Research Article

Vocal Loudness Variation With Spectral Slope

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Objective: This investigation addresses the loudness variations in sones achievable with spectral slope variations (higher harmonic energy) in human vocalization and compares it to the sound pressure level (SPL) variations typically reported in the voice range profile (VRP).

Method: The primary methodology was computational. The ISO standard 226 was used to convert SPL values to sones for a 125- to 1000-Hz range of fundamental frequency and a -3 dB/octave to -12 dB/octave range of spectral slope. In addition, a retrospective analysis of human subjects' VRPs

was conducted, and the experimental results were compared to the theoretical results.

Results: A very small range of SPL variation (less than 5 dB) in the VRP can produce a large range of loudness. The sensitivity can be on the order of 4 sones per dB SPL change.

Conclusion: For vocalization in the modal register, loudness variation is not well described by SPL change in dB, especially at high fundamental frequencies where the SPL range in the VRP becomes very small but sizeable loudness variations are still possible.

Vocal loudness is often assessed by measuring sound pressure level (SPL). It is well known, however, that loudness quantified perceptually in “sones” does not have a direct proportionality to SPL in dB, especially when the sound is complex (Fletcher & Munson, 1933; Rasch & Plomp, 1999). The auditory system is more sensitive to some frequency components than others. Thus, in speaking and singing, some frequency components can contribute differently to loudness than to SPL. The distinction between loudness and SPL is known and discussed in the speech science community, but the quantitative analysis has not received much attention. It is generally not possible to reinforce harmonics in a balanced loudness fashion because resonances of the vocal tract cluster and spread apart for vowel and consonant production. Thus, the assessment of vocal loudness is multidimensional. It involves the average trend in the spectrum and the peaks. Here, we address the first step in a quantitative analysis, the average trend known as spectral slope.

Zwicker's loudness model uses four steps to estimate the loudness of complex tones in sones (Zwicker & Scharf,

1965). In the first step, the transfer functions of the outer and middle ears are computed. In the second step, the excitation pattern from the physical spectrum is computed. In the third step, specific loudness patterns are computed from excitation patterns, and in the final step, overall loudness is computed from specific loudness by integrating them across frequencies. This model was later revised by Moore and Glasberg (1996) in such a way that equal-loudness contours change more accurately with sound level.

On the production side, at least three mechanisms for increasing vocal sound intensity have been described, one below the larynx, one within the larynx, and one above the larynx (Titze, 2000, Chap. 9). Below the larynx, increasing subglottal pressure is by far the most effective mechanism (Björklund & Sundberg, 2016; Titze & Sundberg, 1992). Generally, there is a 6- to 9-dB rise in SPL with a doubling of lung pressure. Within the larynx, vocal intensity is controllable by increasing or decreasing the spectral slope of harmonics (Sundberg & Nordenberg, 2006), which can dramatically change in different voice registers (Herbst, Hess, Müller, Švec, & Sundberg, 2015). Above the larynx, configuring the vocal tract for optimal source-filter interaction and sound radiation are further mechanisms of choice (Titze, 2008; Titze & Palaparthi, 2018). Although some attempts are made by the vocalist to control these mechanisms separately, the results are generally not independent. For example, raising subglottal pressure can theoretically raise all frequency components uniformly, but subglottal pressure can also alter the effective glottal closure in the low intensity range. When the amplitude

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of vibration is on the order of the mean glottal width, vocal fold contact is highly variable. Thus, subglottal pressure can alter the spectral slope with a variable closed quotient (Herbst et al., 2015). Furthermore, changing the airway geometry can alter both the source and the filter characteristics due to interaction. Given that all of the mechanisms can alter spectral content to some degree, vocal loudness is not a simple prediction and deserves quantitative analysis.

The fundamental question to be answered in this study is to what extent SPL can be used as a measure of loudness in vocalization across fundamental frequencies and voice registers. Is the voice range profile (VRP) an accurate description of loudness range over fundamental frequency? The initial focus here is on loudness regulation with spectral slope. Tuning vocal tract resonances to single or clusters of harmonics is left for a subsequent study. Although the theory behind this investigation is already in the form of an ISO standard, the community of voice scientists has not fully benefited from its direct application to voice production and perception.

Method

This study was primarily computational, but some retrospective analysis of human subject data is included. A mathematical quantification of the international standard ISO 226 for the Fletcher and Munson (1933) equal-loudness curves was the primary tool of analysis. A subroutine published by Tackett (2005) was used to convert SPL to loudness level in “phons” and then to loudness in “sones” in the range of 10–90 “phons.” The standard is set up for the following specific third-octave frequencies,

$$nf = [20\ 25\ 31.5\ 40\ 50\ 63\ 80\ 100\ 125\ 160\ 200\ 250\ 315\ 400\ 500\ 630\ 800\ 1000\ 1250\ 1600\ 2000\ 2500\ 3150\ 4000\ 5000\ 6300\ 8000\ 10000\ 12500] \text{ Hz.} \quad (1)$$

Specific mapping coefficients af , Lu , and Tf were provided for these frequencies to relate dB to phons and then to sones

$$af = [0.532\ 0.506\ 0.480\ 0.455\ 0.432\ 0.409\ 0.387\ 0.367\ 0.349\ 0.330\ 0.315\ 0.301\ 0.288\ 0.276\ 0.267\ 0.259\ 0.253\ 0.250\ 0.246\ 0.244\ 0.243\ 0.243\ 0.243\ 0.242\ 0.242\ 0.245\ 0.245\ 0.254\ 0.271\ 0.301], \quad (2)$$

$$Lu = [-31.6\ -27.2\ -23.0\ -19.1\ -15.9\ -13.0\ -10.3\ -8.1\ -6.2\ -4.5\ -3.1\ -2.0\ -1.1\ -0.4\ 0.0\ 0.3\ 0.5\ 0.0\ -2.7\ -4.1\ -1.0\ 1.7\ 2.5\ 1.2\ -2.1\ -7.1\ -11.2\ -10.7\ -3.1], \quad (3)$$

$$Tf = [78.5\ 68.7\ 59.5\ 51.1\ 44.0\ 37.5\ 31.5\ 26.5\ 22.1\ 17.9\ 14.4\ 11.4\ 8.6\ 6.2\ 4.4\ 3.0\ 2.2\ 2.4\ 3.5\ 1.7\ -1.3\ -4.2\ -6.0\ -5.4\ -1.5\ 6.0\ 12.6\ 13.9\ 12.3]. \quad (4)$$

For example, for a given loudness level LL at any of the 29 frequencies nf above, a function Af is first computed using the following equation,

$$Af = 4.47E-3 * (10^{(0.025 * LL) - 1.15}) + (0.4 * 10^{(((Tf(nf) + Lu(nf))/10) - 9))} * af(nf). \quad (5)$$

Interpolation is used for any frequency between the third-octave frequencies. We used linear interpolation because the points are spaced relatively close to each other. The above equations assume that loudness level LL is the known input variable. By computing Af from Equation (2), SPL can then be computed explicitly from Af using the following relation,

$$SPL = ((10/af(nf))^* \log_{10}(Af(nf)) - Lu(nf) + 94. \quad (6)$$

For the current application, however, SPL is the known input variable. The equations cannot be inverted algebraically to solve explicitly for LL in terms of SPL. To obtain a numerical solution for a given SPL, trial loudness levels LL were incremented in 1,000 steps from 10 to 90 phons for the given SPL, from which Af was computed in each iteration. A trial SPLt was then calculated at each step, and the absolute error $|SPLt - SPL|$ was minimized with repeated trials. The loudness L in sones was then computed from the LL corresponding to the minimum error:

$$L(nf) = \left(\frac{LL}{40}\right)^{2.86} - 0.005 \quad LL < 40 \text{ phons}, \quad (7)$$

$$L(nf) = 2 \left(\frac{LL - 40}{10}\right) \quad LL \geq 40 \text{ phons}. \quad (8)$$

Fundamental frequencies for this investigation were chosen to be 125, 250, 375, 500, 625, 750, 875, and 1000 Hz, covering much of the range of human male and female vocalization (Pabon & Ternström, 2018; Pabon, Ternström, & Lamarche, 2011). The range of f_o values was chosen because it placed the important harmonics (up to the 12th) in the range of the 3rd octave band frequencies in Equation (1), allowing all the coefficients in Equations (3)–(5) to be interpolated for the harmonic frequencies. The range of f_o was sufficient to make meaningful interpretations for singing and speaking.

Although the spectral envelope of the radiated pressure from the mouth has peaks and valleys (formant structure), a general trend can be identified by the spectral slope. Focusing on this feature in isolation, uniformly sloping harmonic spectra were selected with -3 , -6 , -9 , and -12 dB/octave spectral slopes. The -6 dB/octave is typical for modal register in speech, considering a -12 dB/octave for the source (Flanagan, 1957) and a $+6$ dB/octave for radiation from the lips (Dejonckere, 2001). For falsetto registration or

breathy voice, the -12 dB/octave slope is typical (Childers & Lee, 1991), and the -3 dB/octave shallow slope represents a harmonically rich voice. For this first analysis, spectral peaks and troughs from source spectra and vocal tract resonances were intentionally not included in the spectrum envelope so that the effect of spectral slope alone could be evaluated. The harmonic series were cut off when contributions from higher harmonics no longer contributed significantly to the total harmonic energy or when total loudness saturated because more than one harmonic occupied a critical band. In the 100- to 500-Hz fundamental frequency range, two critical bands (one for Harmonics 13–15 and one for harmonics 16–18) satisfied this criterion. In the 500- to 1000-Hz region, one critical band for Harmonics 11–13 satisfied the criterion. Calculation of loudness within critical bands was conducted by converting SPL values of harmonics to intensity, adding the intensities, and converting back to SPL. The loudness was then computed at the center frequency of the critical band.

Data from human subjects were analyzed retrospectively from recent publications of the VRP by Pabon and Ternström (2018). Spectra were made available for points (SPL- f_0 cells) along the softest and loudest boundary productions in both modal register and falsetto register. Pabon measured the short-term Fast Fourier Transform spectra using the following settings: sampling frequency of 44100 Hz, frame size of 2,048 samples, frequency resolution of 21.5 Hz, overlap length of 1,024 samples, frame update rate of 43 Hz, and Hanning window. A single-mean spectral slope was extracted from the spectrum of a given cell in the VRP. The slope was computed by fitting a linear regression line to the SPLs of fundamental frequency and its harmonics.

This slope was anchored to the level of the fundamental frequency in all cases. All computations were performed with MATLAB Version 9.6.0 (R2019a).

Results

Variation of Loudness With Spectral Slope

Figure 1 shows the results for $f_0 = 125$ Hz. Part (a) shows the Fletcher–Munson curves for equal-loudness levels (10, 20, 30...90 phon curves) in the 100- to 10000-Hz range. Part (b) shows the four spectral slopes in solid lines and 18 harmonics in vertical dashed lines. All spectral slopes begin with a common 50 dB at f_0 , which normalized the spectra to the fundamental frequency amplitude. The spectra were cut off at the 18th harmonic because harmonics beyond this number contributed negligible amounts to the overall SPL. Part (c) shows loudness in sones for each harmonic at the four spectral slopes. (By definition, 1 sone is the loudness of a 1000-Hz sinusoid at 40 dB SPL.) Harmonics beyond 12 were interactive in critical bands and contributed little to the overall loudness. As expected, the loudness curves have a contour that mirrors the Fletcher–Munson equal-loudness curves. There is much contribution to total loudness from harmonics 5–10 because they lie in the sensitive region around 1000 Hz. There is not much contribution to loudness from harmonics above 2000 Hz.

Part (d) of Figure 1 shows the total SPL in dB (dashed line) and total loudness in sones (solid line with data points) as a function of spectral slope from all harmonics combined. Total SPL was computed by converting SPL to intensity for each harmonic, summing the intensities, and converting

Figure 1. Spectral slope variation at $f_0 = 125$ Hz, (a) equal-loudness levels, (b) sound pressure level (SPL) for four spectral slopes, (c) loudness across harmonics, and (d) total SPL in dB (dashed line) and total loudness in sones (solid line) for all spectral slopes.

Figure 2. Spectral slope variation at $f_o = 1000$ Hz, (a) equal-loudness levels, (b) sound pressure level (SPL) for four spectral slopes, (c) loudness across harmonics, and (d) total SPL in dB (dashed line) and total loudness in sones (solid line) for all spectral slopes.

back to SPL. Total loudness was computed by adding sones directly for harmonics isolated in a critical band, augmented by loudness values from critical bands that contain more than one harmonic. Note the decrease in both total SPL and total loudness with greater negative spectral slope. Loudness ranges from 12 sones for a -3 dB/octave slope to three sones for a -12 dB/octave. Total SPL has a smaller range, from about 56 dB to 51 dB, underscoring the fact that the 1st harmonic (here at 50 dB) contains almost all the harmonic energy for a uniformly decreasing spectral envelope.

Figure 2 shows the same data for a high fundamental frequency, $f_o = 1000$ Hz. Here, the 2nd, 3rd, and 4th harmonics pick up the sensitivity of the auditory system in the 2000- to 3000-Hz region. The 3rd harmonic is particularly

well positioned at $f_o = 3000$ Hz. Total loudness range and total SPL ranges are not much different from what was seen at 125 Hz because there is very little contribution from harmonics greater than the 4th. The important result is that, for both high and low f_o , spectral slope variation from -3 dB/octave to -12 dB/octave delivers about two doublings in loudness with less than 5-dB variation in overall SPL. In other words, loudness is very sensitive to small changes in SPL.

Range of Loudness and Sensitivity of Loudness to Spectral Slope Change

It is informative to compare the range of loudness variation with the range of SPL variation across a wide range of fundamental frequencies. Figure 3 shows this comparison. SPL values for spectral slope variation from -3 dB/octave to -12 dB/octave are shown with dashed lines. Only the -3 dB/octave line shows a 5-dB increase in SPL, all others showing 2 dB or less over the entire 125- to 1000-Hz f_o range. With that small SPL variation, a relatively wide loudness variation (up to 15 sones, solid lines) is achieved. There is a slight frequency dependence, the loudness range maximizing at 400–500 Hz.

To show this loudness change more clearly, Figure 4 shows the “rate of change of loudness with change in SPL.” Differences between the four lines in Figure 3 were taken to obtain the three lines in Figure 4. The difference functions can be expressed as $\Delta L/\Delta \text{SPL}$ in sones per dB. This represents the sensitivity of loudness variation to SPL variation. Spectral slope can deliver between 2 and 5 sones per dB

Figure 3. Range of loudness in sones (solid lines) and range of sound pressure level (SPL) in dB (dashed lines) with four spectral slopes variation.

Figure 4. $\Delta L/\Delta SPL$ in sones per dB sound pressure level (SPL) with spectral slope variation at three loudness levels.

SPL or 20 and 50 sones per 10-dB increase. This rate of change is high compared to what a standard pure tone at 1000 Hz can offer with a 10-dB increase from 50 to 60 dB, namely, 2–4 sones. The broad maximum in spectral slope sensitivity at about 400 Hz is clearly visible in the $\Delta L/\Delta SPL$ curve. This maximum is very important for vocalization because important voice register events take place in the 300- to 500-Hz range. Vocal register shift often involves a dramatic spectral slope change in the source spectrum. Vocal loudness can therewith change dramatically in a change from modal register to falsetto register.

A Loudness Range Profile for Vocalization

The VRP has become an accepted assessment tool for some of the vocal capability of an individual. With an

upper and lower bound, it plots the range of the two most easily defined acoustic variables in the vocal output, f_0 and SPL. Given the above calculated sensitivity of loudness to the manner in which SPL variations are produced, the question arises as to how a loudness VRP differs from an SPL-VRP. A monumental work on the spectral content associated with every data point on the VRP has recently been published, not only on the perimeter (loudest and softest) but also for many points inside the VRP (Pabon, 2018; Pabon & Ternström, 2018). We were given permission to access Pabon's database retrospectively. Figure 5 shows the spectral envelopes for points along the upper (loud) and lower (soft) boundaries for a cohort of five normal female subjects. The spectra were divided into four groups, 14 spectra for loud modal voice, 32 spectra for loud falsetto voice, 15 spectra for soft modal voice, and 24 spectra for soft falsetto voice. The spectra had been averaged over multiple productions by the individuals. For all spectra, the vowel was an /a/. Note that a peak in all spectra occurs in the 800- to 1500-Hz range due to the combined first and second resonances of the /a/ vowel. Although this peak dominates the overall SPL level and the overall loudness, there is much variation with spectral slope, as will be seen below. Spectral slope was computed by fitting a linear regression equation to the harmonic amplitudes in a spectrum, with the line starting at the amplitude of the fundamental (see Figure 6).

Figure 7 shows a histogram of the spectral slopes in each of the four categories of voicing. The distribution is comparatively tight for loud modal register, centered on -3 dB/octave. For loud falsetto register, the distribution is much wider, centered around -15 dB/octave. For soft modal register, the distribution is not normal but skewed toward

Figure 5. Spectra of an /a/ vowel for two levels of loudness and two vocal registers. SPL = sound pressure level.

Figure 6. Linear regression equation fit to measured amplitudes of harmonics (data points) of a spectrum. The x-axis is represented in octaves. SPL = sound pressure level.

large spectral slopes that are likely to be inconsistent in modal register. Modal register is difficult to sustain at low intensity due to high variability in vocal fold contact. Near threshold of phonation, the system often alternates between near-sinusoidal vibration without vocal fold contact and

vibration with some vocal fold contact. In soft falsetto register, the spectral slope distribution is not much different from that in loud falsetto, indicating that loudness is not controlled much by spectral slope.

Figure 8 shows a typical SPL-VRP (top row) and a never-before-drawn L-VRP (bottom). The left half is for modal voice, and the right half is for falsetto voice. All data points are color coded for spectral slope, with the range indicated on the bar at the right. In modal register, both SPL and loudness variation are highly defined by spectral slope, which varies between -3 and -15 dB/octave. There is much less dependency on spectral slope for falsetto register, where the range of spectral slope is -15 to -25 dB/octave, and the variability is much greater.

A second major finding is that the shape of the SPL-VRP does not follow the shape of the L-VRP. At higher fundamental frequencies, the range of loudness in sones widens, whereas the range of SPL narrows. This is particularly the case for modal voice. A 30-dB increase at about 500 Hz produces a range of loudness between 5 and 110 sones, much more than a doubling for every 10 dB. In falsetto voice, increase in loudness appears to be more regulated with overall raising of the spectral level or perhaps formant tuning. A 50-dB increase in SPL is needed for a range of about 5–125 sones, which is a little less than a doubling for every 10 dB.

Discussion

A fundamental question to be answered was the degree to which SPL relates to loudness in vocalization. In general, the doubling of loudness per 10-dB SPL increase

Figure 7. Histogram of spectral slopes in dB/octave for two levels of loudness at two vocal registers.

Figure 8. Sound pressure level (SPL) voice range profile with spectral slope color code (top) and loudness voice range profile with spectral slope color code (bottom).

above 1.0 sone at 40 dB (the pure-tone standard at 1000 Hz) is a rough approximation for complex vocal sounds across a fundamental frequency range of 125–1000 Hz. Varying the spectral slope (more or less energy distributed into higher harmonics) is highly effective for regulating a large loudness range (from 10 sones to about 120 sones, or four doublings, with an SPL range of 30 dB). In musical notation, this

would allow nearly a doubling of loudness in each step from *pp* to *p* to *mp* to *mf* to *f* to *ff*. Spectral slope change may saturate, however, at both high and low lung pressure. At low lung pressure, it may be difficult to maintain a consistent glottal closure interval for higher harmonic generation because the vibrational amplitude is small and vocal fold contact is variable near phonation threshold. At large lung

Figure 9. Sound pressure level (SPL) voice range profile with higher harmonic content color coded, (a) modal register in foreground with falsetto register in background and (b) falsetto register in foreground with modal register in background. After Pabon and Ternström (2018), *Journal of Voice*, by permission.

pressures, an open quotient much less than 0.5 is difficult to obtain with growing amplitude of vibration because the glottal area is in the form of a truncated sinusoid. Unless the glottal airflow is skewed (its peak delayed), spectral slope increase at the source tends to saturate at a value near -12 dB/octave. However, the glottal airflow can be skewed with inertive reactance of the vocal tract. Thus, it is reasoned that loudness change with spectral slope change is likely to be most effective if source-filter interaction can be invoked. Without source-filter interaction, talkers tend to press their voices to increase loudness in search of a shallower spectral slope (Jackson, 1928; Titze, 2000, pp. 351–352).

The discussion leads back to the findings of Pabon and Ternström (2018). One of the parameters they isolated from the spectra was the combined energy level of all higher harmonics (above f_0) divided by the level of f_0 . This measure is strongly correlated with the spectral slope. Figure 9 shows this parameter in color for an averaged VRP over 16 untrained female subjects. Two VRPs are overlaid, one in the foreground and one in the background. In Figure 9a, modal (chest) register is in the foreground, and in Figure 9b, falsetto (head) register is in the foreground. It is evident that increased higher harmonic energy (spectral slope decrease) is the major regulatory mechanism for increasing SPL in modal register. The range of the level of the higher harmonics relative to the level of f_0 is 55 dB (30 + 25 from the color bar on the far right) in a total SPL range of 70 dB (110–40 on the vertical axis) from very soft to very loud. In falsetto register, the level of the higher harmonics relative to the level of the fundamental does not increase at all at high f_0 and is mostly below that of the fundamental. Some mild spectral slope variation is seen in the transition region between modal and falsetto registers (perhaps mixed register) in the 300- to 500-Hz range.

Pabon and Ternström (2018) further displayed the VRP with the sound level of the f_0 as the parameter. They showed that, in modal register, the level of the fundamental rises about 35 dB in an overall SPL range of 70 dB (40–110) from very soft to very loud. On the other hand, in falsetto register, the level of f_0 rises 80 dB (40–120) in about the same SPL range from very soft to very loud.

Conclusion

Spectral slope is a major factor for loudness regulation in modal register vocalization. For this regulatory mechanism, ranges in SPL do not accurately reflect ranges in loudness. A very small range of SPL can produce a wide range of loudness, especially at fundamental frequencies in the 300- to 500-Hz range, where voice register change is a prominent factor. The VRP, often used to quantify loudness range over fundamental frequency range, is not a good predictor of loudness range at high fundamental frequencies in modal register. In this register, a small change in SPL with spectral slope can produce a large change in loudness. In falsetto register, spectral slope is generally too

steep to make much difference in loudness. An increase in the magnitude of the flow pulse is the more likely control mechanism.

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