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Effect of vocal tract resonances on the sound spectrum of the saxophone

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Summary

Variation in the radiated sound spectrum, p_{rad}, is an expressive technique that can be achieved on the saxophone by employing different vocal tract configurations that change the vocal tract impedance spectrum Z_{mouth}. However, the relation between p_{rad} and the vocal tract impedance spectrum Z_{mouth} has not previously been measured for orchestral instruments. In this study, p_{rad} and Z_{mouth} were measured simultaneously over the frequency range from 100 to 10000 Hz while saxophonists played. For notes sounded over the normal and altissimo playing range, experienced saxophonists are able to produce distinctive variations in the spectral envelope of the radiated sound, without changing the pitch or the amplitude of the fundamental, using different vocal tract configurations. When Z_{mouth} was adjusted to have magnitudes comparable with the input impedance of the bore, Z_{bore}, harmonics of p_{rad} were usually increased at nearby frequencies, both for the range over which the saxophone has strong resonances (100-2000 Hz) and for the higher range (2-10 kHz). Less experienced players who are unable to produce strong peaks in Z_{mouth} produce much smaller variations in p_{rad}. p_{rad} correlates more strongly with the series impedance $Z_{\mathrm{mouth}} + Z_{\mathrm{bore}}$: for large values of $|Z_{\mathrm{mouth}}|$, larger series impedance at a particular frequency always produced larger radiated power. The change in sound inside the mouth is proportionally larger than that in p_{rad}, which explains why players judge the timbre to be more changed than do listeners.

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1. Introduction

Musical expression is of great importance in music performance. Musicians usually have several ways to achieve this, *e.g.* adding vibrato, changing loudness, subtly varying the timing and pitch, adjusting articulation and varying the timbre. Saxophonists vary the spectrum of their sound in different musical styles and contexts, especially when playing jazz music. Many players report that they achieve this by adjusting the shape of their vocal tract. This could change the acoustic load 'seen' by the reed, which could alter the motion of the reed and/or the acoustic flow past it. A change in the acoustic flow would in turn change the spectrum of the radiated sound, and also the sound in the player's mouth, though by different factors. In this paper, the vocal tract impedance spectrum is measured during playing using an impedance head built into the mouthpiece and compared with the spectrum of the radiated sound.

Vocal tract configurations used for different expressive effects are often described by players in terms of various vowel-like mouth shapes (*e.g.* 'oo', 'ee', 'ah' [1, 2, 3]). In music pedagogy, saxophone teachers also emphasise the importance of adjusting the tongue positions to change the timbre. For example, Watkins [4] recommends using vowels such as 'oo' for the low register and vowels 'ee' for mid-to-upper register; further, if timbre is too bright or too 'stuffy', the vowel used should be slightly modified to adjust timbre in order to keep it 'balanced'. Similarly, on the clarinet, Gingras teaches students to visualise the syllables 'ha', 'he' and 'hee' in order to influence timbre [1]. It should be noted that the two chief determinants of vowels are the tongue shape and the lip aperture. Because the latter is not a free parameter when the lips are sealed around the mouthpiece, the use of vowel configurations in this context is thought to refer largely to tongue shape.

The vocal tract configuration presumably affects the quality of the sound via changes in its acoustic impedance. In Benade's simple model of a reed driven by the pressure difference across it [5], flow continuity requires that the acoustic impedances of the bore (Z_{bore}) and the mouth (Z_{mouth}), act in series to load the reed. Thus, for sufficiently large values of Z_{mouth}, the shape of the vocal tract could influence the sound pitch and spectrum.

Backus [6] attempted to measure Z_{mouth} and found its value to be negligible in comparison with Z_{bore}. However, Fritz and Wolfe [7] used an impedance head mounted in the mouthpiece to measure Z_{mouth} while players mimed playing. They found that the different mouth shapes used by players for different musical effects can have different impedance spectra and that their magnitude can be comparable with Z_{bore}. More recently, measurements of Z_{mouth} have been made on saxophone and clarinet players during playing [8, 9, 10]. These studies found that large peaks in $|Z_{\mathrm{mouth}}|$ can be produced by advanced players and tuned at or near the playing frequency to play the altissimo range, to 'bend' notes or to control multiphonics. These results showed that peaks in Z_{mouth} were tuned for musical effects, but none of these studies related Z_{mouth} to the spectrum of the output sound.

A complementary technique is to measure simultaneously the acoustic pressure in the mouth (p_{mouth}) and the mouthpiece (p_{bore}) [11, 12, 13]. Continuity at the reed requires that the flow into the bore, U, at each frequency f, is the opposite of that into the mouth. These and the definitions of the impedance of the mouth and the bore, measured at the reed, give

$$-\frac{p_{\mathrm{mouth}}(f)}{Z_{\mathrm{mouth}}(f)} = U(f) = \frac{p_{\mathrm{bore}}(f)}{Z_{\mathrm{bore}}(f)} \quad (1)$$

Consequently

$$\frac{Z_{\mathrm{mouth}}(f)}{Z_{\mathrm{bore}}(f)} = -\frac{p_{\mathrm{mouth}}(f)}{p_{\mathrm{bore}}(f)} \quad (2)$$

Scavone *et al*. [12] observed changes in the ratio $p_{\mathrm{mouth}}/p_{\mathrm{bore}} = -Z_{\mathrm{mouth}}/Z_{\mathrm{bore}}$ when players were instructed to change the tongue position while playing a single note; this is consistent with variations in the vocal tract impedance affecting the output sound.

Using the two techniques described above, changes in the acoustic response of the vocal tract have thus been shown to be related to various advanced playing techniques, including performing in the altissimo register, bugling, multiphonics, pitch bending and glissando [7-14]. However none of these studies have compared the impedance spectrum in the mouth Z_{mouth} with the spectrum of the sound, either p_{bore} or p_{rad}.

How could Z_{mouth} affect the radiated sound? And would an increase in $|Z_{\mathrm{mouth}}|$ at the frequency of a higher harmonic increase or decrease the power output of the instrument at that frequency?

The varying force on the reed is proportional to the acoustic pressure difference across it, $p_{\mathrm{bore}} - p_{\mathrm{mouth}}$, which equals $U(Z_{\mathrm{bore}} + Z_{\mathrm{mouth}})$. Consequently, as Benade points out, the two impedances act in series as an acoustic load to the reed [5]. For a given fingering, temperature profile and gas composition, Z_{bore} is fixed, but all the other terms in the equations above vary. Consequently, when the player varies Z_{mouth}, p_{mouth} does not simply vary in proportion with that change, because p_{bore} varies as well. We define the transpedance T that relates the radiated pressure, p_{rad}, to the acoustic flow U into the mouthpiece: $p_{\mathrm{rad}} = TU$. Like Z_{bore}, T depends on the instrument alone and is constant for a given fingering, temperature profile, gas composition and measuring position. So

$$p_{\mathrm{rad}}(f) = -T(f) \cdot \frac{p_{\mathrm{mouth}}(f)}{Z_{\mathrm{mouth}}(f)} = T(f) \cdot U(f) \qquad (3)$$

One of the control parameters available to the player is the vocal tract configuration, which determines Z_{mouth}. All else equal, variations in Z_{mouth} are expected to vary the output U and thus the radiated sound spectrum, p_{rad}, in ways that are not proportional to the changes in Z_{mouth} (or to those in p_{mouth}).

To our knowledge, the relation between p_{rad} and Z_{mouth} has only been measured for the didjeridu [15], a lip-valve instrument; we know of no study in which p_{rad} or p_{bore} and Z_{mouth} have been compared for reed instruments. It is worth emphasising that the equations above do not tell us how p_{rad} depends on p_{mouth}: this relationship depends on how the flow U is related to these pressures. Consider two hypotheses:

Hypothesis A. Using the Benade argument [5, 16], $Z_{\mathrm{bore}} + Z_{\mathrm{mouth}}$ acts in series on the reed, so it could be that, with appropriate phase, an increased magnitude of Z_{mouth} at the frequency of a harmonic could alter the reed vibration so as to increase the acoustic current at that frequency, which would lead to increased p_{rad}: Peaks in $|Z_{\mathrm{mouth}}|$ produce formants – broad peaks in the envelope of the sound. If this were the case, then equation (3) requires that p_{mouth} is increased by a greater factor than p_{rad}, which agrees with the observation (discussed later) that listeners hear a smaller effect than do players.

Hypothesis B. Suppose that a large magnitude of Z_{mouth} inhibits the flow U into or out of the mouth, and that this effect dominates. In that case, equation (3) predicts the opposite effect: p_{rad} decreases for harmonics that fall near maxima in Z_{mouth}: Peaks in $|Z_{\mathrm{mouth}}|$ produce antiformants in the envelope of the sound.

Both of the hypotheses are based on equation (3): for hypothesis A, an increase in Z_{mouth} and a greater increase in p_{mouth} lead to an increase in p_{rad}. While for hypothesis B, an increase in Z_{mouth} and a smaller increase in p_{mouth} lead to a decrease in p_{rad}.

What determines the relative magnitudes of the harmonics of p_{bore} and p_{mouth}? For individual harmonics, linear relations (1) relate flow to p_{bore} and p_{mouth}. However, the relative amplitudes of the harmonics depend on a nonlinear time-domain differential equation for flow past the reed. This has been solved using the harmonic balance method [17] for a simplified model of a clarinet with no vocal tract effects [18]. Kergomard *et al.* [19] use the variable truncation method for a clarinet-like model. Fletcher *et al.* [20] use a method like harmonic balance for a simplified cylindrical lip-reed instrument including an upstream resonator.

Z_{bore} usually has a very large value at the playing frequency, and often at the first few harmonics. Consequently with either hypothesis, Z_{mouth} is expected to contribute significantly to the series combination only if the peaks of Z_{mouth} have large magnitude and if the fundamental or harmonics of the note fall near those peaks. Measurements of the impedance spectrum of the tract have been made during performance using a broadband acoustic current source and an impedance head built into the mouthpiece.

Varying the vocal tract geometry changes Z_{mouth} across a wide range of frequencies, so the influence of Z_{mouth} on the amplitude of harmonics of the sound is a possible mechanism that could cause the changes in spectral envelope across that range. Scavone *et al.* [12] investigated the influence of the vocal tract on the saxophone sound spectrum, as well as other advanced performance techniques, by looking at the ratio of the acoustic pressure measured in the player's mouth to that inside the mouthpiece during playing. Their results showed that, for three of their subjects, changes in p_{mouth} were usually in the same direction as those in p_{bore}. That study, like previous measurements of vocal tract impedance [10, 14], was limited to 2 kHz, while the sound of the saxophone has strong harmonics at frequencies well above this [21].

To our knowledge, no previous study on reed instruments has measured the vocal tract impedance spectrum and its effect on the spectral envelope of the sound (either radiated or in the bore), or studied how changes in the vocal tract affect the spectrum above 2 kHz, although the harmonics of the saxophone sound extend well above this limit. Both are reported here. Expert and less experienced saxophone players were asked to produce the same note with different vocal tract configurations, aiming to produce substantially different sounds, but with the same pitch and loudness. A measurement head mounted in the mouthpiece measured the impedance spectrum in the mouth from 100 to 10000 Hz. Simultaneously, the sound inside the player's mouth and the radiated sound were recorded. The preliminary results of a pilot study on this topic, using only three subjects, a smaller frequency range, and without any of the detailed analysis presented in this paper, have been previously published in a conference proceeding [22].

2. Materials and Methods

The same instrument, a Yamaha Custom EX Tenor Saxophone with a Yamaha 5C mouthpiece was used for all experiments. The same Légère synthetic saxophone reed, with the maker's rating of 'hardness' 3, was used throughout; synthetic reeds have the advantage that they can be played dry, disinfected quickly and have stable physical properties over long studies [23].

The acoustic impedance spectra of the saxophone bore (Z_{bore}) were taken from the database [24] measured previously on the same instrument that was used for the present study. These impedance spectra were measured from 80 to 4000 Hz with a spacing of 1.35 Hz using the three-microphone-two-calibration (3M2C) method calibrated with two non-resonant loads [25].

To measure directly the acoustic impedance of the player's vocal tract during playing, an acoustic impedance measurement head based on the capillary method was modified from Chen *et al.* [8]. The measurement head (Figure 1) consists of a narrow stainless steel tube with internal cross sectional area of 2 mm^2 integrated into the saxophone mouthpiece. An Endevco 8507C-2 miniature pressure transducer of 2.42 mm diameter was similarly fitted in the mouthpiece, adjacent to the stainless steel tube. The relative positions of the tube, the pressure transducer and the tip of the reed are thus fixed – this ensures that Z_{mouth} is measured at the same position as the acoustic load on the tip of the reed. These modifications increase the thickness of the mouthpiece by 2 mm at the bite point. However, this is not regarded as a significant disturbance by players [9], some of whom routinely use mouthpieces with different geometry for different styles of music. A broadband acoustic current with harmonics from 100 to 10000 Hz with a spacing of 5.38 Hz was injected into the player's mouth through the stainless steel tube during playing. The pressure transducer measured the sound pressure in the player's mouth, which includes both that produced by the vibrating reed and the response of the vocal tract to the injected probe current. The impedance measurement system was calibrated by connecting the impedance head in the modified mouthpiece to an acoustically infinite cylindrical waveguide (length 197 m, internal diameter 26.2 mm), which provides a purely resistive impedance for axial modes (the first propagating non-axial mode is the (0,1) mode at 16 kHz). The impedance system was tested on finite pipes with known geometry over the frequency range to 10 kHz. The system was calibrated before each experimental session.

Eight saxophonists having both classical and jazz backgrounds were involved in this study. Six of them were expert players with more than 10 years' music training and extensive professional experience playing in orchestras and as soloists. Two were amateurs without formal music training, playing the saxophone occasionally. Using the modified mouthpiece described above, the players were asked to produce at least two different mouth configurations. One was described as like 'ee', with the tongue high in the mouth, and the other like 'ah' with the tongue low. The actual tongue position is itself not important; the aim is to alter Z_{mouth} which we then measure. Using shapes approximating these, they were asked to achieve different timbres by only adjusting the tongue position while keeping other parameters and variables constant (*e.g.* bite force on the reed, embouchure, pitch and loudness). Of these, only the playing frequency and sound level were monitored during the measurements: data were not used if the playing frequency between pairs of measurements for 'ee' and 'ah' differed by more than 6 cents or the sound level differed by more than 1.4 dB. Before each experimental session began, the players were asked to practise on the modified mouthpiece to become accustomed to it. Then they were asked to keep the pitch constant using visual feedback from a pitch meter placed in front of them. All the players were asked to produce a series of notes (written G4, C5, G5, C6 and E6) and to play each note at least twice for the same vocal tract configuration. For each measurement, the player was asked to sustain the note for at least 6 seconds, while the broadband current was injected into the player's mouth and its response recorded. The acoustic impedance of the player's vocal tract, ranging from 100 to 10000 Hz, was measured in two separate measurements over the ranges 100 to 5000 Hz and 5000 to 10000 Hz.

Another microphone (Rode NT3) was positioned one bell radius from and on the axis of the bell of the saxophone to record the radiated sound for spectral analysis. The saxophone position was fixed and the recordings made in a room treated to reduce background noise and reverberation. The pressure transducer on the acoustic impedance measurement head (mounted in the modified mouthpiece) was also used to record the sound inside each player's mouth.

The raw acoustic impedance spectra were then analysed and treated [10] to remove the harmonics generated by the vibrating reed and filtered to reduce the noise introduced by airflow turbulence inside the mouth.

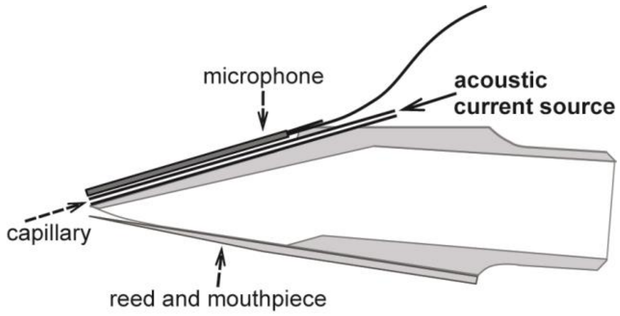

Figure 1. A schematic cross-section of the mouthpiece showing the capillary method measurement head (mounted in the mouthpiece) used to measure the vocal tract impedance during playing.

3. Results and Discussion

All of the six expert players were able to produce systematically different spectral envelopes in the radiated sound by changing their vocal tract configuration, for notes across the normal and altissimo playing range. In contrast, the two less-experienced amateur players produced relatively small variations in the spectral envelope of the radiated sound at constant pitch. Further, neither of these two players was able to play any notes in the altissimo range.

All subjects reported that it was much easier to produce larger timbre changes when they were allowed to change the pitch, typically by ten or more cents. One possible reason is that large changes in the vocal tract configuration produce a change in the acoustic load on the reed that not only changes the harmonic content but also the frequency of vibration: a small change in the fundamental frequency has an n times greater effect on the nth harmonic, which may be enough to shift it from coinciding with a bore resonance to not coinciding, or *vice versa*. Whether or not a harmonic coincides with a bore resonance has a large effect on the radiated sound, so modest tuning changes can vary the spectral envelope. However, once the players were asked to keep the pitch constant using a pitch meter to provide visual feedback, the timbre variation in the radiated sound was then less salient to the experimenter and, for the less experienced players, sometimes hardly noticeable. Nevertheless, all the expert players were still able to maintain the pitch while varying the sound spectrum noticeably. The discussion in this study is restricted to the changes produced at constant pitch.

In an interview before the experiment, players described how they varied timbre. All reported that they used various vowel-like mouth shapes, of which the most commonly cited were 'ah' and 'ee'. Most subjects reported using the 'ah' vocal tract configuration as their default position during normal performance for jazz playing, while the 'oo' tongue position was regarded as a common position for playing classical music and the 'ee' vocal tract configuration is unusual, which some players use to create a deliberate timbre variation. The vocal tract configurations for each vowel probably vary from one player to another and thus probably produce different sound spectra; in this study, subjects were asked to produce configurations approximating 'ah' and 'ee' and the differences between these for each player are analysed. The subjects in the study by Scavone *et al.* also reported thinking that they influenced the sound by vocal tract variations [12].

Figure 2 shows the radiated sound spectra of one note (written C5 on tenor saxophone, sounding B♭3 (233 Hz, near the top of the lowest register of the instrument) and the measured vocal tract impedance spectra of one expert subject. The note was played with different sound spectra by adjusting tongue position: in (a), the subject reported using an 'ah' vocal tract configuration (the normal position reported by this player) and in (b) the 'ee' tongue position. $|Z_{\text{bore}}|$ for the fingering used for this note is also shown. In each case, the sound level at one bell radius from the bell was 107 dB. The amplitudes of the fundamentals of the two notes are similar.

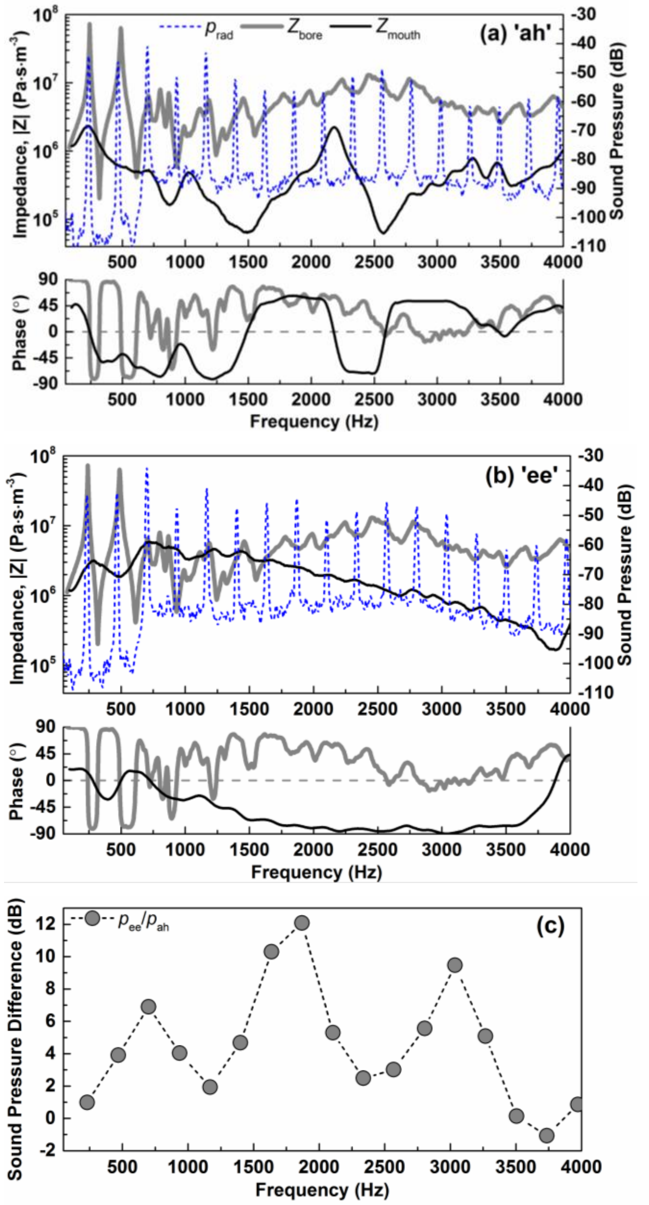

Figure 2. An expert player produced different sound spectra for the same note by adjusting tongue position: (a) 'ah'-like and (b) 'ee'-like vowel. In each case, the radiated sound spectrum (dashed blue line) of the sounded note B♭3 (nominally 233 Hz) is plotted on the same graphs as the magnitude of the impedance spectra of the vocal tract (thin black line). The impedance magnitude of the bore of the saxophone for that fingering is also plotted on those graphs (broad grey line). The phases of the tract and bore impedances are plotted on separate graphs. Figure (c) shows the difference in the amplitude of the harmonics of the radiated spectrum between the 'ah' and 'ee' vocal tract configurations.

Further, their spectral centroids are almost equal (1.18 kHz for 'ah' and 1.19 kHz for 'ee'). For spectra like those shown in Figure 2 (a) and (b), it is formants (broad local peaks in the spectral envelope) that give them different sounds, not overall properties like the centroid. Figure 2(c) shows the difference in the amplitude of the harmonics of the radiated spectrum between 'ah' and 'ee' vocal tract configurations. In the frequency range of 700 to 3000 Hz, the amplitudes of most of the harmonics in the radiated spectra for the 'ee' vocal tract configuration are greater than those for the 'ah' vocal tract configuration: for the 3rd, 6th, 9th, 12th and 14th harmonics, the amplitude difference is about 5 dB and for the 7th, 8th and 13th harmonics, the amplitude difference is about 10 dB. This is consistent with the increase in harmonic components in the range 800 to 2000 Hz that was observed by Scavone *et al*. when the tongue was moved towards the reed [12].

How are these modifications in the spectral envelope produced? There appears to be a correlation between formants in the radiated sound and the magnitude of vocal tract impedance. In Figure 2, for the 'ah' vocal tract configuration, $|Z_{\mathrm{mouth}}|$, is smaller for 'ah' than for 'ee' over the range 300 to 3000 Hz, except for a narrow region near 2300 Hz. For the lower half of this range, $|Z_{\mathrm{mouth}}|$ for 'ee' is comparable with $|Z_{\mathrm{bore}}|$, whereas, $|Z_{\mathrm{mouth}}|$ for the 'ah' configuration is much smaller than $|Z_{\mathrm{bore}}|$. The results suggest a possible correlation between changes in the amplitude of the harmonics in the radiated sound and changes in the magnitude of the vocal tract impedance Z_{mouth}, a correlation that might be quantified by examining a larger data set.

Although the sound levels of the notes for 'ee' and 'ah' were always within 1.4 dB of each other, they were always slightly different. Consequently for analysis, the amplitude of each harmonic in the radiated sound was normalised by dividing it by the amplitude of the fundamental to give the relative amplitude p'. (The fundamentals, with relative amplitude 1 by definition, are omitted from Figures 3 and 4 and the following analysis.) The relative amplitudes were then compared for the vocal tract configurations players produced when asked for configurations resembling 'ee' and 'ah'. In Figure 3, the ratio of the p' for the two configurations is plotted against the ratio of the measured values of Z_{mouth} at the frequency of each harmonic. The saxophone bore only

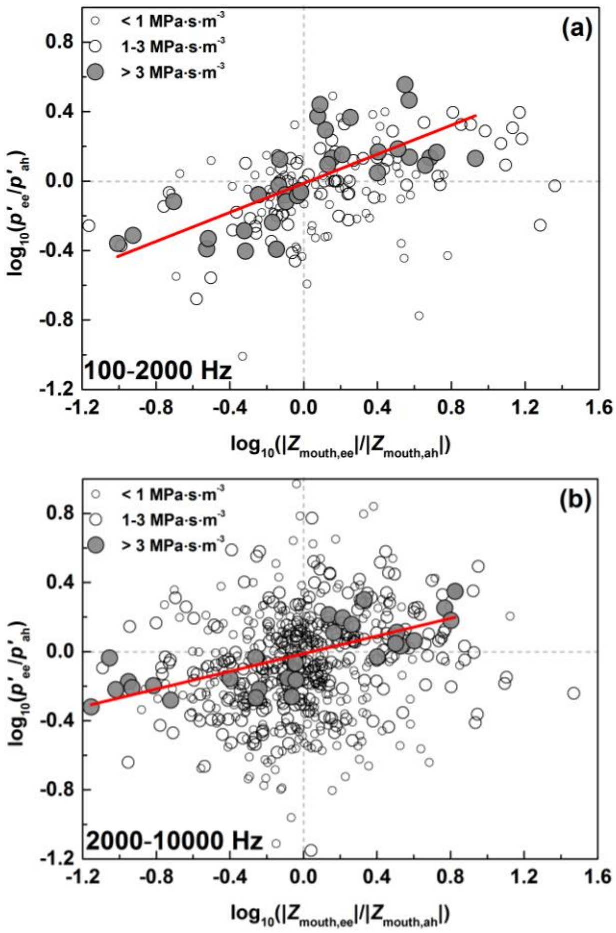

Figure 3. Changes in vocal tract impedance and changes in the radiated sound produced by the expert players for all the notes. p' is the relative pressure amplitude of harmonics: the ratio of p to that of the fundamental. For two different vocal tract configurations ('ee' and 'ah'), $p'_{\mathrm{ee}}/p'_{\mathrm{ah}}$ is plotted against $|Z_{\mathrm{mouth,ee}}|/|Z_{\mathrm{mouth,ah}}|$), *i.e*. against the ratio of the magnitudes of Z_{mouth} for those two configurations. (a) shows the range from 100 to 2000 Hz and (b) from 2000 to 10000 Hz. The size of each circle represents the magnitude of the larger of the two values of Z_{mouth}, as indicated in the legend. Filled grey circles have at least one value of $|Z_{\mathrm{mouth}}|$ > 3 MPa·s·m^{-3}, and the superposed lines show the linear fit to these data on this log-log scale indicating the degree of correlation.

Table I. Linear regression analysis of the data shown in Figure 3.

Frequency range	$\lvert Z_{mouth} \rvert$	Slope	R^2	p-value	Number of samples
100–2000 Hz	< 1 MPa·s·m^{-3}	0.082	0.011	0.36	81
	1–3 MPa·s·m^{-3}	0.27	0.36	0.00000006	68
	> 3 MPa·s·m^{-3}	0.42	0.51	0.0000004	38
2000–10000 Hz	< 1 MPa·s·m^{-3}	0.12	0.014	0.02	378
	1–3 MPa·s·m^{-3}	0.18	0.074	0.000007	265
	> 3 MPa·s·m^{-3}	0.26	0.61	0.0000002	31

Table II. Linear regression analysis of the data shown in Figure 4.

Frequency range	$\lvert Z_{mouth} \rvert$	Slope	R^2	p-value	Number of samples
100–2000 Hz	< 1 MPa·s·m^{-3}	-0.04	0.009	0.50	50
	1–3 MPa·s·m^{-3}	0.004	0.0004	0.09	22
2000–10000 Hz	< 1 MPa·s·m^{-3}	0.07	0.007	0.27	180
	1–3 MPa·s·m^{-3}	0.07	0.021	0.11	123
	> 3 MPa·s·m^{-3}	0.29	0.603	0.005	11

exhibits strong maxima in the range from 100 to 2000 Hz and, for this reason, the data have been analysed in two frequency ranges: (a) 100 to 2000 Hz and (b) from 2000 and 10000 Hz. The figure collates data measured from the six expert players. Because the magnitude of Z_{mouth} is expected to be important, it has been indicated by the size of the symbols. The values of Z_{mouth} have thus been binned into the three following ranges; smaller than 1 MPa·s·m^{-3}, from 1 to 3 MPa·s·m^{-3} and larger than 3 MPa·s·m^{-3}.

Figure 3 shows a large range in $\lvert Z_{mouth,ee} \rvert / \lvert Z_{mouth,ah} \rvert$, because of the variation in the resonances of the vocal tract with tract configuration. There is also considerable scatter, both in this plot and in individual plots for each player (individual plots not shown). The scatter is different for different frequency ranges and for different ranges of $\lvert Z_{mouth} \rvert$. Consider first the frequency range from 100 to 2000 Hz, the range over which $\lvert Z_{bore} \rvert$ exhibits strong peaks. Table I and Figure 3 show that the correlation and the dependence of log (p'_{ee}/p'_{ah}) on log ($\lvert Z_{mouth,ee} \rvert / \lvert Z_{mouth,ah} \rvert$) is not significant for $\lvert Z_{mouth} \rvert$ < 1 MPa·s·m^{-3} (small circles) and modest for $\lvert Z_{mouth} \rvert$ < 3 MPa·s·m^{-3} (small and medium sized circles in Figure 3(a)). This is as expected according to the Benade model [5] with Z_{bore} and Z_{mouth} acting in series: variation in $\lvert Z_{mouth} \rvert$ has little systematic effect when $\lvert Z_{mouth} \rvert << \lvert Z_{bore} \rvert$. However, the slopes of the regression increase with the magnitude of $\lvert Z_{mouth} \rvert$. For $\lvert Z_{mouth} \rvert$ > 3 MPa·s·m^{-3} the R^2 value is 0.512 and the p-value is 4×10^{-7}, indicating a strong, though incomplete, correlation (large grey circles and the superposed coloured line in Figure 3(a)). The positive correlation indicates that peaks in $\lvert Z_{mouth} \rvert$ tend to increase the amplitude of harmonics at nearby frequencies in the radiated sound. The consequent increase in harmonic amplitude can be several-fold. (There are differences among players: for example, for $\lvert Z_{mouth} \rvert$ larger than 3 MPa·s·m^{-3} in the frequency range of 100–2000 Hz, the slope for each player varies from 0.28 to 0.78 and the R^2 value varies from 0.269 to 0.985.)

In the range 2000-10000 Hz, the bore impedance spectrum has no strong peaks. In this range, there is also a significant dependence of $\log(p'_{ee}/p'_{ah})$ on $\log(|Z_{mouth,ee}|/|Z_{mouth,ah}|)$. However, the slope value obtained in the regression analysis shows a weaker effect of the Z_{mouth} on the radiated sound than that in the lower frequency range.

Table II and Figure 4 present the data for the less experienced players, in the same format as Table I and Figure 3, respectively. An obvious difference is that there are many fewer data with $|Z_{mouth}| > 3$ MPa·s·m^{-3}, especially at low frequency: these less-experienced players were generally unable to produce large values of $|Z_{mouth}|$ in the range below 2000 Hz, which also explains why they were unable to play in the altissimo range (about 700—2000 Hz) [8, 9]. Apart from that, the R^2 and p-values for $|Z_{mouth}|$ smaller than 3 MPa·s·m^{-3} present similar features as those in Table I: when the magnitude of Z_{mouth} is smaller than 3 MPa·s·m^{-3}, the amplitude change in the harmonics of the radiated sound does not depend strongly on the change in $|Z_{mouth}|$. Nevertheless, the several grey circles in Figure 4(b) tend to show similar correspondence between the difference of magnitude of Z_{mouth} and the difference in the relative amplitude of the harmonics. In Table II, the R^2 value for $|Z_{mouth}|$ larger than 3 MPa·s·m^{-3} in the frequency range from 2000–10000 Hz is close to that shown in Table I.

Figures 3 to 4 and Tables I and II show that the correlation is stronger when the magnitude of Z_{mouth} is large. This is consistent with the Benade series model and hypothesis A from the introduction: if the effect on U is due to changes in the series impedance $|Z_{mouth} + Z_{bore}|$, $|Z_{mouth}|$ should be comparable with $|Z_{bore}|$ or greater to have a strong effect on the radiated sound.

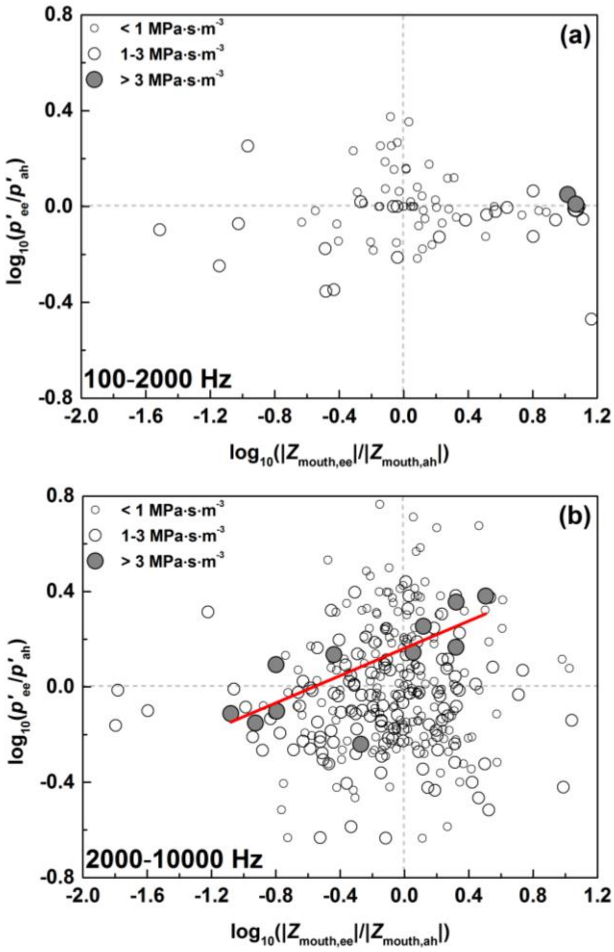

Figure 4. Changes in vocal tract impedance and changes in the sound produced by less experienced players for all the notes (*cf.* Fig 3). For two different vocal tract configurations ('ee' and 'ah'), the ratio of magnitudes of p' is plotted against the ratio of magnitudes of mouth impedance. (p' is the ratio of pressure in a given harmonic to the pressure in the fundamental.)

Table III. Linear regression analysis of the data shown in Figure 5.

Frequency range	$\lvert Z_{mouth}\rvert$	Slope	R^2	p-value	Number of samples
100–2000 Hz	> 3 MPa·s·m^{-3}	0.54	0.339	0.0003	34
2000–4000 Hz	> 3 MPa·s·m^{-3}	0.34	0.294	0.003	27

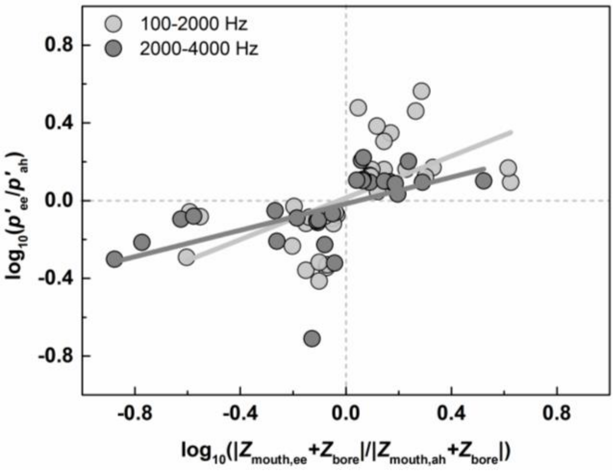

Figure 5. The correlation between changes in the acoustic impedance loading the reed and changes in the radiated sound for the expert players. For two different vocal tract configurations ('ee' and 'ah'), p'_{ee}/p'_{ah} is plotted against $|Z_{mouth,ee}+Z_{bore}|/|Z_{mouth,ah}+Z_{bore}|$), *i.e.* against the ratio of the magnitudes of $Z_{mouth}+Z_{bore}$ for those two configurations. Light and dark grey circles show the range from 100 to 2000 Hz and from 2000 to 10000 Hz respectively. For each point, the magnitude of the larger of the two values of Z_{mouth} is greater than 3 MPa·s·m^{-3}.

For this reason, Figure 5 and Table III examine the correlation between changes in the acoustic impedance loading the reed and changes in the radiated sound for the expert players. In this plot, all points lie in the first or third quadrants: an increase in $|Z_{mouth}+Z_{bore}|$ always leads to an increase in the amplitude of harmonics of the radiated sound at nearby frequencies when $|Z_{mouth}|$ is comparable to $|Z_{bore}|$.

Figure 6 compares the different effects of Z_{mouth} on the sound spectra in the mouth and in the radiated sounds. An expert player sounded B♭3, (nominally 233 Hz and written C5 on tenor saxophone), using the 'ah' and 'ee' vocal tract configurations. The altered tract produces a substantial change in the radiated spectra: the relative level of several harmonics is varied by 5 to 10 dB. However, a larger change is evident in the spectra measured inside the mouth, as predicted by equation (3): inside the player's mouth, the relative amplitude of most harmonics is varied by more than 5 dB and sometimes by more than 15 dB. This result is consistent with the players' observations: following the experiment, subjects listened to recordings of the radiated sound produced by the two articulations. They reported that the difference in sound in the recording is less than what they hear when playing. This is not surprising: when playing, subjects can hear the sound inside the mouth via the bones and tissues [26], and so hear changes in the sound spectrum that are considerably larger than those heard in the recording or by other listeners.

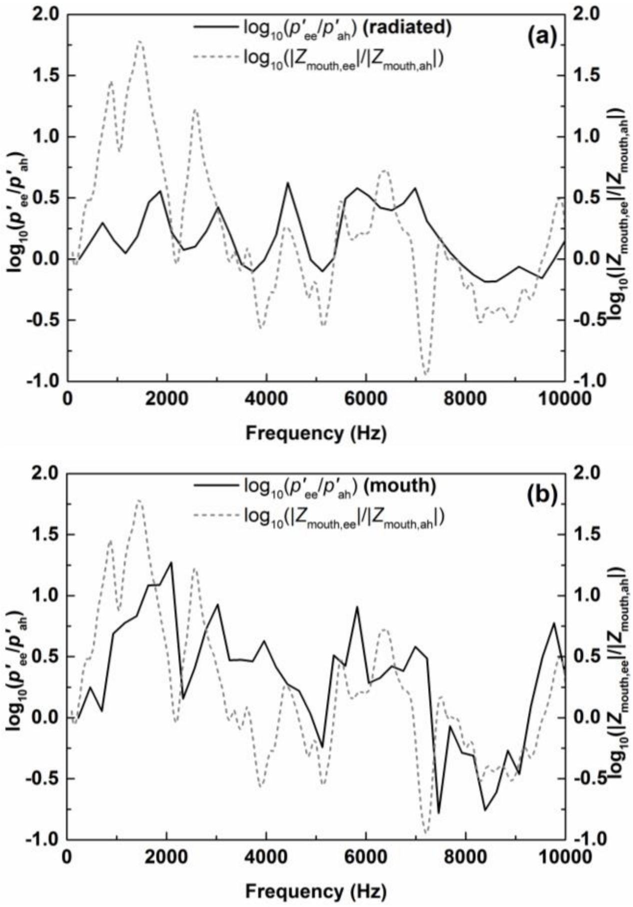

Figure 6. The ratios of the magnitude of Z_{mouth} (dashed line), and the relative amplitudes of harmonics (a) in the radiated sound and (b) in the mouth, as a function of frequency for the configurations 'ee' and 'ah'.

To our knowledge, the only other instrument for which Z_{mouth} and p_{rad} have been studied is the didjeridu [15]. For this low-pitched lip-valve instrument, it is observed that maxima in $|Z_{\mathrm{mouth}}|$ coincide very closely with *minima* in the spectral envelope of $|p_{\mathrm{rad}}|$ in that instrument: *i.e.* peaks in $|Z_{\mathrm{mouth}}|$ suppress flow between the lips at nearby frequencies. For that instrument, the modeling [20] supports hypothesis B of the introduction.

For the saxophone, the correlation is in the opposite direction: maxima in $|Z_{\mathrm{mouth}}|$ are correlated with *maxima* in $|p_{\mathrm{rad}}|$, and the correlation, while strong, is not closely tuned, as in the didjeridu. The two instruments are very different, of course. The didjeridu has a large input diameter, which means that both the characteristic impedance and the peaks in $|Z_{\mathrm{bore}}|$ are much smaller than those of the saxophone. Consequently, even modest peaks in $|Z_{\mathrm{mouth}}|$ can have large influence on the output sound of the didjeridu. Though the $|Z_{\mathrm{bore}}|$ of the saxophone is larger than that of the didjeridu, expert players are still able to create a strong vocal tract resonance whose magnitude is comparable with that of Z_{bore} to vary the sound spectrum.

The valves of the instruments are also very different. The lip has a much larger mass and, in lip-valve instruments, it is thought that its natural frequency lies close to the playing frequency [13, 27], which is about 80 Hz for the didjeridu: well below the frequency of peaks in Z_{mouth}. It is therefore plausible that the presence of a large acoustic impedance at frequencies well above that of the lip motion might have relatively little effect on the motion of the lip itself. In contrast, reed resonances usually lie above the playing frequency [28] and can contribute to the sounding formants in reed instruments [29]. Further, simulations of the interaction of a clarinet reed with standing waves in a pipe [30] show that the higher modes of the reed vibration are driven at frequencies somewhat displaced from their eigenfrequencies. Although the details are not yet known, it appears likely that, in the frequency bands where high pressures are generated in the mouth, the motion of the reed is modified by the increased acoustic load of the tract and that this can increase the acoustic current and thus the radiated pressure at those frequencies.

Implications of this study may influence students and teachers of saxophone and other reed instruments. To produce strong variations in the radiated sound spectrum at constant pitch and loudness requires the generation of peaks in Z_{mouth} of magnitude at least a few MPa.s.m^{-3}. This value is comparable with those required to play in the altissimo range [9, 12], suggesting that it may be possible to teach the two different techniques together. Further, the spectrum modifications do not require tuning of the peaks in $|Z_{\mathrm{mouth}}|$, so it should be an easier technique to master than playing the altissimo, which many students find very difficult. However, students need to be aware that the variation they hear is much greater than that in the radiated sound, so it may be useful to practise using headphones to deliver the p_{rad} signal.

4. Conclusions

When playing at a constant frequency and amplitude, saxophone players can vary the spectral envelope of the radiated sound considerably by altering their vocal tract configuration. The variation in the sound radiated and thus heard by listeners is rather smaller than that inside the player's mouth, which influences the player's perception.

The relation between Z_{mouth} and p_{rad} was measured over the range from 100 to 10000 Hz. At frequencies where the amplitude of the Z_{mouth} is at least comparable with those of Z_{bore}, *i.e.* several MPa·s·m^{-3} or more, larger amplitudes in Z_{mouth} usually enhance the level of harmonics in the radiated sound. A stronger correlation is observed when the series impedance is considered: when the magnitude of Z_{mouth} is comparable with Z_{bore}, increases in $|Z_{\mathrm{mouth}} + Z_{\mathrm{bore}}|$ at any frequency always increase the radiated pressure at that frequency. These results indicate that an increased magnitude of Z_{mouth} at the frequency of a harmonic could alter the reed vibration to increase the acoustic current at that frequency, leading to increased p_{rad}. (This result contrasts with the case of the didjeridu (the other instrument for which Z_{mouth} and p_{rad} have been compared). In the didjeridu, large values of $|Z_{\mathrm{mouth}}|$ reduce the magnitude of p_{rad}.)

Compared with experienced players, less experienced players who are unable to produce strong peaks in Z_{mouth} have smaller variations in the radiated sound spectra. For saxophone students, this suggests that the key to achieving variations in sound spectrum without changing the pitch is learning to produce strong vocal tract resonances using an appropriate vocal tract configuration – a skill that is also needed to play in the altissimo range.

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