmental factors and ability to function with almost aperiodic signals,[33,34] but there is a clear lack of application of cepstral measures in singing-voice research using sung tasks. Stoller and Dixon[35] found CPPS to be useful in distinguishing 'breathy' from all other phonation modes in single sung vowels across a pitch range of approximately 274 Hz. Castellana et al[36] observed differences in CPPS distribution between spoken and sung tasks and asserted that this was due to 'a better control of vocal folds during singing performance'. Mendes et al[37] and Toles et al[38] also incorporated CPPS in their research using sung tasks but found contrasting results regarding the difference between speech and sung-task CPPS values: Mendes et al[37] found that CPPS values were higher in singing than speech, while Toles et al[38] found the opposite. No detailed discussion was offered in either study as to how the cepstral measures used may have been affected by singing voice parameters across a wide range of f_o.

As little is known regarding the specific effects of singing-voice variables on cepstrum-based measures, the interpretations of the CPPS outcomes in the above studies are somewhat hindered. Using controlled synthesized tones, the present exploratory study sought to determine the effects of systematic changes in f_o, VE, source-spectrum tilt, and the amplitude of the voice-source fundamental on CPPS values. Gross shifts in f_o are usually perceptually evident and have clear physiological attributes.[27,39] Changes in vocal-fold length, vibratory mass, and tension that result in rising and falling f_o have effects on the oscillatory properties of the vocal-folds, perceived as timbral changes between singing registers.[40–43] A few studies have observed the gender differences in CPP, CPPS, and other acoustic perturbation measures, in both normophonic and dysphonic subjects,[37,44–46] which may be related at least in part to an f_o effect. If so, we may find differences in CPPS values between the normative speaking f_o ranges of male and female voices, even in synthesized tones. Ferrer-Riesgo and Nöth[47] predicted a non-monotonic relationship between f_o and CPP, whereby CPP would increase with f_o as the waveform shape becomes more sinusoid, and then begin decreasing as upper rahmonics become more prominent due to the increasingly impulse-like shape of the waveform ie, reducing the CPP.

Smaller oscillatory f_o changes such as those seen in VE in Western classical singing are also perceptually evident but appear to only be one aspect in a larger interaction between breath pressure, flow, and vocal-tract shaping that contributes to vibrato characteristics.[48–54] The f_o changes during vibrato may have a 'smearing' effect on the smoothed cepstrum and thus obscure accurate CPPS measurement – a large VE may 'smear' the cepstrum to a greater degree than a small VE. As SPL has been seen to significantly affect CPPS values in the speaking voice – where increased SPL results in increased CPPS[16,17] – we may expect to see the same effect in the singing voice. However, as the measurement of SPL can be impacted by recording conditions and methods and is influenced by the first formant,[55,56] the use of source-spectrum tilt (dB/octave) as an indication of intensity may be a more reliable parameter to consider, as it specifically relates to the spectrum of the voice source.[57–59] The relative amplitude of the first harmonic (H1) has been related to the severity of perceived breathiness in several studies and appears to be determined by glottal adduction and P_{sub}.[11,60–62] Therefore, it seems relevant to test the effect of changing the relative H1 amplitude of the source-spectrum on CPPS values. This study used controlled synthesized tones to explore the relationships between these voice-source parameters and CPPS. Results from such an exploration may strengthen the conclusions of existing research that used CPPS in sung tasks or contribute toward alternative interpretations.

MATERIALS AND METHODS

Independent conditions

The effects of increasing f_o, VE, source-spectrum tilt, and the amplitude of the source-spectrum fundamental on CPPS were analyzed systematically. Each tone was generated for a length of approximately ten seconds using the freeware *Madde*,[63] at a sampling rate of 44.1 kHz and a bit depth of 16-bits. *Madde* is a formant synthesizer that follows a linear source-filter type model that enables the user to independently control voice-source parameters, and so was an ideal tool for the present study. While relatively new, it has shown

TABLE 1.
Conditions Used to Test the Effect of Various Voice-source Parameters on CPPS Values (/a/ vowel)

Condition	f_o (Hz)	Vibrato Rate (Hz)	Vibrato Extent (Semitones)	Source-Spectrum Tilt (dB/octave)	H1 Amplitude (dB re dB/octave)	*N* of tones
1.1	87 – 699 (stepwise)	5.5	0.4	-6	0	37
1.2	87 – 699 (stepwise)	0.0	0.0	-6	0	37
2.0	220	5.5	0.0 to 1.0 ST in 2-ST increments	-6	0	6
3.0	220	5.5	0.4	-18 to -6 in 2-dB/octave increments	0	7
4.0	220	5.5	0.4	-6	-10 to 10 in 5-dB increments	5
						92

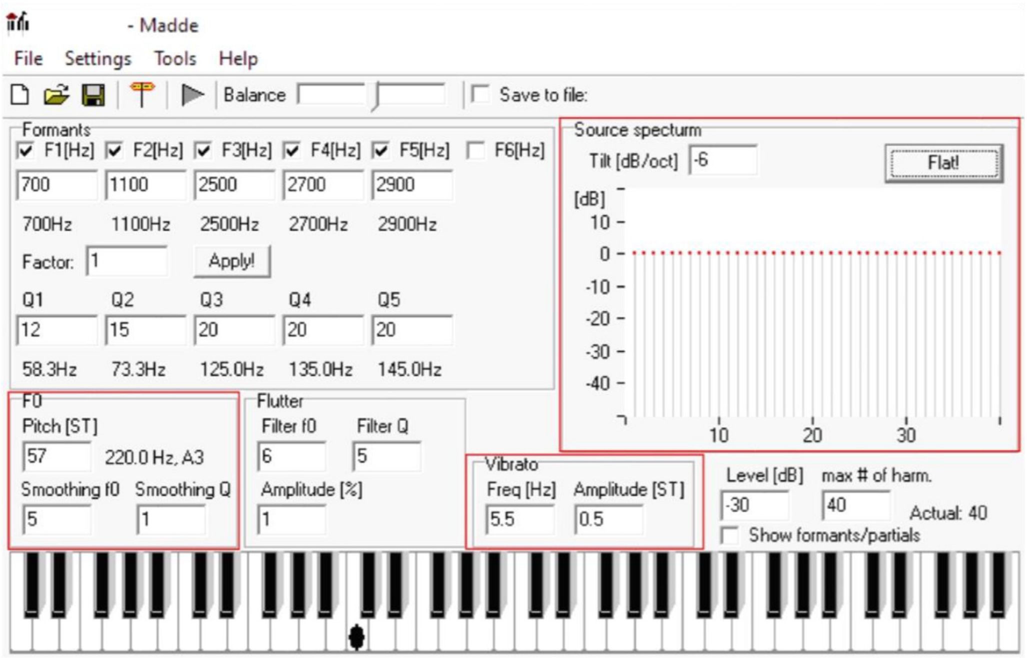

FIGURE 2. Screenshot of Madde configuration.

promise in both pedagogical and research use.[64,65] Table 1 shows the conditions of the synthesized tones, each of which were generated and analyzed separately. Figure 2 shows the programme interface, with the relevant sections for the present study highlighted.

Fundamental frequency and vibrato (Condition 1.1 and 1.2)

In Condition 1.1 37 stepwise (chromatic) tones over three octaves (87 to 699 Hz) were generated. This range was determined to be inclusive of the *tessiture* of all *Fächer* in both male and female Western classical singing. Vibrato was maintained at a rate of 5.5 Hz and extent of 0.4 semitones (ST). In Condition 1.2, the same stepwise scale was generated with identical *Madde* configuration, apart from VE, which was set at 0.0 ST. Intensity was not controlled through the scales.

While changing formant frequencies in a linear formant synthesizer such as *Madde* should not produce an effect on the voice source, the effect of formant frequencies on the overall spectrum may be relevant. To test this sub-inquiry, another three-octave stepwise scale was generated, using the same parameters as Condition 1.1, but with formant frequencies set to produce an /i/ vowel. CPPS values for /a/ and /i/ in Condition 1.1 could then be compared to observe any significant difference.

Vibrato extent (Condition 2.0)

Vibrato extent was varied from 0.0 to 1.0 ST, separately and in increments of 0.2 ST while a f_o of 220 Hz and all other configurations in *Madde* were held constant.

Source-spectrum tilt (Condition 3.0)

While SPL can be superficially changed simply by varying the overall signal amplitude digitally, a change in intensity that reflects voice-source behaviour is reflected in the degree of source-spectrum tilt. Thus to explore the effect of changes in intensity on CPPS values, source-spectrum tilt was reduced independently in 2-dB/octave increments from -18 to -6 dB/octave while a f_o of 220 Hz and all other configurations in *Madde* were held constant.

Amplitude of voice-source fundamental (Condition 4.0)

The amplitude of the voice-source fundamental was increased from -10 to 10 dB separately and in 5-dB increments while f_o of 220 Hz and all other configurations in *Madde* were held constant.

Data analysis

The output files were converted to WAV format in *Sopran.*[66] The medial five-second portion of each ten-second signal was extracted to avoid any onset or offset artifacts[67] and analyzed using *PRAAT*[68] (v. 6.1.5 for mac), which has been used extensively in both voice research and clinical applications and has proven validity in cepstral analysis.[1,3,16,69] CPPS was determined for each tone using the 'To PowerCepstrogram' function, following the method reported in Watts et al,[3] and used by others.[1,16,19] It is important to note that the 'Peak search pitch range (Hz)' was increased from 60 to 330 Hz (standard) to 60 to 1000 Hz to accommodate the f_o of all generated tones in Conditions 1.1 and 1.2. *PRAAT* has two available methods

TABLE 2.
Descriptive Statistics of CPPS Values From All Conditions: Increasing *fo* With and Without Vibrato (1.1 and 1.2), Increasing Vibrato Extent (2.0), Increasing Intensity (3.0), and Increasing the Amplitude of the Voice-source Fundamental (4.0)

Condition	*N* of tones	Range	Minimum	Maximum	Mean	*SD*
1.1	37	9.6	17.1	26.7	24.4	2.63
1.2	37	10.3	16.5	26.8	23.0	2.97
2.0	6	1.84	24.75	26.59	26.0	0.708
3.0	7	4.7	21.9	26.6	24.2	1.63
4.0	5	0.28	26.45	26.73	26.6	0.099

for determining CPPS, however the newer method used here has proven to be robust and is simpler in implementation.[1,3] Raw data were entered into *Excel* for graphing and the computation of trends. IBM *SPSS* (v. 27 for Mac) was used to perform correlation analyses (Kendall's tau-b) between the singing-voice variables and CPPS values. A Related-Samples Wilcoxon Signed Rank Test was used to compare Condition 1.1 and 1.2, and vowel differences between /a/ and /i/ in the Condition 1.1 sub-question. Data were transformed into z-scores before statistical analysis.

RESULTS

Across all conditions a total of 129 tones (92 /a/ vowel + 37 /i/ vowel) were generated for analysis. Table 2 shows descriptive statistics for CPPS values from all the /a/ vowel conditions.

Fundamental frequency and vibrato (1.1 and 1.2)

Condition 1.1 showed two distinct patterns (Figure 3). From 80 to 175 Hz CPPS increases steeply, τ = 1, P < 0.001. Subsequently CPPS magnitude begins to decline from 180 to 699 Hz, τ = -0.971, P < 0.001. Partial correlation analysis confirmed a strong relationship between f_o and CPPS in both ranges when controlling for intensity (dB), r = 0.909 and -0.996 respectively.

Condition 1.2 displayed similar patterns (Figure 3), with CPPS values increasing from 80 to 175 Hz (τ = 1, P < 0.002) and decreasing from 180 to 699 Hz, τ = -0.993, P < 0.001. Partial correlation analysis confirmed the relationship between f_o and CPPS when controlling for intensity: r = 0.866 for the lower band, and r = -0.988 for the upper. A Related-Samples Wilcoxon Signed Rank test showed a non-significant difference between Condition 1.1 (M = 23.4) and 1.2 (M = 23.0) CPPS values (z = -1.803, P= 0.071, r = -0.21) – ie, the presence or absence of vibrato did not cause a statistically significant difference in CPPS values under these two conditions.

Two linear equations were used to account for the f_o dependent changes in CPPS: one for tones between 80 and 175 Hz, and another for tones between 175 and 699 Hz. To determine the point of inflection for these two trendlines several points were systematically varied to ensure the best fit, using the optimal R^2 value as criterion. Figure 4 shows these linear equations generated from Condition 1.1, both with a robust fit, R^2 > 0.900. Figure 5 illustrates the successful

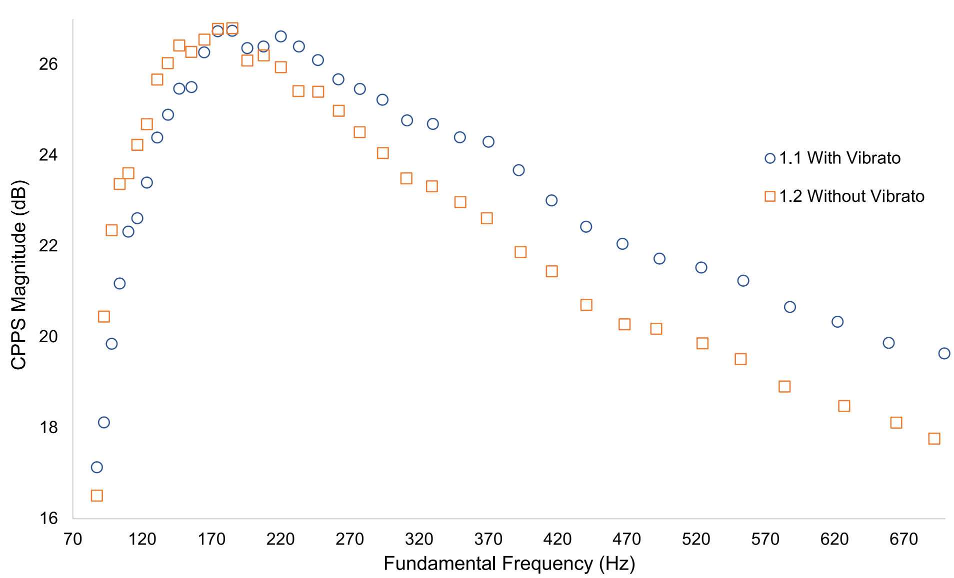

FIGURE 3. Relationship between CPPS and f_o for with and without vibrato (Conditions 1.1 and 1.2).

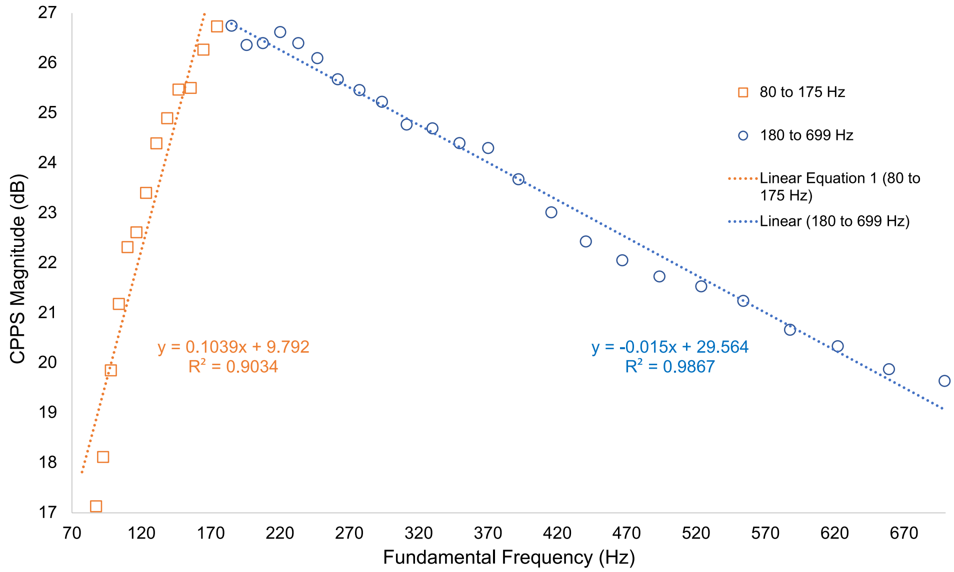

FIGURE 4. Relationship between CPPS and f_o with linear approximations (dotted lines) and their equations.

correction of the f_o effect using the relevant equations, where the range of CPPS across three octaves is reduced from 9.61 dB (Figure 3) to 2.83 dB.

$$y = 0.1039x + 9.792 \tag{1}$$

$$y = -0.015x + 29.564 \tag{2}$$

The larger deviation of corrected CPPS values below 175 Hz can be attributed to the more curved shape of the Condition 1.1 CPPS data in this frequency range, thus deviating further from the linear approximation. However, the linear fit line maintained a robust R^2 value and was therefore used for simplicity. Furthermore, the magnitude of the deviation in this part of the scale is minimal (SD = 0.96).

In all conditions, the frequencies of the first and second formants were 700 and 1100 Hz, respectively, producing an /a/ vowel. To explore the effect of different formant frequencies, the same three-octave chromatic scale and *Madde* configuration for Condition 1.1 was recreated with formant frequencies set to produce an /i/ vowel (see Figure 6). While there was a small overall decrease in CPPS values (/a/ M = 23.4; /i/ M = 23.2), the difference did not reach statistical significance in a Related Samples Wilcoxon Signed-Rank test, z = 389 P = 0.572. The shape of the CPPS data across the frequency range is strikingly similar to that seen in for the /a/ vowel (Figure 3) and indicates that formant frequencies alone do not have a significant bearing on the effect of f_o on CPPS values.

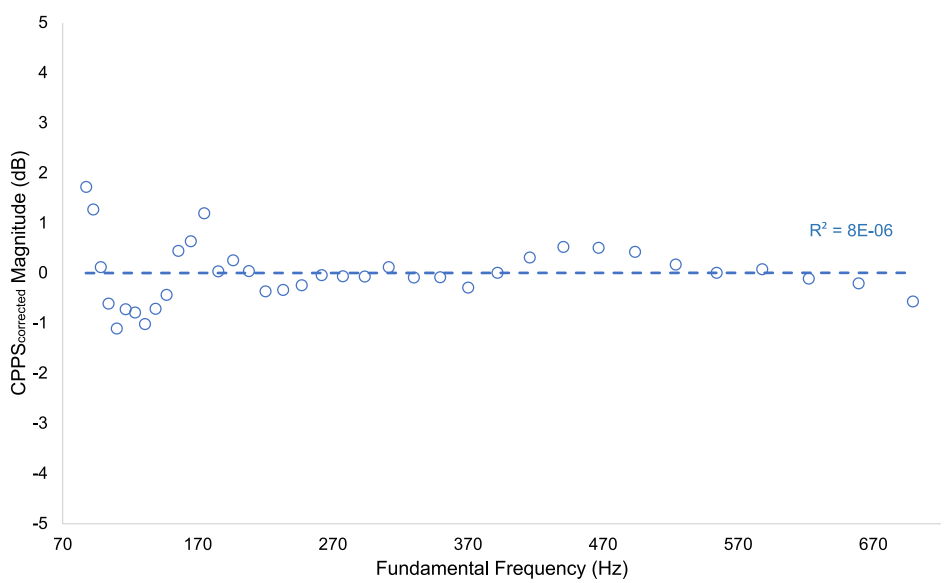

FIGURE 5. Relationship between CPPS f_o after correcting the CPPS values with Equation (1) for tones between 80 and 175 Hz, and Equation (2) for tones between 180 and 699 Hz.

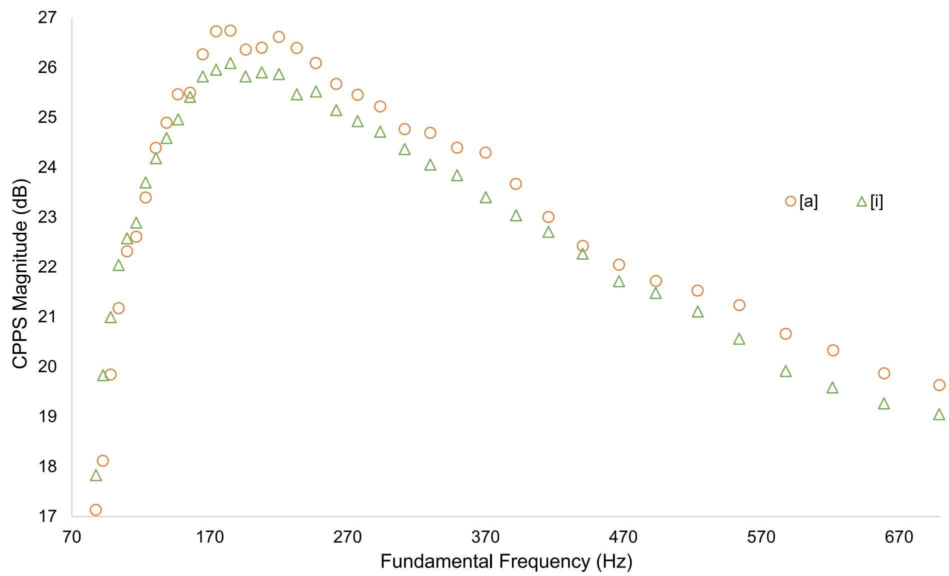

FIGURE 6. Relationship between CPPS for the vowels (a) and (i), and f_o.

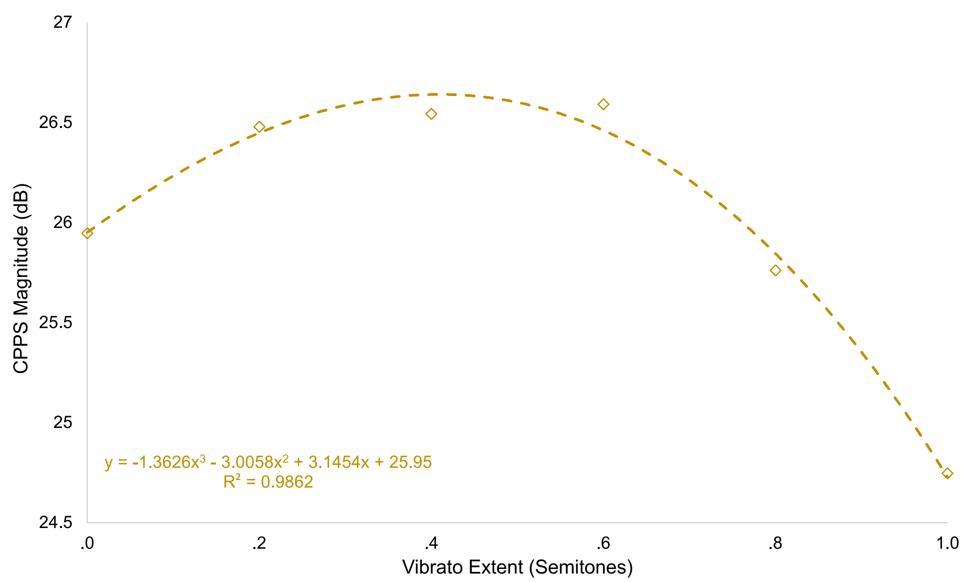

FIGURE 7. Relationship between CPPS and VE (Condition 2.0), approximated by the cubic equation and its R^2 value shown.

CPPS with increasing vibrato extent (2.0)

Increasing VE had an overall degrading effect on CPPS values (Figure 7). There was a small increase in CPPS values from 0.0 to 0.6 ST (approximately 0.5 dB), and a decrease of nearly 2 dB with the increase in VE from 0.6 to 1.0 ST. Although Figure 7 displays a systematic dependence, this was not statistically significant (τ = -0.200, P = 0.537), which likely reflects the small number of data points rather than a lack of association.

Source-spectrum tilt (3.0)

Source-spectrum tilt was reduced by 2-dB/octave increments from -18 to -6 dB/octave. A strong association was seen between source-spectrum tilt (intensity) and CPPS (Figure 8), τ = 1, P = 0.002. While the curve of the data is not strictly linear, a linear fit line maintained a robust R^2 value of 0.968.

Amplitude of voice-source fundamental (4.0)

No significant relationship was seen between CPPS and the amplitude of the voice-source fundamental, R^2 Cubic = 0.248, τ = 0.200, P = 0.624.

DISCUSSION

Fundamental frequency

The systematic exploration using synthesized sung tones presented in this study reveals several relevant interactions

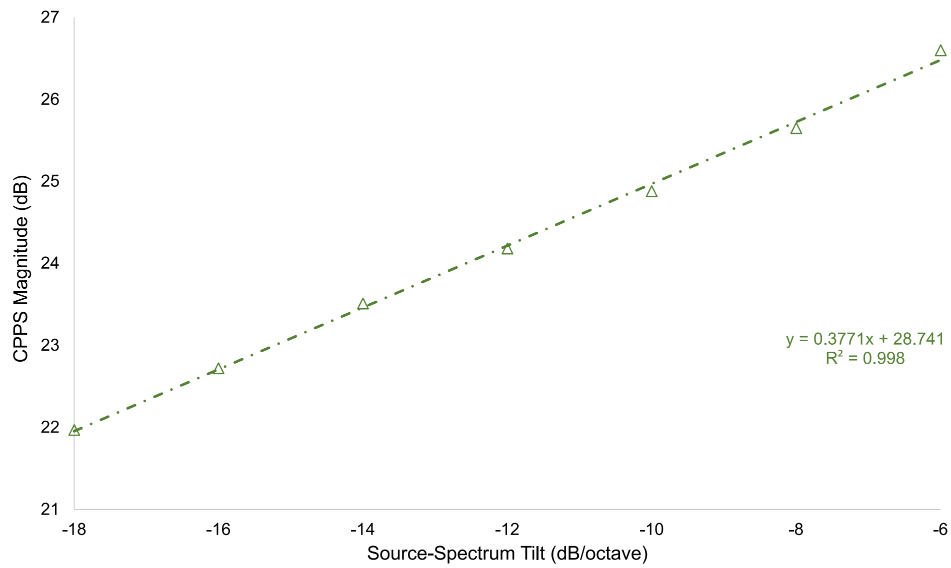

FIGURE 8. Relationship between CPPS and source-spectrum tilt with an approximated linear fit line and equation with the associated R^2 value (Condition 3.0).

between common singing-voice parameters and CPPS. The largest effect is that of f_o. First, a steep increase in CPPS was seen between f_o values of 80 and 175 Hz. Skowronski et al[18] observed a similar trend in cepstral peak (CP) values from 70 to approximately 150 Hz. Second, CPPS reduced in magnitude between f_o values of 180 and 699 Hz. The non-monotonic relationship between f_o and CPPS seen here supports earlier theoretical predictions, the technicalities of which have been considered in some prior research.[47,70,71] Here, we have focused on the effects of voice-source variation relevant to singing voice analysis. To the authors' knowledge, this is the first study to report on the systematic decline in CPPS values as an association of f_o values greater than 300 Hz.

This large f_o effect on CPPS may shed some light on the findings of Toles et al,[38] who observed lower CPP values for singing than for speech in a cohort of singing majors. In their study, the mode f_o for participants during singing phonation over one week (measured using ambulatory voice monitors) was reported as over 100 Hz higher than that of speech (325 and 203 Hz respectively, $P < 0.001$). These findings are consistent with those of the present study (see Figure 3).

Conversely, Mendes et al[37] – who considered CPPS in a population of one hundred normophonic Fado singers – found that sung tasks (a sung /a/ vowel and a chorus from a Fado song) produced higher CPPS values than speech tasks (a speech-voice sustained /a/ vowel and a reading passage). No SPL or f_o data were provided in the paper – it appears that all conditions were performed at a comfortable loudness and habitual pitch. In light of the findings of the present work, questions arise as to the interpretation of the higher CPPS in the singing voice found in Mendes et al's study. The authors describe the acoustic characteristics of Fado as a 'rough, but not breathy, hoarse and tense voice with a laryngopharyngeal resonance' and a generally lowered f_o. This description of the Fado singing voice paired with their data highlights the uncertainty regarding what CPPS represents for different singing styles and voices. If CPPS primarily reflects strength of spectrum partials, ie, the degree of spectrum tilt, then even some dysphonic voices (such as hyperfunction) may achieve normophonic values through unhealthy compensatory vocal functions. Further, if in Mendes et al's data the average f_o of the sung task was similar to that of the speech task, then increased P_{sub} in sung phonation could contribute to increased medial compression of the vocal folds and greater closed-phase duration of the glottal waveform, thus strengthening harmonic components in the sung task.

An interaction between the amplitude of the voice-source fundamental and f_o may be relevant here. In Condition 1.1 and 1.2, f_o approached the frequency of the first formant (F_1): 700 Hz. As f_o increases and begins to approximate the region of F_1, the amplitude of the first harmonic increases while spectral energy in the higher frequencies is reduced. A strong source-spectrum fundamental is also a characteristic of breathy phonation or greater open-phase duration.[59,72,73] Traditionally, a skilled classical or operatic singer would raise the frequency of F_1 to reduce this acoustic effect, a manoeuvre usually facilitated through mandibular depression, slight laryngeal elevation, or a combination of both.[74,75] Pedagogically, this is known as *aggiustamento* or vowel modification.[76] Although no significant association between CPPS and the amplitude of the voice-source fundamental was found in the present study, formant frequencies were not adjusted across the studied f_o range. It may be that a more complex interaction between formant frequencies and the amplitude of the voice-source fundamental contributed to the decrease in CPPS magnitude seen in f_o frequencies above 200 Hz. Although Awan et al[20] highlight the need for consideration of vowel effects on CPPS magnitude, results from this study did not show significant effects of formant frequency on CPPS for the /a/ and /i/ vowels (Figure 4). This may be simply due to the linear nature of the synthesized tones used here, ie, no voice-source interaction with formant frequencies. Nonetheless, it may be useful to adhere to a standardized vowel to improve comparability of data between studies. Patel et al[4] recommend an /a/ vowel for *glissandi* and sustained vowels in acoustic analysis.

Results from the present investigation considering the effects of f_o on CPPS bring into question whether the change in f_o is the primary cause of the decreasing CPPS values, and if this is independent from P_{sub} variation, particularly as *Madde* does not incorporate non-linear aerodynamic voice-source interaction in its synthesis.[65] Regardless of the cause, f_o has a significant effect on CPPS, which should be taken into account.

Vibrato extent and CPPS

In Condition 1.1 and 1.2, VE was set at 0.4 and 0.0 ST respectively. We considered a VE of 0.4 ST to be typical for the Western classical singing voice (WCSV), however there is a wide range of aesthetically acceptable vibrato rate and extent within the genre.[53,77] The differences in CPPS values between Conditions 1.1 (VE of 0.4 ST) and 1.2 (VE of 0.0 ST), while not negligible in the upper frequencies, did not reach statistical significance overall ($P = 0.07$). Under Condition 2.0, the question arises as to why CPPS values increased when VE increased from 0.0 to 0.6 ST, and then rapidly decreased when VE increased from 0.6 to 1.0 ST. Perhaps a moderate f_o oscillation contributes to the cepstral representation of a resonance-harmonics interaction,[53] whereby the strongest partial in the spectrum approximates F_1, thus varying overall equivalent sound level (L_{eq}) and harmonic strength.

In real voices, both muscular and aerodynamic non-linear interactions characterize vibrato in Western classical singing and interact with the voice in a manner in which even small changes are perceivable to the discerning ear.[48,50–52,54] Singers are trained in various pedagogical schools that manifest in variations of phonatory mechanisms such as P_{sub}, glottal adduction, and vocal-tract configuration, as well as inherent aesthetic values regarding the rate and extent of vibrato.[52,76,78] Through expert tuition and practice singers hone their proprioceptive abilities to a degree that allows them to sense subtle changes in phonatory patters,[76,79–81] perhaps even to the small magnitudes seen under Condition 2.0. Further research that includes synchronous acoustic and aerodynamic measures in real singers may help to determine more definitively whether or not vibrato characteristics affect CPPS values to a clinically significant degree.

Source-spectrum tilt and CPPS

Condition 3.0 showed a strong association between source-spectrum tilt (intensity) and CPPS values, $\tau = 1$, $P = 0.002$. In the speaking voice, intensity habitually increases as f_o rises. In the WCSV, artistic and historical performance conventions require independent control of pitch and intensity, ie, a high f_o does not necessarily mean higher SPL. Several studies have found that CPPS improved with increased SPL values.[15,17,19,20] In these studies, voice samples were taken from spoken passages and elicited and sustained vowel conditions, all within habitual speech range and at various levels of intensity.

Data gathered under Condition 1.1 and 1.2 may offer an alternative hypothesis for this effect of increasing intensity. There is clearly an increase in CPPS for f_o values between 80 and 220 Hz – within the speaking voice range. While it is possible that previously reported increases in CPPS for speech tasks were due to increased SPL alone, it may have been that an increase in f_o accompanied increased SPL in these habitual speech data, and that it was an f_o increase that contributed significantly to CPPS improvement in this range, seen in previous studies.

Naturally, conclusions regarding the influence of a wide range of f_o and changes in intensity (such as those found in the singing voice) on CPPS cannot be drawn from works that have solely analyzed speaking-voice samples within the normative speech range, nor can the findings be generalized to singing-voice analysis. While the clear increase of CPPS with intensity seen in Condition 3.0 (Figure 8) suggests that there is a relevant relationship between intensity and CPPS in singing-voice conditions, this interaction appears to be dynamic and non-linear and most likely reflects a complex interaction of multiple physiological parameters. In the present study source-spectrum tilt was varied on a constant f_o of 220 Hz, but the same interaction cannot be assumed for other f_o values. Thus, while the association between CPPS and increased intensity seems clear, a simple correction for the effects of intensity on CPPS may at this time be premature.[78,79]

Limitations and future research

The present study was limited to synthesized tones. This allowed for systematic analysis of well-defined tone properties. The results improve the possibilities to identify what voice properties underlie variation in CPPS values. For example, our results have shown how CPPS is affected by variation in f_o, vibrato extent, and source-spectrum tilt. However, in real voices many aspects of vocal sounds are interdependent, both in speech and singing, thus the correcting equations presented in Condition 1.1 (section 4.1) should be considered as proof-of-concept – further analyses using data from real voices are necessary before real-world clinical application of such correcting formulae. In future research it would be worthwhile to analyze how the CPPS measure varies under different phonatory conditions, for example during variation of f_o, vocal loudness, phonation type, register, and vowel. In such analyses it may be advantageous to first use trained singers as participants, as they typically have good awareness of and control over voice properties. The use of aerodynamic measurements as a complement to the cepstral analysis would help to identify the non-linear influences on cepstral measures that were not considered in the present work. The inclusion of perceptual tools such as the Evaluation of Ability to Sing Easily (EASE)[82] may also shed light on whether CPPS is sensitive to the subtle voice changes singers perceive.

CONCLUSIONS

Smoothed cepstral peak prominence has shown great promise in clinical and exploratory analysis of voice due to its robustness against varying environmental factors and signal types. Findings from this study reveal several important effects of voice-source parameters on CPPS values. As f_o increases from 80 to 175 Hz, CPPS values increase, while they decrease in the range between 180 and 699 Hz. This interaction was seen for both /a/ and /i/ vowels and was not significantly affected by the presence or absence of vibrato. As correcting equations derived from real-voice data are not yet available, prescribing a target f_o rather than using "comfortable" or habitual pitches would help to reduce variation between pre and posttreatment assessments, and between data from different subjects and studies. Varying VE did not have a statistically significant effect on CPPS values, however the interaction between WCSV vibrato production and physiological, spectral, and cepstral components is an avenue of future research worth pursuing. While varying source-spectrum tilt significantly affected CPPS, the nature of the effect is difficult to separate from the f_o effect and thus requires further non-linear examination considering interactions between multiple voice-source variables.

Professional singing-voice users presenting with voice complaints require diagnostic tools that can detect small changes in vocal-fold behavior and standardized protocols that include singing-voice tasks. There is a paucity of literature considering the utility of CPPS for use with the singing voice, and explanations of what physiological processes are represented by CPPS are lacking. Thus, caution is warranted when considering using CPPS for objective singing voice analysis. Systematic analyses such as those presented in the current work and future research with real singers will aid the interpretation of CPPS and offer new insights into whether or not this cepstral measure can be used reliably with the singing voice.

CONFLICT OF INTEREST

The authors declare no conflicts of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

1. Maryn Y, Weenink D. Objective dysphonia measures in the program PRAAT: smoothed cepstral peak prominence and acoustic voice quality index. *J Voice*. 2015;29:35–43. https://doi.org/10.1016/j.jvoice.2014.06.015.
2. Heman-Ackah YD, Heuer RJ, Michael DD, et al. Cepstral peak prominence: a more reliable measure of dysphonia. *Ann Hum Biology*. 2003;112:324–333. https://doi.org/10.1177/000348940311200406.
3. Watts CR, Awan SN, Maryn Y. A comparison of cepstral peak prominence measures from two acoustic analysis programs. *J Voice*. 2017;31:387.e1–387.e10. https://doi.org/10.1016/j.jvoice.2016.09.012.
4. Patel RR, Awan SN, Barkmeier-Kraemer J, et al. Recommended protocols for instrumental assessment of voice: American speech-language-hearing association expert panel to develop a protocol for instrumental assessment of vocal function. *Am J Speech Lang Pathol*. 2018;27:887–905. https://doi.org/10.1044/2018_AJSLP-17-0009.
5. Heman-Ackah YD, Michael DD, Goding GS. The relationship between cepstral peak prominence and selected parameters of dysphonia. *J Voice*. 2002;16:20–27. https://doi.org/10.1016/S0892-1997(02)00067-X.
6. Titze IR. *Workshop on Acoustic Voice Analysis: Summary Statement*. National Center for Voice and Speech; 1995.
7. Oppenheim AV, Schafer RW. Dsp history - From frequency to quefrency: a history of the cepstrum. *IEEE Signal Process Mag*. 2004;21:95–106. https://doi.org/10.1109/MSP.2004.1328092.
8. Noll AM. Cepstrum pitch determination. *J Acoust Soc Am*. 1967; 41:293–309. https://doi.org/10.1121/1.1910339.
9. Noll AM. Short-time spectrum and "Cepstrum" techniques for vocal-pitch detection. *J Acoust Soc Am*. 1964;36:296–302. https://doi.org/10.1121/1.1918949.
10. Hillenbrand J, Cleveland RA, Erickson RL. Acoustic correlates of breathy vocal quality. *J Speech Hear Res*. 1994;37:769–779. https://doi.org/10.1044/jshr.3704.769.
11. Hillenbrand J, Houde RA. Acoustic correlates of breathy vocal quality: dysphonic voices and continuous speech. *J Speech Hear Res*. 1996;39:311–321. https://doi.org/10.1044/jshr.3902.311.
12. Childers DG, Skinner DP, Kemerait RC. The cepstrum: a guide to processing. *Proceedings of the IEEE*. 1977;65:1428–1443. https://doi.org/10.1109/PROC.1977.10747.
13. Awan SN, Roy N, Dromey C. Estimating dysphonia severity in continuous speech: application of a multi-parameter spectral/cepstral model. *Clin Linguist Phonet*. 2009;23:825–841. https://doi.org/10.3109/02699200903242988.
14. Maryn Y, Roy N, de Bodt M, et al. Acoustic measurement of overall voice quality: a meta-analysis. *J Acoust Soc Am*. 2009;126:2619–2634. https://doi.org/10.1044/2017_JSLHR-S-16-0188.
15. Sampaio M, Masson MLV, Soares MF de P, et al. Effects of fundamental frequency, vocal intensity, sample duration, and vowel context in cepstral and spectral measures of dysphonic voices. *J Speech Lang Hear Res*. 2020;63:1326–1339. https://doi.org/10.1044/2020_JSLHR-19-00049.
16. Sampaio MC, Bohlender JE, Brockmann−Bauser M. Fundamental frequency and intensity effects on cepstral measures in vowels from connected speech of speakers with voice disorders. *J Voice*. 2019;35:422–431. https://doi.org/10.1016/j.jvoice.2019.11.014.
17. Brockmann-Bauser M, van Stan JH, Sampaio MC, et al. Effects of vocal intensity and fundamental frequency on cepstral peak prominence in patients with voice disorders and vocally healthy controls. *J Voice*. 2021;35:411–417. https://doi.org/10.1016/j.jvoice.2019.11.015.
18. Skowronski MD, Shrivastav R, Hunter EJ. Cepstral peak sensitivity: a theoretic analysis and comparison of several implementations. *J Voice*. 2015;29:670–681. https://doi.org/10.1016/j.jvoice.2014.11.005.
19. Munier C, Brockmann-Bauser Meike, Laukkanen AM, et al. Relationship between laryngeal signs and symptoms, acoustic measures, and quality of life in Finnish primary and kindergarten school teachers. *J Voice*. 2020;34:259–271. https://doi.org/10.1016/j.jvoice.2018.12.006.
20. Awan SN, Giovinco A, Owens J. Effects of vocal intensity and vowel type on cepstral analysis of voice. *J Voice*. 2012;26:670.e15–670.e20. https://doi.org/10.1016/j.jvoice.2011.12.001.
21. Halberstam B. Acoustic and perceptual parameters relating to connected speech are more reliable measures of hoarseness than parameters relating to sustained vowels. *ORL*. 2004;66:70–73. https://doi.org/10.1159/000077798.

22. Lauchsinger R, Arnold GE, Arnold GE, et al. *Voice-Speech-Language – Clinical Communicology: Its Physiology and Pathology*. Wadsworth Publishing Company, Inc.; 1965.
23. Hirano M. Vocal mechanisms in singing: laryngological and phoniatric aspects. *J Voice*. 1988;2:51–69. https://doi.org/10.1016/S0892-1997(88)80058-4.
24. Miller R. How singing is not like speaking. *NATS J*. 1992;48:20.
25. Herbst CT, Hess M, Müller F, et al. Glottal adduction and subglottal pressure in singing. *J Voice*. 2015;29:391–402. https://doi.org/10.1016/j.jvoice.2014.08.009.
26. Brown Jr WS, Hunt E, Williams WN. Physiological differences between the trained and untrained speaking and singing voice. *J Voice*. 1988;2:102–110. https://doi.org/10.1016/S0892-1997(88)80065-1.
27. Lindblom B, Sundberg J. The human voice in speech and singing. In: Rossing TD, ed. *Springer Handbook of Acoustics. Second*. Springer-Verlag; 2014. https://doi.org/10.1007/978-1-4939-0755-7.
28. Sanchez K, Oates J, Dacakis G, et al. Speech and voice range profiles of adults with untrained normal voices: methodological implications. *Logoped Phoniatr Vocol*. 2014;39:62–71. https://doi.org/10.3109/14015439.2013.777109.
29. Goy H, Fernandes DN, Pichora-Fuller MK, et al. Normative voice data for younger and older adults. *J Voice*. 2013;27:545–555. https://doi.org/10.1016/j.jvoice.2013.03.002.
30. Schultz BG, Rojas S, John MS, et al. A cross-sectional study of perceptual and acoustic voice characteristics in healthy aging. *J Voice*. 2021. https://doi.org/10.1016/j.jvoice.2021.06.007.
31. Sundberg J. Vocal tract resonance in singing. *NATS J*. 1988;44:11–31.
32. Sundberg J, Salomão GL, Scherer KR. Analyzing emotion expression in singing via flow glottograms, long-term-average spectra, and expert listener evaluation. *J Voice*. 2019;35:52–60. https://doi.org/10.1016/j.jvoice.2019.08.007.
33. Heman-Ackah YD. Reliability of calculating the cepstral peak without linear regression analysis. *J Voice*. 2004;18:203–208. https://doi.org/10.1016/j.jvoice.2004.01.005.
34. Bottalico P, Codino J, Cantor-Cutiva LC, et al. Reproducibility of voice parameters: the effect of room acoustics and microphones. *J Voice*. 2020;34:320–334. https://doi.org/10.1016/j.jvoice.2018.10.016.
35. Stoller D, Dixon S. Analysis and classification of phonation modes in singing. In: Mandel MI, Devaney J, Turnbull D, Tzanetakis G, eds. *17th International Society for Music Information Retrieval*. 20161–7. Accessed from:; http://qmro.qmul.ac.uk/xmlui/handle/123456789/13500. Accessed 6 July 2021.
36. Castellana A, Leocata I, Carullo A, et al. Singing voice quality assessment in professional singers using microphones and contact sensors. *Eruonoise 2018: 11th European Congress and Exposition on Noise Control Engineering. European Acoustics Association*. 20181843–1854. Accessed from:; https://www.euronoise2018.eu/docs/papers/311_Euronoise2018.pdf. Accessed 6 July 2021.
37. Mendes AP, Nunes N, Ibrahim S, et al. Cepstral measures in the Fado voice: gender, and phonatory tasks. *J Voice*. 2020. https://doi.org/10.1016/j.jvoice.2020.09.010.
38. Toles LE, Ortiz AJ, Marks KL, et al. Amount and characteristics of speaking and singing voice use in vocally healthy female college student singers during a typical week. *J Voice*. 2020. https://doi.org/10.1016/j.jvoice.2020.04.029.
39. Sonninen A, Hurme P, Laukkanen AM. The external frame function in the control of pitch, register, and singing mode: radiographic observations of a female singer. *J Voice*. 1999;13:319–340. https://doi.org/10.1016/s0892-1997(99)80039-3.
40. Murry T, Xu JJ, Woodson GE. Glottal configuration associated with fundamental frequency and vocal register. *J Voice*. 1998;12:44–49. https://doi.org/10.1016/S0892-1997(98)80074-X.
41. Sundberg J, Högset C. Voice source differences between falsetto and modal registers in counter tenors, tenors and baritones. *Logoped Phoniatr Vocol*. 2001;26:26–36. https://doi.org/10.1080/14015430116949.
42. Kochis-Jennings KA, Finnegan EM, Hoffman HT, et al. Laryngeal muscle activity and vocal fold adduction during ches, chestmix, headmix, and head registers in females. *J Voice*. 2012;26:182–193. https://doi.org/10.1016/j.jvoice.2010.11.002.
43. Dippold S, Voigt D, Richter B, et al. High-speed imaging analysis of register transitions in classically and jazz-trained male voices. *Folia Phoniatr Logop*. 2015;67:21–28. https://doi.org/10.1159/000381095.
44. Balasubramanium RK, Bhat JS, Fahim S, et al. Cepstral analysis of voice in unilateral adductor vocal fold palsy. *J Voice*. 2011;25:326–329. https://doi.org/10.1016/j.jvoice.2009.12.010.
45. Brockmann M, Storck C, Carding PN, et al. Voice loudness and gender effects on jitter and shimmer in healthy adults. *J Speech Lang Hear Res*. 2008;51:1152–1160. https://doi.org/10.1044/1092-4388(2008/06-0208.
46. Brockmann M, Drinnan MJ, Storck C, et al. Reliable jitter and shimmer measurements in voice clinics: the relevance of vowel, gender, vocal intensity, and fundamental frequency effects in a typical clinical task. *J Voice*. 2011;25:44–53. https://doi.org/10.1016/j.jvoice.2009.07.002.
47. Ferrer-Riesgo CA, Nöth E. What makes the cepstral peak prominence different to other acoustic correlates of vocal quality? *J Voice*. 2020;34:806.e1–806.e6. https://doi.org/10.1016/j.jvoice.2019.01.004.
48. Nandamudi S, Scherer RC. Airflow vibrato: dependence on pitch and loudness. *J Voice*. 2019;33:815–830. https://doi.org/10.1016/j.jvoice.2018.05.007.
49. Hirano M, Hibi S, Terasawa R, et al. Relationship between aerodynamic, vibratory, acoustic and psychoacoustic correlates in dysphonia. *J Phonet*. 1986;14:445–456. https://doi.org/10.1016/S0095-4470(19)30687-4.
50. Horii Y. Acoustic analysis of vocal vibrato: a theoretical interpretation of data. *J Voice*. 1989;3:36–43. https://doi.org/10.1016/S0892-1997(89)80120-1.
51. Shipp T, Doherty ET, Haglund S. Physiologic factors in vocal vibrato production. *J Voice*. 1990;4:300–304. https://doi.org/10.1016/S0892-1997(05)80045-1.
52. Sundberg J. Acoustic and psychoacoustic aspects of vocal vibrato. *STL-QPSR*. 1994;35:45–68.. Accessed at: November 20, 2021. Accessed from:; https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.638.6561&rep=rep1&type=pdf.
53. Horii Y. Frequency modulation characteristics of sustained /a/sung in vocal vibrato. *J Speech Hear Res*. 1989;32:829–836. https://doi.org/10.1044/jshr.3204.829.
54. Large J, Iwata S. Aerodynamic study of vibrato and voluntary 'straight tone' pairs in singing. *Folia Phoniatr Logop*. 1971;23:50–65. https://doi.org/10.1159/000263482.
55. Titze IR. Acoustic interpretation of the voice range profile (Phonetogram). *J Speech Lang Hear Res*. 1992;35:21–34. https://doi.org/10.1044/jshr.3501.21.
56. Gramming P, Sundberg J. Spectrum factors relevant to phonetogram measurement. *J Acoust Soc Am*. 1988;83:2352–2360. https://doi.org/10.1121/1.396366.
57. Nordenberg M, Sundberg J. Effect on LTAS of vocal loudness variation. *Logoped Phoniatr Vocol*. 2004;29:183–191. https://doi.org/10.1080/14015430410004689.
58. Gauffin J, Sundberg J. Spectral correlates of glottal voice source waveform characteristics. *J Speech Hear Res*. 1989;32:556–565. https://doi.org/10.1044/jshr.3203.556.
59. Childers DG, Lee CK. Vocal quality factors: analysis, synthesis, and perception. *J Acoust Soc Am*. 1991;90:2394–2410. https://doi.org/10.1121/1.402044.
60. Haji T, Horiguchi S, Baer T, et al. Frequency and amplitude perturbation analysis of electroglottograph during sustained phonation. *J Acoust Soc Am*. 1986;80:58–62. https://doi.org/10.1121/1.394083.
61. Sundberg J. Objective characterization of phonation type using amplitude of flow glottogram pulse and of voice source fundamental. *J Voice*. 2020. https://doi.org/10.1016/j.jvoice.2020.03.018.
62. Ferrer-Riesgo CA, Bodt M de, Maryn Y, et al. Properties of the cepstral peak prominence and its usefulness in vocal quality measurements. *Models and Analysis of Vocal Emissions for Biomedical Applications: 5th International Workshop*. Firenze University Press; 2007:.93–96..

Accessed from: https://www.isca-speech.org/archive_v0/maveba_2007/mv07_093.html. Accessed 22 August 2021.
63. Granqvist S. Madde. 2021. Accessed from: www.tolvan.com. Accessed 2 February 2021.
64. Bozeman K. New technology for teaching voice science and pedagogy: the madde synthesizer (Svante Granqvist). *J Sing*. 2012;68:415–418. https://www.nats.org/cgi/page.cgi/_article.html/Journal_of_Singing/New_Technology_for_Teaching_Voice_Science_and_Pegagoy_The_-Madde_Synthesizer_Svant_Granqvist_2012_Mar_Apr . Accessed 11 August 2021.
65. Bozeman K. *Practical Vocal Acoustics: Pedagogical Applications for Teachers and Singers*. Pendragon Press; 2013.
66. Sopran. 2021. Accessed from: www.tolvan.com. Accessed 4 March 2021.
67. Półrolniczak E, Kramarczyk M. Comparison of singing voice quality from the beginning of the phonation and in the stable phase in the case of choral voices. In: Ganzha M, Maciaszek L, Paprzycki M, eds. *Federated Conference on Computer Science and Information Systems*. ACSIS; 2019. https://doi.org/10.15439/2019F316.
68. Boersma P, Weenink D. PRAAT. 2021. Accessed from: www.praat.org. Accessed 10 July 2021.
69. Sauder C, Bretl M, Eadie T. Predicting voice disorder status from smoothed measures of cepstral peak prominence using Praat and analysis of dysphonia in speech and voice (ADSV). *J Voice*. 2017;31:557–566. https://doi.org/10.1016/j.jvoice.2017.01.006.
70. Fraile R, Godino-Llorente JI. Cepstral peak prominence: A comprehensive analysis. *Biomed Signal Process Control*. 2014;14:42–54. https://doi.org/10.1016/j.bspc.2014.07.001.
71. Murphy PJ. On first rahmonic amplitude in the analysis of synthesized aperiodic voice signals. *J Acoustic Soc Am*. 2006;120:2896–2907. https://doi.org/10.1121/1.2355483.
72. Hejná M, Šturm P, Tylečkova L, et al. Normophonic breathiness in Czech and Danish: are females breathier than males? *J Voice*. 2019;35:498.e1–498.e22. https://doi.org/10.1016/j.jvoice.2019.10.019.
73. Wayland R, Jongman A. Acoustic correlates of breathy and clear vowels: the case of Khmer. *J Phonet*. 2003;31:181–201. https://doi.org/10.1016/S0095-4470(02)00086-4.
74. Johansson C, Sundberg J, Wilbrand H. X-ray study of articulation and formant frequencies in two female singers. *STL-QPSR*. 1982;23:117–134. Accessed from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.643.7161&rep=rep1&type=pdf. Accessed 26 August 2021.
75. Kent RD. Vocal tract acoustics. *J Voice*. 1993;7:97–117. https://doi.org/10.1016/S0892-1997(05)80339-X.
76. Stark J. *Bel Canto: A History of Vocal Pedagogy*. University of Toronto Press Incorporated; 2008.
77. Mitchell HF, Kenny DT. Change in vibrato rate and extent during tertiary training in classical singing students. *J Voice*. 2010;24:427–434. https://doi.org/10.1016/j.jvoice.2008.12.003.
78. Elliott M. *Singing in Style: A Guide to Vocal Performance Practices*. Yale University Press; 2006.
79. Miller R. *The Structure of Singing: System and Art in Vocal Technique*. Schirmer; 1996.
80. Miller Richard. Training Tenor Voices. Schirmer Books; 1993.
81. Schutte HK, Stark JA, Miller DG. Change in singing voice production, objectively measured. *J Voice*. 2003;17:495–501. https://doi.org/10.1067/S0892-1997(03)00009-2.
82. Phyland DJ, Pallant JF, Benninger MS, et al. Development and preliminary validation of the EASE: a tool to measure perceived singing voice function. *J Voice*. 2013;27:454–462. https://doi.org/10.1016/j.jvoice.2013.01.019.