4pMU1. Do trumpeters tune resonances of their vocal tract?

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In most wind instruments, the acoustic output is generated by airflow through a non-linear valve, whose sounding frequency is largely determined by resonances in the bore of the instrument (an acoustic duct downstream of the valve) and mechanical properties of the non-linear valve that converts DC to AC power. The player's vocal tract (a second duct, upstream) also has acoustic resonances, which - in particular cases - play a significant role in performance technique. For example, when executing advanced techniques (e.g. pitch-bending, altissimo playing) on the clarinet and saxophone, we showed that expert control of vocal tract resonances is essential for performance (Chen, Smith, & Wolfe, 2008. Science, 319, 726). To understand how such a tract-valve-bore system might interact during trumpet performance, we measured the acoustic impedance spectrum in seven trumpeters’ mouths as they played normal notes, high-register notes and while pitch-bending below and above the normal note. Unlike the behavior seen in saxophonists and clarinetists, none of the trumpeters studied showed any systematic adjustment of their vocal tract resonances to the notes played. The much greater control that trumpeters have over the natural frequency of the vibrating valve may explain the difference with clarinetists and saxophonists.
I. INTRODUCTION

For most wind instruments, the acoustic output is generated by airflow through a non-linear valve that converts DC to AC power. The sounding frequency is largely determined by resonances in the instrument bore (an acoustic duct downstream of the valve) and mechanical properties of the valve. In trumpets and other brass instruments, the player’s lips are the valve, vibrating to modulate the air flowing between them (Elliot & Bowsher, 1982; Fletcher & Rossing, 1998). Fletcher (1993) characterizes valves thus: a reed valve is closed by upstream pressure and opened by downstream pressure (–,+) or (+,–), while a lip valve can either be (+,–) or (+,+) i.e. opened by pressure on either side.

The player’s vocal tract (a second duct, upstream) also has acoustic resonances and, in certain wind instrument performance techniques, these can play a significant role in controlling the valve. The resonances of the two ducts – above and below the valve – are characterized by the peaks of their respective acoustic impedance spectra: $Z_{\text{Bore}}$ is the ratio of acoustic pressure to the flow into the instrument bore, while $Z_{\text{Tract}}$ is the ratio of acoustic pressure to the flow into the player’s vocal tract, both measured near the valve.

Benade (1985) described a simple model based on the continuity of acoustical flow at the valve: the flow into the instrument plus that into the mouth must add to zero. It follows that, for a (+,–) or (–,+), the pressure difference generated across the valve is the acoustical flow times the sum $Z_{\text{Bore}} + Z_{\text{Tract}}$. The valve "sees" the series combination of the impedances of the two ducts, $Z_{\text{Series}}$. In a (+,+), however, the pressure that acts to open the valve has positive contributions from the pressures in both ducts, leading to an impedance load with a form like $aZ_{\text{Bore}} - bZ_{\text{Tract}}$, where $a$ and $b$ are constants that depend on the geometry.

The frequency and magnitude of these tract resonances has been shown to depend on how the position of the tongue in the mouth changes: Fritz and Wolfe (2005) measured the effect of raising or lowering the tongue by clarinetists who mimed playing. Tarnopolsky et al. (2005) used broadband excitation to measure the impedance spectrum inside the mouths of didjeridu players while they were playing. Wilson (1996) and Scavone et al. (2008) used the harmonics of the reed signal as their source and simultaneously measured the acoustic pressure in both the player’s mouth and inside clarinet and saxophone mouthpieces respectively. These studies showed that the two pressures can become comparable during pitch-bending or when playing in the highest range of the instrument. Impedance spectra measurements were also made directly in the mouths of musicians as they played the saxophone (Chen et al., 2008, 2011) and clarinet (Chen et al., 2009). These have shown how, in these instruments, strong peaks in $Z_{\text{Mouth}}$ can influence the sounding frequency either continuously (when pitch-bending) or by changing the register.

In pitch-bending, a strong peak in $Z_{\text{Mouth}}$ when added in series with $Z_{\text{Bore}}$, can shift the frequency of the combined peak by as much as 20%. To play notes in the highest range of the instruments, players tune one of the broad maxima in $Z_{\text{Mouth}}$ to be near the much narrower peak in $Z_{\text{Bore}}$ corresponding to the desired register, increasing the magnitude of $Z_{\text{Bore}} + Z_{\text{Mouth}}$ at the desired frequency, and thus determining the playing regime.

Like the saxophone, the trumpet has a high-playing range with weak bore resonances, which make these notes inaccessible to many players. Could vocal tract effects be similarly used to control the playing pitch and to select the bore resonance involved in the playing regime? To produce the desired note, trumpeters adjust their lips such that the natural frequency of the lips lies close to that of the note played. Over most of the playing range, the operating regime involves a strong peak in $Z_{\text{Bore}}$, but these peaks become weaker above 1 kHz. Is it possible that in this very high range (where peaks in $Z_{\text{Bore}}$ are relatively weak), players use $Z_{\text{Mouth}}$ to provide a strong impedance peak at the desired frequency? Our previous studies show that a suitable vocal tract resonance is available: the vocal tracts of saxophonists and clarinetists can produce large magnitude impedance peaks around 1 kHz. One might also ask if trumpet players use vocal tract resonances for pitch-bending in the way saxophonists do: i.e. adjusting its frequency so that the combined tract, bore and valve impedance results in a peak at the desired sounding frequency?

This paper reports $Z_{\text{Mouth}}$ measured directly in trumpeters’ mouths as they played normally across the trumpet’s range, and while pitch-bending downwards and upwards from its normal value. As this paper accompanies an invited presentation to discuss previously published work (Chen et al., 2012), some earlier figures are reproduced here.

II. MATERIALS AND METHODS

A. Measuring $Z_{\text{Bore}}$ and $Z_{\text{Mouth}}$

The experimental trumpet (King model 600, Cleveland, OH) was used for all measurements, except for two investigations of the high playing range (here, the players used their own instruments for greater familiarity). The impedance spectrum of the bore was measured in the plane of the mouthpiece rim using a three microphone head and three non-resonant calibrations (Dickens et al., 2007).
Chen et al.

$Z_{\text{Mouth}}$ was measured in the mouth of trumpeters using a system adapted from Tarnopolsky et al. (2006) and Chen et al. (2008), consisting of a narrow tube (internal cross-sectional area 3.5 mm²) to supply a broadband acoustic current of characteristic source impedance 120 MPa.s.m⁻³ into the player’s mouth, and another narrow tube (cross-sectional area 4 mm²) positioned alongside it leading to a microphone (Brüel & Kjær 4944A) 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). To remove noise arising from the vibrating lips and turbulent airflow in the mouth, the raw acoustic impedance spectrum measured in the player’s mouth is then analysed and smoothed in a manner reported earlier (Chen et al., 2009). The phase spectra were considerably noisier than the magnitude spectra, and are not shown here.

B. Subjects and Protocol

Seven trumpeters were studied: four were professionals, with three of them specializing in playing the high register. Three experienced amateurs, each with more than 12 years experience, volunteered for the study.

Subjects were asked to position the impedance head to the side of their mouth and locate the measurement tip behind and above the front teeth. Because the measurement tip is displaced by a centimetre or so from the vibrating lips, at high frequencies the measured resonance frequencies can be expected to slightly overestimate those 'seen' by the lips (at 1 kHz, the quarter wavelength is 86 mm). 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 behind and above the front teeth were similar. With the impedance head in place, they were asked to play notes in an ascending diatonic scale to the top of their range, beginning with written C4 (sounding B♭3). Each note was sustained for several seconds, during which a three-second impedance measurement was made.

With the impedance head similarly positioned, they were also asked to play notes whose pitch they could comfortably “bend” up or down, preferably without changing their lip tension. The notes chosen were from the series played using no valves, i.e. written C4, G4, C5, E5 and G5 (sounding B♭3, F4, B♭4, D5, and F5, respectively).

III. RESULTS AND DISCUSSION

Figure 1 shows the impedance spectrum $Z_{\text{Bore}}$ (grey) measured for the trumpet played with no valves depressed (the fingering used for written notes C5 and G6). 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 first resonance is not normally used).

Figure 1 also shows $Z_{\text{Mouth}}$ measured while a trumpeter played normally the written notes C5 (466 Hz, sounding B♭4), a note in the middle of the trumpet’s range, and G6 (1397 Hz, sounding F6), a very high note for the trumpet. Now, the note produced by the vibrating lips, as measured in the trumpet’s mouth, is much louder than the probe signal introduced by the impedance head, so these impedance measurements have an artefact: narrow spikes corresponding to the harmonics of the sounded note appear superposed over the broadband $Z_{\text{Mouth}}$ spectrum. We retain these artefacts because they indicate the frequency of the note played; e.g. we can see here that the sounding frequencies of both notes fall slightly sharper than their respective bore resonances. In fact, Figure 2 shows this is true for most of the trumpet’s playing range because, while high CO₂ content in the player’s breath tends to decrease the bore resonance frequencies (particularly for long held notes; Fuks, 1997), both an increase in air temperature and humidity above the ambient conditions tend to raise its resonance frequency (Young & Webster, 1959).

Figure 1 also shows a feature found in nearly all our $Z_{\text{Mouth}}$ measurements in trumpeters: resonances in $Z_{\text{Mouth}}$ have impedance maxima typically weaker than those in $Z_{\text{Bore}}$.

Although not shown here, a peak in $Z_{\text{Mouth}}$ (first vocal tract resonance) was usually found between about 100 and 350 Hz, similar to that reported in saxophonists and clarinetists (Chen et al., 2008, 2009 & 2011). Another peak (the second tract resonance) was usually observed between about 500 and 1400 Hz, corresponding to the tract resonance used by clarinettists and saxophonists for resonance tuning. Another peak (the third tract resonance) was usually measured above 1500 Hz. Its upper limit may have sometimes exceeded 2500 Hz, which was the upper limit of our measurements. Figure 3A shows these distributions.

A. Normal Playing

Figure 3 plots the second and third vocal tract resonance frequencies ($f_2$ and $f_3$) against the sounding frequency $f$ of the note played normally: (A) shows the measurements for trumpeters, and (B) for tenor saxophonists. For trumpeters, there are relatively fewer points at high pitch. First, notes above 1 kHz are difficult for most trumpeters.
FIGURE 1. Here, $Z_{\text{Bore}}$ and $Z_{\text{Mouth}}$ are plotted for the written notes C5 (blue) and G6 (red). The same $Z_{\text{Bore}}$ (no valves depressed) is used to play both notes. The $Z_{\text{Mouth}}$ shown here are superposed with an artifact: The narrow peaks are the harmonics of the note sounded. (After Chen et al., 2012)

FIGURE 2. The deviation (in cents) of the sounding frequency from the frequency of the corresponding trumpet bore resonance, plotted (in blue) for 400 measurements of players playing normally for notes written C4 to G6 (sounding B3 to F6). The points appear quantized because the precision is limited by the uncertainty principle and the window length used in both impedance and playing frequency measurements. Consequently, each blue cross usually indicates the results of many points. Accordingly, the mean (red) and standard deviation (grey bars) are also shown for each note.
FIGURE 3. Normal playing: The top graph (A) shows frequencies of the second ($f_2$ – red circles) and third ($f_3$ – blue squares) vocal tract resonances plotted against the sounding frequency measured during normal trumpet playing. The magnitudes of the impedance maxima (binned in half decade bands) are indicated by the size of the symbols, while dashed vertical lines indicate nominal sounding frequency of some of the musical notes played. In a comparable plot for normal saxophone playing, the bottom graph (B) shows frequencies of the saxophonist’s second vocal tract resonance $f_2$ plotted against the sounding frequency $f$ for notes measured over the saxophone’s range: five experts (red circles) and three amateurs (green dots). Similarly, the magnitude of the corresponding impedance maxima (binned in half decade bands) is indicated by the size of each circle, while the vertical line indicates the transition from standard to altissimo range (written F#6 to G6, sounding 659–698 Hz). In both plots, the diagonal line is the equation: vocal tract resonance frequency = sounding frequency. (After Chen et al., 2011 & 2012)
Second, with the impedance measurement head in the mouth, players found it difficult to sustain steady notes at the highest pitches of their range. Third, it is sometimes impossible to identify tract resonances because there were often high levels of turbulent noise superimposed on the probe signal for measurements on the highest notes.

Apart from the frequency of the higher tract resonance $f_i$ decreasing somewhat with increasing $f$, Figure 3A reveals no other consistent relation between $f$ and $f_i$ or between $f$ and $f_i$. (This observation is unaffected by the possibility that the measurements of $f_i$ and $f$ may be overestimates at high frequencies.) There is also no consistent relation between $f_i$ or $f$ with the harmonics of $f$ over the notes measured ($f$ and $f_i$ are well separated, as are $f$ and $f_i$).

In theoretical models of the valve-duct interaction, the phase of the acoustic load is important (Fletcher, 1993). For frequencies just below an impedance peak, the impedance is inertive: the pressure here leads the flow; at frequencies just above the peak, it is compliant. For many measurements in Figure 3A, the vocal tract impedance is inertive at the sounding frequency (when $f$ is close to, but below $f_i$), but become compliant at the highest notes sounded (when $f$ exceeds $f_i$).

The magnitude of the peaks in $Z_{\text{Mouth}}$ for the second and third resonances at each sounding frequency is also indicated in Figure 3A, binned in half decade bands. Over most of the trumpet range, the magnitude of peaks in $Z_{\text{Bore}}$ (50-100 MPa.s.m$^{-3}$) are considerably larger than those in $Z_{\text{Mouth}}$ (1-10 MPa.s.m$^{-3}$), but become comparable above 1 kHz for two reasons. First, the magnitude of the second peak in $Z_{\text{Mouth}}$ increases slightly with increasing $f$, consistent with a tongue position that moves somewhat higher for high notes (Fritz and Wolfe, 2005; Tarnopolsky et al., 2006). Second, and more importantly, the magnitude of the peaks in $Z_{\text{Bore}}$ decreases at high $f$. Accordingly, $Z_{\text{Mouth}}$ can be expected to contribute significantly to the combination $Z_{\text{Bore}} + Z_{\text{Mouth}}$, or to $\alpha Z_{\text{Bore}} - \beta Z_{\text{Mouth}}$ in two cases. First, the sounding frequency $f$ during pitch-bending is not close to a peak in $Z_{\text{Bore}}$, so the magnitude (and contribution) of $Z_{\text{Bore}}$ is lower at $f$. Second, the peaks in $Z_{\text{Bore}}$ are very weak in the very highest range of the trumpet.

For contrast with a system where vocal tract tuning is present, Figure 3B shows the saxophonist’s vocal tract resonance frequency plotted against the sounding frequency, across the player’s range (650 measurements from eight saxophonists). Here, expert players adjust their tract resonance frequency close to that of the note sounded, beginning in the saxophone’s upper standard range and over its entire altissimo range. Furthermore, the magnitude of peaks in $Z_{\text{Mouth}}$ for these tract resonances are large (10-30 MPa.s.m$^{-3}$) and comparable in magnitude with peaks in the saxophone $Z_{\text{Bore}}$, particularly in the altissimo range (10-30 MPa.s.m$^{-3}$). The amateur players, who neither tune their vocal tract resonances nor have large impedance maxima, are unable to play in the altissimo range.

### B. High Note Playing

All the trumpeters were asked to play notes as high as they comfortably could with the impedance head in the mouth. Figures 1 and 3A show these players playing in the highest range, measured without adjusting a peak in $Z_{\text{Mouth}}$ near the frequency of the sounded note, and with the magnitude of $Z_{\text{Mouth}}$ at the sounding frequency rather less than that of $Z_{\text{Bore}}$. For these players, we assume that the appropriate $Z_{\text{Bore}}$ peak is selected by adjusting other control parameters involving properties of the lips and regulating the steady air pressure in the mouth.

The presence of the impedance head in the mouth imposes an important limitation to our discussion of high note playing: when playing the very highest notes, teachers and players often report that the tongue is raised close to the hard palate (e.g., Sherman, 1979). The presence of the impedance head passing between the lips and teeth may be a significant perturbation to holding a steady note for three seconds. Our players adjusted quickly to this condition for the normal range and reported that it was not particularly disruptive after some practice. However, because all our players reported raising their tongue to reach the very top of their range, the presence of the impedance head in the mouth interfered with these highest notes, thus reducing their available top range by a few notes.

Although we found no evidence of resonance tuning in these studies, we have not completely ruled out the possibility that it might still be used, particularly in the extreme altissimo range. First, only seven trumpeters were measured and we are wary of making too broad a conclusion. Second, it is possible that for some of our subjects, playing the very highest range could possibly involve a vocal tract resonance with a high impedance peak tuned close to the desired note, but the insertion of the impedance head in the mouth precludes the usual tract geometry required to achieve this. In other words, there may be a tuning regime, required for the very highest one or two notes, and that this was experimentally inaccessible to us because of the perturbation presented by the probe. Alternatively, it is possible that the high tongue position facilitates high note 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 players may never engage resonance tuning, even for the very highest notes, and that the absence of the very highest note or two in this experiment is because the tubes of the impedance head passing between the player’s lips in the corner of the mouth prevent the players from achieving the combination of lip muscle tensions required for these very highest notes.
FIGURE 4. Pitch-bending: The top graph (A) shows frequencies of the second ($f_2$ – red circles) and third ($f_3$ – blue squares) vocal tract resonances plotted against the sounding frequency $f$ measured during trumpet pitch-bending, for the notes sounding B♭3, F4, B♭4, D5 and F5 [dashed vertical lines indicate nominal (unbent) frequencies]; filled symbols indicate upward-bending pitch and unfilled symbols indicate downward-bending pitch. In a comparable plot for pitch-bending measured on the clarinet, the bottom graph (B) shows frequencies of the clarinetist’s second vocal tract resonance $f_2$ plotted against sounding frequency $f$. Data from five players include both normal playing (blue circles) and downward pitch-bending (red circles) in the range between written G4 (349 Hz) and G6 (1397 Hz). The magnitude of the vocal tract impedance maxima measured here is indicated by the size of the circles (binned in half decade bands), while typical $Z_{Bore}$ magnitudes for the first and second clarinet registers are also shown for comparison. In both plots, the diagonal line is the equation: vocal tract resonance frequency = sounding frequency. (After Chen et al., 2009 & 2012)
C. Pitch-Bending

Trumpeters can, in principle, bend the sounding pitch by several different means without using valves or slides: they can change the natural frequency of the lip vibrations by adjusting the tension of their lips or other parameters, or vary its vibration between (+,+) and (+,–) modes. Players can also regulate the steady air pressure in the mouth, or adjust 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 modifying their vocal tract shape or varying the degree of glottal opening. To this end, the players were asked to bend the note without changing any properties of their lips; we did not measure parameters of the lips, however, and therefore could not ascertain that this instruction was followed.

Figure 4 shows the results for pitch-bending. Again, no systematic adjustment of tract resonances is observed in trumpet pitch-bending (Figure 4A), and the magnitude of peaks in $Z_{\text{Mouth}}$ (1-12 MPa.s.m$^{-3}$) do not differ significantly from that of normal playing (1-10 MPa.s.m$^{-3}$). Further, the tract resonance frequency $f_2$ lies consistently above the sounding frequency $f$ for both upward and downward pitch-bending, suggesting that the phase of the tract resonance was not of primary importance in this exercise; other pitch control parameters are operating here.

In contrast, Figure 4B shows the clarinettist’s vocal tract resonance frequency plotted against the sounding frequency, both when playing normally and when pitch-bending downwards. When pitch-bending, these clarinettists are seen to tune their vocal tract resonance very tightly with the sounding frequency of the ‘bent’ note, while producing very strong peaks in $Z_{\text{Mouth}}$ (10-50 MPa.s.m$^{-3}$) which are comparable in magnitude with the peaks in $Z_{\text{Bore}}$ (40-50 MPa.s.m$^{-3}$). Interestingly, when playing normally, these clarinettists are also seen to loosely adjust their vocal tract resonance about 200 Hz higher than the frequency of the note played (thus the vocal tract impedance is inertive at the sounding frequency), albeit with only rather modest maxima in $Z_{\text{Mouth}}$ (4-11 MPa.s.m$^{-3}$).

IV. CONCLUSIONS

For the highest range of the trumpet, we observe players can produce a vocal tract resonance with impedance peaks comparable in magnitude with those of the trumpet bore. This study shows, however, that trumpeters can play above 1 kHz and as high as 1.5 kHz without having to tune their vocal tract resonances. In fact, our trumpeters in this study were not seen to adjust their tract resonances in a systematic way, for normal playing, high note playing, nor during pitch-bending. Further, the variation in resonance frequencies used by different players suggests that the seven players in this study use very different vocal tract configurations over their playing range.

The trumpet, like the saxophone, has weak impedance peaks in its highest range because of its slight conicity and flaring bell. However, unlike saxophonists who can only access this range by tuning their vocal tract resonances, the trumpeters in this study are able to play in the highest range without tuning their vocal tract resonances. This difference is probably due to the greater control that trumpeters have over their vibrating valve (Chen et al., 2012). For over most of the normal playing range, the frequency $f_2$ of the trumpeter’s second tract resonance usually lies above the sounding frequency $f$, suggesting that the phase of the vocal tract impedance here is usually inertive at the sounding frequency. In contrast, in the highest range of the trumpet, $f$ typically exceeds $f_2$, suggesting that the vocal tract impedance here is usually compliant.

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