Do trumpet players tune resonances of the vocal tract?

Jer-Ming Chen, a) John Smith, and Joe Wolfe

School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia

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The acoustic impedance spectrum was measured in the mouths of seven trumpeters while they played normal notes and while they practiced “bending” the pitch below or above the normal value. The peaks in vocal tract impedance usually had magnitudes rather smaller than those of the bore of the trumpet. Over the range measured, none of the trumpeters showed systematic tuning of the resonances of the vocal tract. However, all players commented that the presence of the impedance head in the mouth prevented them from playing the very highest notes of which they were normally capable. It is therefore possible that these players might use either resonance tuning or perhaps very high impedance magnitudes for some notes beyond the measured range. The observed lack of tuning contrasts with measurements for the saxophone which, like the trumpet, has weak resonances in the third and fourth octaves. Saxophonists are only able to play the highest range by tuning resonances of the vocal tract, so that the series impedance has a very strong peak at a frequency near that of the desired note. This difference is explained by the greater control that the trumpet player has over the natural frequency of the vibrating valve.

An important consequence of these differences is that, while reed valves will support air column oscillations over a very wide band of frequencies below the mechanical resonance frequency of the reed, lip valves will support air column oscillations only in a narrow frequency range near the natural frequency of the lips themselves (Fletcher and Rossing, 1998, Fig. 13.6). It follows that the brass player must control the natural frequency of the valve with more precision than is required of the player of reed instruments.

The two ducts above and below the valve are often characterized by their acoustic impedances: $Z_{\text{Bore}}$ is the ratio of acoustic pressure to flow into the bore, and $Z_{\text{Tract}}$ that of acoustic pressure to flow into the tract, both measured near the valve. In a widely used, simple model (Benade, 1985), continuity of acoustical flow at the valve requires that the flow into the instrument plus that into the mouth add to zero. How these impedances act on the lip valve depends on whether the lips are an “opening door” $(+,-)$ or a “sliding door” $(+,+)$.

In the $(+,-)$ case, the pressure difference that acts across the valve is the acoustical flow times the sum $Z_{\text{Bore}} + Z_{\text{Tract}}$. The valve is loaded by the series combination of the impedances of the two ducts, $Z_{\text{Series}}$. In the $(+,+)$ case, pressure that acts to open the valve has positive components due to the pressures in both ducts. This leads to an impedance load with a form like $\alpha Z_{\text{Bore}} - \beta Z_{\text{Tract}}$, where the constants $\alpha$ and $\beta$ depend on the geometry.

Players informally report that changing the position of the tongue can produce a small change to the pitch (e.g., Gordon, 1987). It can also sometimes cause a change in register—causing the playing regime to shift to a different resonance of the bore, with a consequent large change in pitch. In a pedagogical text, Sherman (1979) advises “The tongue should also remain in the bottom of the mouth as if singing the syllable aah.” Sherman also notes that “it may be
impossible to incorporate this lowered tongue when playing in the high register.” Changing the position of the tongue in the mouth changes the frequency of peaks in $Z_{\text{tract}}$. The effect of raising or lowering the tongue has been measured in the mouths of clarinet players miming (Fritz and Wolfe, 2005) and didjeridu players while they played (Tarnopolsky et al., 2005). In a study using a mechanical (+,–) reed to “play” a trombone, an upstream constriction near the valve raised the playing frequency a little, and also, over part of the range, allowed the valve to operate at a higher resonance of the bore (Wolfe et al., 2010).

More is known about the involvement of the vocal tract in playing reed instruments than brass. Wilson (1996) placed a microphone inside a clarinet mouthpiece and another inside the player’s mouth to show that, in some circumstances, the acoustic pressure in the mouth could be comparable with that in the mouthpiece. A similar technique used on a saxophone (Scavone et al., 2008) also showed that the two could be comparable when performing a technique called pitch bending or when playing in the highest ranges of the instrument. The tract–reed–bore system has been modeled with that in the mouth. A similar technique used on a trumpet was measured using a system adapted from that of Tarnopolsky et al. (2006) and Chen et al. (2009). A narrow tube with internal cross-sectional area of 3.5 mm$^2$ was used to supply a broadband acoustic current of characteristic source impedance 120 MPa s m$^{-3}$ into the player’s mouth during performance, as shown in Fig. 1. Positioned alongside it was another narrow tube with area 4 mm$^2$ leading to a microphone (Brüel & Kjær 4944 A, Nærum, Denmark) located just outside the mouth. This constituted the impedance measurement head, which was calibrated using a reference load consisting of an acoustically infinite tube of length 197 m and internal diameter 26.2 mm (comparable in cross section with the vocal tract). The raw acoustic impedance measured in the player’s mouth is then analyzed and smoothed in a manner reported earlier (Chen et al., 2009) to remove noise arising from the strong signal from turbulent airflow and the vibrating valve in the mouth. The phase spectra were considerably noisier than the magnitude spectra and are not shown here.

**II. MATERIALS AND METHODS**

**A. Measurements of $Z_{\text{mouth}}$**

The impedance inside the mouths of the trumpet players was measured using a system adapted from that of Tarnopolsky et al. (2006) and Chen et al. (2009). A narrow tube with internal cross-sectional area of 3.5 mm$^2$ was used to supply a broadband acoustic current of characteristic source impedance 120 MPa s m$^{-3}$ into the player’s mouth during performance, as shown in Fig. 1. Positioned alongside it was another narrow tube with area 4 mm$^2$ leading to a microphone (Brüel & Kjær 4944 A, Nærum, Denmark) located just outside the mouth. This constituted the impedance measurement head, which was calibrated using a reference load consisting of an acoustically infinite tube of length 197 m and internal diameter 26.2 mm (comparable in cross section with the vocal tract). The raw acoustic impedance measured in the player’s mouth is then analyzed and smoothed in a manner reported earlier (Chen et al., 2009) to remove noise arising from the strong signal from turbulent airflow and the vibrating valve in the mouth. The phase spectra were considerably noisier than the magnitude spectra and are not shown here.

**B. Measurements of $Z_{\text{bore}}$**

The impedance of the bore of the trumpet (King model 600, Cleveland, OH) was measured in the plane of the mouthpiece rim, using a system described previously (Dickens et al., 2007). This trumpet was used for all investigations, except for two investigations of the high range where players used their own instruments.

**C. Subjects and protocol**

Seven players were studied. Four were professionals, and three of these specialized in playing the high register. Three experienced amateurs, each with more than 12 years experience, volunteered for the study. One of the amateurs returned for a second session to allow more measurements and thus a larger data set on one subject was collected. Subjects were asked to position the tubes of the impedance head

**FIG. 1.** Schematic of the impedance measurement head, as positioned at the player’s mouth during trumpet playing. To facilitate measurement, the tip of the impedance head is positioned behind and above the player’s front teeth, “looking” into the player’s mouth.
to the side of the mouth opening and to position the tip of the impedance head behind and above the front teeth. (One player was able to play over his normal range to written D6 with the impedance head placed between his front teeth and the vibrating lips. The results obtained with the impedance head in front of and behind the teeth were similar.) With the impedance head in place, they were asked to play notes in an ascending diatonic scale, beginning with written C4 (sounding B♭3). Each note was held for several seconds, during which a 3 s measurement of impedance spectrum was made.

They were also asked to play notes in the comfortable range whose pitch they could “bend” up or down, preferably without changing the tension in their lips. These notes were chosen from the series using no valves, i.e., written C4, G4, C5, E5, and G5 (sounding B♭3, F4, B♭4, D5, and F5, respectively). They played these with the impedance head in position while ZMouth was measured.

III. RESULTS AND DISCUSSION

A. Normal playing

Figure 2 shows the impedance spectra ZMouth measured in the mouth of a trumpet player while he played, in his normal style, the note written C5 (nominally 466 Hz, sounding B♭4 on the trumpet, a transposing instrument), and G6 (1397 Hz, sounding F6). The former is a note in the middle of the range, the latter a very high note for the trumpet. Because the probe signal from the impedance head is much weaker than the sound produced in the vocal tract by the vibrating lips, these measurements have an artifact: Narrow spikes corresponding to the harmonics of the note played appear superposed over the broadband response that indicates ZMouth. These artifacts are retained because they indicate the note being played.

On the same graphs is plotted ZBore measured for the trumpet with no valves depressed, the fingering used for these two notes. It is a B♭ trumpet, so the second and higher impedance peaks all fall close to frequencies in a harmonic series on the note sounding B♭2. (The frequency of the first resonance is well below that of B♭2 and this resonance is not normally used.)

These measurements show a feature typical of nearly all of the measurements made of ZMouth: The resonances of the vocal tract produce peaks in ZMouth that are usually much smaller than those in ZBore.

The lower bound of the frequency range used to measure ZMouth was varied for different parts of the experiment and for different subjects. As well as the harmonics of the note played, there is turbulent noise in the mouth, and this limits the signal-to-noise ratio in ZMouth, which is itself measured with a broadband signal. The turbulent noise is greatest at low frequencies, so the low frequency limit is varied, depending on the frequency range to be measured and the level of noise present.

When the low frequency limit allowed, a peak in ZMouth was usually found between about 100 and 350 Hz, as was the case for measurements of ZMouth in players of the saxophone (Chen et al., 2008) and clarinet (Chen et al., 2009). Although measurements were never made at frequencies below 100 Hz, this peak is hereafter called first resonance.

Another peak, hereafter called the second resonance, was usually measured between about 500 and 1400 Hz. This corresponds to the resonance used by clarinettists and saxophonists for resonance tuning. Another, hereafter the third resonance, was usually measured above 1500 Hz. Its upper limit may have sometimes exceeded 2500 Hz, which was the upper limit of our measurements. These distributions are shown in Fig. 3.

To gain an intuitive idea of these resonances, one may imagine a hypothetical cylindrical vocal tract, 170 mm long, nearly closed at the glottis and with lips sealed around the impedance head. This would have impedance peaks at 1000 and 2000 Hz, corresponding approximately to the second and third resonances we measure. Departures from cylindrical shape would produce a distribution of frequencies. If the glottis were nearly closed, the first resonance would have a very low frequency and a quarter wavelength rather longer than the distance from lips to glottis. With this approximation, the air in the glottis and in the upper tract, respectively, could be represented as the mass and spring of a Helmholtz resonance. The frequency of this resonance would depend relatively weakly on the position of the tongue, but strongly...
on the area of the glottis. On the other hand, the shape of the
tongue, and especially the position of a constriction between
the tongue and the roof of the mouth, can vary the frequen-
cies of the second and third resonances considerably.

Figure 3 plots, for normal playing, the frequencies of the second and third vocal tract resonance \( f_2 \) and \( f_3 \) against the frequency \( f \) of the note being played while \( Z_{\text{Mouth}} \) was being measured. The scarcity of points at high pitch was due to three factors. First, notes above 1 kHz are difficult on the trumpet for most players. Second, players found it difficult to sustain steady notes at the highest pitches in their range with the impedance head in the mouth. Third, there were often high levels of turbulent noise superimposed on the probe signal, making it sometimes impossible to identify resonances. Because the impedance head is displaced by a centimeter or so from the vibrating lips for most measurements, the measured resonance frequencies are expected to overestimate those “seen” by the lips, especially at high frequencies. (At 1 kHz, the quarter wavelength is 86 mm.)

Figure 3 shows that, overall, there is no consistent relation between \( f \) and \( f_2 \). This observation is not affected by the possibility that the measurements of \( f_2 \) and \( f_3 \) may be overestimates at high frequencies. For the player who undertook the more extensive study, several measurements of \( f_2 \) for normal playing lie in the vicinity of \( f \) near the top of his range, but there is no clear tuning. Overall, the frequency of the higher resonance \( f_3 \) decreases slightly with increasing \( f \). Figure 3 also shows that there is no consistent relation between \( f_2 \) or \( f_3 \) with the harmonics of \( f \) over the range measured.

The phase of the acoustic load is important in theoretical models of the valve–duct interaction (Fletcher, 1993). At frequencies close below that of an impedance peak, the imped-
ance is inerteive: The pressure leads the flow. At frequencies just above that of the peak, it is compliant. Figure 3 shows that, for many of these measurements (when \( f \) is close to but below \( f_2 \)), the vocal tract impedance was inerteive at the playing frequency, but that, especially for those at the highest pitches (when the playing frequencies exceed that of the impedance peak), the tract impedance was compliant.

Figure 4 shows the magnitude of the peaks in \( Z_{\text{Mouth}} \) for the second and third resonances as a function of the playing frequency \( f \). (As shown in Fig. 3, \( f \) and \( f_2 \) are, in general, well separated, as are \( f \) and \( f_3 \).) Figure 4(A) shows the second resonance \( f_2 \) and Fig. 4(B) shows \( f_3 \). For comparison, \( Z_{\text{Bore}} \) for the trumpet is shown for the fingering that plays B♭3, F4, B♭4, D5, and F5 (the fingering used for the pitch bending measurements). Over most of the range, the peaks in \( Z_{\text{Bore}} \) are considerably larger than those in \( Z_{\text{Mouth}} \). The magnitudes become comparable above 1 kHz for two reasons: First, there is a slight increase in the magnitude of the second peak in \( Z_{\text{Mouth}} \) with increasing \( f \). This would be consistent with a
tongue position that was somewhat higher for high notes (Fritz and Wolfe, 2005; Tarnopolsky et al., 2006). Second, and more important, the magnitude of the peaks in $Z_{\text{Bore}}$ decreases at high $f$. Consequently, one would expect that $Z_{\text{Mouth}}$ could make a significant contribution to the combination $Z_{\text{Bore}} + Z_{\text{Mouth}}$ or to $\alpha Z_{\text{Bore}} - \beta Z_{\text{Mouth}}$ only in two cases. First, in pitch bending, the frequency of the lip vibration is not close to a peak in $Z_{\text{Bore}}$, so the magnitude of $Z_{\text{Bore}}$ is lower at the frequency $f$. Second, in the very highest range of the trumpet, the peaks in $Z_{\text{Bore}}$ are very weak.

### B. Pitch bending

Without using valves or slides, the players of brass instruments could, in principle, bend the pitch by several different means. They could change the tension or other parameters of their lips, so as to change the natural frequency of the lip vibrations, or change its vibration between $(+,-)$ and $(-,+)$ operation. They could change the pressure in the mouth. Alternatively, they might change the frequency of the peak in the impedance combination $Z_{\text{Bore}} + Z_{\text{Mouth}}$ or $\alpha Z_{\text{Bore}} - \beta Z_{\text{Mouth}}$ by changing the shape of the vocal tract or by varying the degree of glottal opening. In this exercise, the players were asked to bend the note without changing any properties of the lips. However, we did not measure parameters of the lips and therefore could not be certain that this instruction was followed.

The results for pitch bending are shown in Figs. 5 and 6. Again, there is no systematic tuning of the resonances near the frequency played, and the magnitude of the peaks in $Z_{\text{Mouth}}$ during pitch bending is not significantly different from normal playing. Further, the frequency $f_2$ lies consistently above the playing frequency $f$. The reason for this is that bending the pitch of the highest notes, a difficult task, was not included in the experiment. $f_2$ lies consistently above $f$ for both lipping up and down, suggesting that the phase of the tract resonance was not of primary importance in this exercise. It appears that these players use other control parameters.

### C. High note playing

All trumpet players were asked to play notes as high as they could with the impedance head in the mouth. Figures 2 and 3 show that these players were able to play in the highest range measured without tuning a peak in $Z_{\text{Mouth}}$ near the frequency of the note played, and with the magnitude of $Z_{\text{Mouth}}$ at the playing frequency considerably less than that of $Z_{\text{Bore}}$. We assume that, for these players, the appropriate peak in $Z_{\text{Bore}}$ is selected by adjusting other control parameters, probably including the properties of the lips and the steady air pressure in the mouth.

An important limitation to the discussion of high note playing is imposed by the presence of the impedance head in the mouth. Teachers and players often observe that the...
tongue may be raised close to the hard palate when playing the very highest notes (e.g., Sherman, 1979).

The requirement to play a steady note for 3 s was complicated by the presence of the impedance head passing between the lips and teeth, which may be a significant perturbation. The players quickly adjusted to this condition for their normal range and reported that it was not particularly disturbing. Unsurprisingly, the upper limit of the pitch at which the trumpeters could play a sustained note with the impedance head in the mouth was lower, typically by a few notes, than the highest note that they could play normally. Further, all reported that they raised their tongues to reach the very highest notes.

It is therefore possible that, for some of our subjects, the very highest range could require a vocal tract resonance with a high impedance tuned to the note to be played, and that the insertion of the impedance head precludes the usual tract geometry required to achieve this. Alternatively, it is possible that the high tongue facilitates high playing, even though a peak is not tuned, perhaps by changing the magnitude or the phase of $Z_{\text{tract}}$ or perhaps by varying the aerodynamic conditions upstream from the lips. Finally, it is also possible that the tubes of the impedance head, which pass between the player’s lips in the corner of the mouth, prevent the players from achieving the combination of lip muscle tensions required for the very highest notes.

**IV. CONCLUSIONS**

Players can produce a vocal tract resonance with peaks in impedance comparable with those of the trumpet bore for the highest range of the instrument. Orchestral trumpeters are rarely asked to play much above 1 kHz. Some specialist jazz players, however, often play rather higher. This study shows, however, that players can play above 1 kHz and as high as 1.5 kHz, without having to tune their vocal tract resonances. Indeed under the conditions of these measurements, the players in this study were not seen to tune the tract resonances in a systematic way, for normal playing, high note playing, or during pitch bending. Further, the considerable variation in the resonance frequencies used by different players suggests that the seven players in this study used very different vocal tract configurations over the playing range.

Like the saxophone, the trumpet has weak impedance peaks in its high range. However, while saxophone players can only use this range by tuning their tract resonances, the trumpet players of this study can play in the high range without tuning resonances. This difference is probably due to the greater control that trumpeters have over the vibrating valve.

That the frequency $f_2$ of the second tract resonance usually lies above the playing frequency $f$ over most of the normal range suggests that the phase of the vocal tract impedance is usually inertive at the playing frequency. In contrast, in the very high playing range, $f$ usually exceeds $f_2$, which suggests that the tract impedance is usually compliant in this range.

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