Do trumpet players tune resonances of the vocal tract?

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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. © *2012 Acoustical Society of America*.
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I. INTRODUCTION

In many wind instruments, acoustic power is generated by airflow through a vibrating valve. In trumpets and other brass instruments, the valve is the player's lips which, when air passes between them, vibrate to modulate the airflow (Elliott and Bowsher, 1982). Usually, the playing frequency is determined, to first order, by the resonances in the bore of the instrument, which is an acoustic duct downstream from the valve, and the resonance frequency of the vibrating lips (Elliott and Bowsher, 1982; Fletcher and Rossing, 1998). Upstream from the valve lies the player's vocal tract—a second duct—with acoustic resonances that can, in some cases, have a large effect on performance technique. In this paper, we examine the acoustical effect of the vocal tract on trumpet performance.

The behaviors of reed valves (oboe, clarinet, etc.) and lip valves (brass, didjeridu, etc.) are very different. Reed valves are blown closed by a steady air pressure in the player's mouth. Lip valves have been modeled by valves that, when mouth pressure increases, are blown open (in the lower part of the range) or blown laterally (in the higher range), or by some combination of these (Yoshikawa, 1995; Adachi and Sato, 1995, 1996; Yoshikawa and Muto, 2003). A general characterization of such valves uses (+,−) for a valve opened by upstream pressure and closed by downstream pressure, (−,+) for one closed by upstream pressure and opened by downstream pressure, and (+,+) for one opened by pressure on either side. With this notation, a reed valve has configuration (–,+) while a lip valve can be either (+,–) or (+,+) (Fletcher, 1993).

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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_{Bore} is the ratio of acoustic pressure to flow into the bore, and Z_{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 $Z_{\mathrm{Bore}} + Z_{\mathrm{Tract}}$: The valve is loaded by the series combination of the impedances of the two ducts, Z_{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 $\alpha Z_{\mathrm{Bore}} - \beta Z_{\mathrm{Tract}}$, where the constants α and β 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

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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_{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 by several authors (e.g., Sommerfeldt and Strong, 1988; Fletcher, 1993; Guillemain, 2007).

Recently, measurements have been made of the impedance spectra in the mouths of musicians while they played saxophone (Chen *et al.*, 2008, 2011) and clarinet (Chen *et al.*, 2009) (here, the impedance measured in the mouth Z_{mouth} is expected to be a good approximation to that of the vocal tract Z_{tract}). These studies have shown how, in these instruments, strong peaks in Z_{Mouth} can change the playing frequency either continuously, when pitch bending, or by changing the register. In pitch bending, a strong peak in Z_{Mouth}, when added in series with Z_{Bore}, can shift the frequency of the combined peak by as much as 20%. To select registers, players tune one of the broad maxima in Z_{Mouth} to be near the (much narrower) peak in Z_{Bore} that corresponds to the desired register. This increases the magnitude of $Z_{Bore} + Z_{Mouth}$ at the desired frequency and determines the playing regime.

Could comparable effects occur in brass instruments and thus contribute to pitch and register changes, and help explain the pedagogical comments cited earlier? Trumpet players must adjust their lips so that the natural frequency of the lips lies close to that of the note to be played. Over most of the range, the operating regime involves a strong peak in Z_{Bore}, but these peaks become weaker in the range 1–2 kHz. Is it possible that players who specialize in this very high range, where peaks in Z_{Bore} are relatively weak, are using Z_{Mouth} to provide a strong impedance peak near the desired frequency? A suitable vocal tract resonance is available: The vocal tracts of saxophone and clarinet players can produce strong resonances around 1 kHz (Chen *et al.*, 2008, 2009). Similarly, one might ask whether trumpet players use vocal tract resonances for pitch bending in the way saxophonists do: That is, adjusting their tract resonance frequency so that the combined impedance of valve, bore, and tract has a peak near the desired playing frequency, and thus a large magnitude at the playing frequency.

This paper reports measurements of Z_{Mouth} in the mouths of musicians while they played the trumpet in a normal playing style. Z_{Mouth} was also measured while trumpet players "bent" the pitch downwards and upwards from its normal value.

II. MATERIALS AND METHODS

A. Measurements of Z_{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_{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

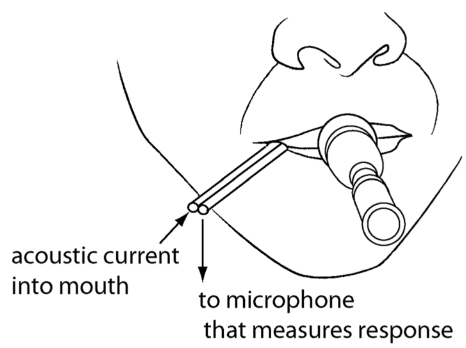

FIG. 1. Schematic of the impedance measurement head, as positioned at the player's mouth during trumpet playing. To facilitate measurement, the tip of the impedance head is positioned behind and above the player's front teeth, "looking" into the player's mouth.

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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 Z_{Mouth} was measured.

III. RESULTS AND DISCUSSION

A. Normal playing

Figure 2 shows the impedance spectra Z_{Mouth} 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 Z_{Mouth}. These artifacts are retained because they indicate the note being played.

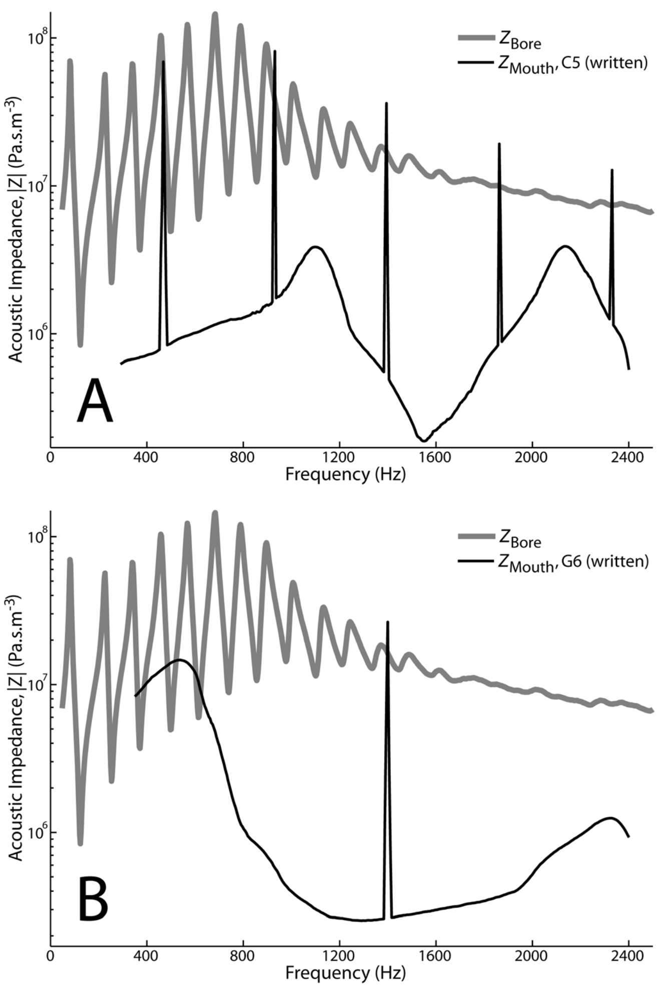

FIG. 2. In this semilog plot, Z_{Bore} and Z_{Mouth} are plotted for the notes written (A) C5 and (B) G6. In both cases, the note is played and Z_{Bore} is measured with no valves depressed. On the plots of Z_{Mouth} are superposed an artifact: The narrow peaks are the harmonics of the note being played.

On the same graphs is plotted Z_{Bore} 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 Z_{Mouth}: The resonances of the vocal tract produce peaks in Z_{Mouth} that are usually much smaller than those in Z_{Bore}.

The lower bound of the frequency range used to measure Z_{Mouth} 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:noise ratio in Z_{Mouth}, 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 Z_{Mouth} was usually found between about 100 and 350 Hz, as was the case for measurements of Z_{Mouth} 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

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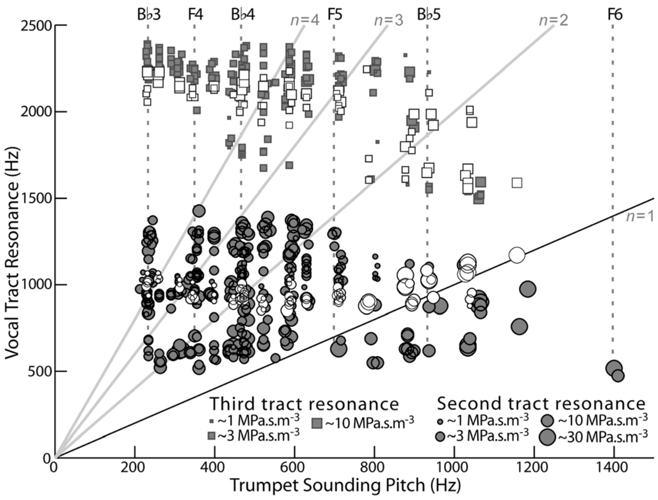

FIG. 3. Frequencies of the second and third vocal tract resonances (circles and squares, respectively) plotted against the frequency of the note sounded during normal playing. The sizes of the symbols represent the magnitudes of the impedance maxima (binned in half decades as shown in the legend), while dashed vertical lines indicate the nominal frequency of some of the musical notes played. The data for the player who participated in the more extensive study are shown using open symbols. The dark straight line shows the following relationship: Tract resonance frequency = pitch frequency. The pale lines show the relationship tract resonance frequency = $n*$pitch frequency, to indicate where the harmonics fall in relation to the tract resonances.

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 frequencies 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_{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 impedance is inertive: 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 inertive 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_{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_{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_{Bore} are considerably larger than those in Z_{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_{Mouth} with increasing f. This would be consistent with a

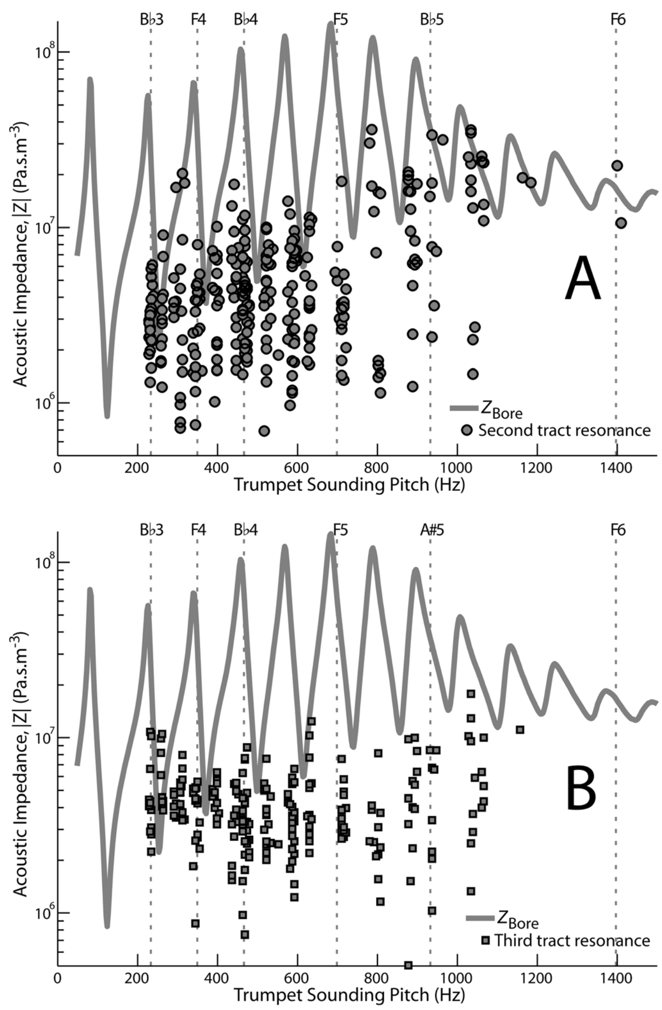

FIG. 4. The magnitudes of the peaks in Z_{Mouth} measured for normal playing are plotted as a function of the frequency of the note played on a semilog scale. The continuous curve shows the impedance spectrum Z_{Bore} for the trumpet, measured with no valves depressed. (Curves for other fingerings have a similar range in the magnitude of Z.) (A) The magnitude of the second resonance (measured at its maximum at f_2, not at f) and (B) that of the third (measured at f_3). Dashed vertical lines indicate the nominal frequency of the musical note played.

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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_{Bore} decreases at high f. Consequently, one would expect that Z_{Mouth} could make a significant contribution to the combination $Z_{Bore} + Z_{Mouth}$ or to $\alpha Z_{Bore} - \beta Z_{Mouth}$ only in two cases. First, in pitch bending, the frequency of the lip vibration is not close to a peak in Z_{Bore}, so the magnitude of Z_{Bore} is lower at the frequency f. Second, in the very highest range of the trumpet, the peaks in Z_{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 $Z_{Bore} + Z_{Mouth}$ or $\alpha Z_{Bore} - \beta Z_{Mouth}$ 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_{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.

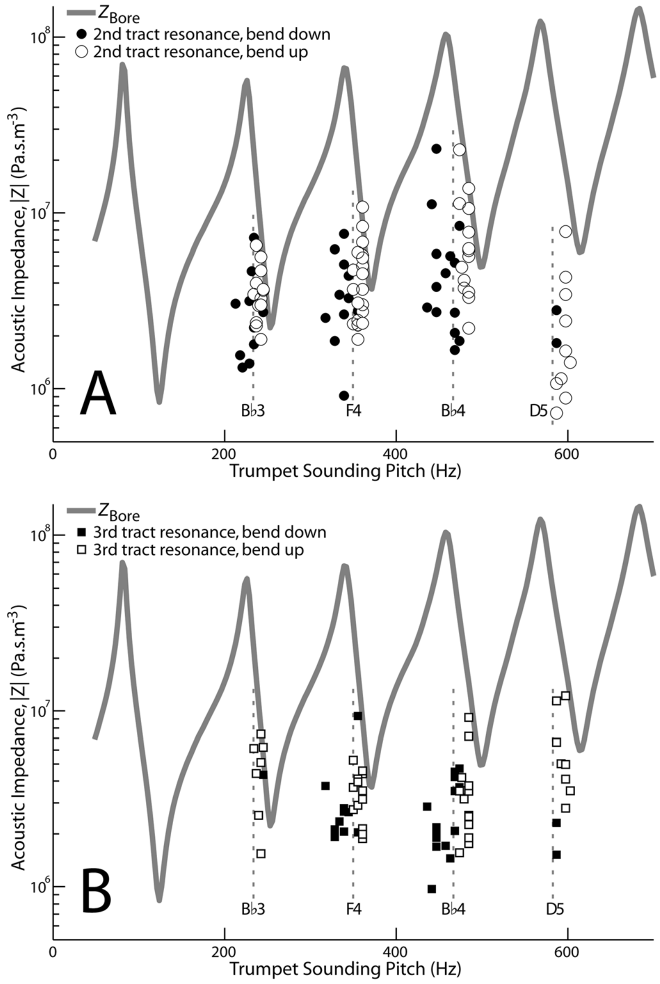

FIG. 6. The magnitudes of the peaks in Z_{Mouth} for pitch bending are plotted as a function of the frequency of the note played on a semilog scale for pitch bending. (The playing frequency and that of the impedance peak in Z_{Mouth} are in general widely spaced.) The continuous curve shows the impedance spectrum Z_{Bore} for the trumpet, measured with no valves depressed—the fingering used for pitch bending (A) shows the second resonance f_2 and (B) f_3. Dashed vertical lines indicate the nominal frequency of the (unbent) musical note played.

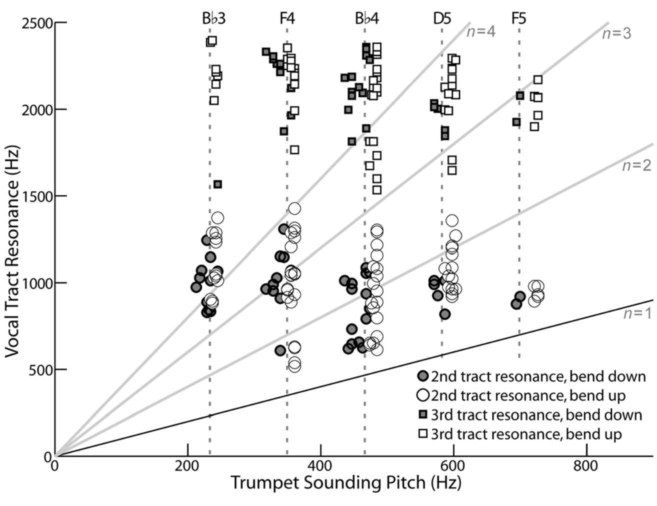

FIG. 5. Frequencies of the second and third vocal tract resonances (circles and squares, respectively) plotted against the frequency f of the note sounded during pitch bending, measured for the notes sounding B♭3, F4, B♭4, D5, and F5 [their nominal (unbent) frequencies are indicated by dashed vertical lines]. Upwards pitch bending is shown with open symbols, while downwards pitch bending is shown with closed symbols. The dark straight line shows the following relationship: tract resonance frequency = pitch frequency. The pale lines show the relationship tract resonance frequency = $n *$ pitch frequency.

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_{Mouth} near the frequency of the note played, and with the magnitude of Z_{Mouth} at the playing frequency considerably less than that of Z_{Bore}. We assume that, for these players, the appropriate peak in Z_{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

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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_{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.

ACKNOWLEDGMENTS

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