SOME EFFECTS OF THE PLAYER'S VOCAL TRACT AND TONGUE ON WIND INSTRUMENT SOUND

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ABSTRACT

In wind instruments, reeds (including lip reeds) interact with the acoustic impedances of the instrument's bore, $\mathbf{Z}_b$ and the player's vocal tract, $\mathbf{Z}_t$. The bore is usually narrow and has high Q resonances whose maxima in $\mathbf{Z}_b$ are large and determine the playing regime to first order. The tract has resonances with lower Q which act on a small area of the reed. So how do the weak maxima in $\mathbf{Z}_t$ affect the timbre and pitch? We answer this question using a mechanical reed with geometrically simple vocal tracts and lungs to model didjeridu and trombone players.

The small area of the reed (or *moving* area of the lips) 'sees' only weak tract resonances ($\mathbf{Z}_t << \mathbf{Z}_b$) if the tongue is low. The tongue, when raised at the tip, acts as an impedance matching transformer linking this small area to the larger cross sectional area of the lower tract. Different tract configurations give strong effects on timbre and considerable effects on intonation, independently of the reed. The effects are consistent with those reported by players and explain some known intonation effects.

1. INTRODUCTION

Many players of wind instruments talk of the perceived importance of the shape of the mouth on the sound. In the case of the didjeridu, the effect on the timbre is so clear as to be incontestable. Among scientists, however, there is considerable variation in opinion about the effect on pitch [1-4]. In this paper we report experiments on well-characterised model systems: artificial wind instrument players. Using plausible values of the relevant parameters, these show that vocal tract shapes can have important effects on both pitch and timbre.

Why do some scientists doubt the musicians?

First, there is the complication that, when a player changes mouth shape, s/he may also, unconsciously, change lip tension and geometry.

Second, it is difficult to explain the effect. In standard simple models, the acoustic currents on either side of the reed are equal, while the force on the reed depends on the difference in pressure. (We use 'reed' to mean either 'reed' in a woodwind or 'lip-reed' in a lip-reed instrument.) Thus the series combination $\mathbf{Z}_t + \mathbf{Z}_b$ acts on the reed. The bore has resonances with large Q. For most instruments, the bore is narrow and so has large characteristic impedance Z_o. How, then, can the relatively weak resonances of the vocal tract have an effect? In the case of the didjeridu, the bore and the tract have comparable dimensions, so the effects may be large. On the trombone, the effect is smaller, but in both cases we argue that it is larger than one might naïvely expect, because of the impedance matching effect of the tongue.

To answer these questions unambiguously, we use an artificial player, so we control vocal tract geometry and reed parameters independently. The reed is a simple cantilever spring. We call this version of the player Phyl, for 'PHYsicist's Lips'. Another version, with fluid-filled latex lips, is called Al, for 'Artificial Lips'. Phyl is less realistic than Al, but she has several advantages. First, she is easy to model mathematically. Second, the reed mass, spring constant and damping are controlled and measured independently of the acoustical experiment. Third, she can be used in the outwards striking mode to model lip reeds (as we do here) or reversed to model woodwinds.

We report measurements on two 'instruments'. One is a simple cylinder, selected from several with different lengths. This is a model of the didjeridu, chosen because of the known effect of the vocal tract on the timbre. We also studied the trombone as an example in which the tract is less well coupled to the bore, because of the mouthpiece constriction. Measurements on a clarinet played with an artificial vocal tract are reported in a companion paper [Fritz et al, this volume].

For simplicity, only geometrically simple vocal tracts are reported here. One is a cylinder, 30 mm in diameter and 180 mm long, representing a vocal tract with the tongue low in the mouth. The other is a cylinder, 9 mm in diameter and 120 mm long (representing the raised tongue) leading to a cone, widening from 9 mm to 30 mm over 60 mm (representing the lower tract). In a related study, (results not shown) we measured the vocal tract of a didjeridu player using MRI. The chosen shapes are idealisations of two tract configurations used in playing that instrument. In the high tongue configuration, the cross-sectional area is small just inside the teeth and above the tongue, and increases towards the lower vocal tract. In the low tongue configuration, there is less variation of area with position along the tract.

2. MATERIALS AND METHODS

Figure 1 represents the apparatus schematically. A source of dry compressed air leads to a cylinder, 30 mm diameter and 240 mm long filled with layers of acoustically absorbent material. The acoustic impedance of this cylinder, measured from the downstream end is largely real (lossy) and only weakly frequency dependent. We use it to model the trachea and lungs, whose highly branching structure is expected to have a similar output impedance.

The glottis is modelled by a plate separating the trachea from the vocal tract. The plate has a round hole with smoothed edges. Its diameter is 5 mm, chosen because proficient wind players are reported to keep the vocal folds almost closed while playing.

Downstream from the glottis is the selected vocal tract (see above) followed by the reed. The reed is a mass-loaded brass cantilever, here swinging outwards to model a lip reed. It is mounted in a plate to which the instrument under study may be attached. The didjeridus were sections of PVC pipe, diameter 44 mm and selected lengths. The trombone was a Yamaha, model YBL 321 bass trombone.

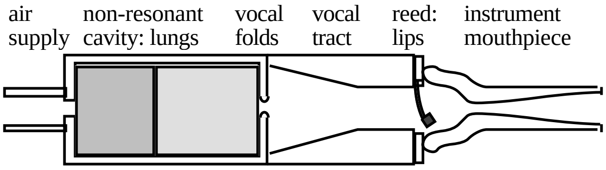

Figure 1: *The artificial lip reed player: not to scale.*

Acoustic impedance was measured using a technique reported elsewhere [5,6]. Sound spectra during playing were measured by a microphone 100 mm from the bell.

3. RESULTS AND DISCUSSION

3.1. The reed/lip 'sees' only a small area

It is important to note that the area of the reed that moves in the player's mouth is relatively small: rather less than 1 cm^2 for most woodwinds and brass. This is true even for the didjeridu [7].

Consequently the vibrating reed or moving part of the lips is not loaded by the impedance of the instrument measured across the whole area of its mouthpiece. In the simple case of a small piston moving in an infinite baffle, the diameter-matching load 'seen' by the piston can be modelled by an end effect rather like a radiation load: the impedance of an ideally open tube with length 0.8 times the piston radius. For a moving lip section of effective radius a in the mouth or at the input of an instrument, the impedance 'seen' is that of the instrument, as measured via an aperture with radius a. For this reason, the vocal tract and instrument impedances reported here are measured with an impedance head with a small radius. It was taken to be 3.9 mm, which gives an area similar to that estimated from [7], and also because one of the semi-infinite waveguides that we use for calibration has this radius.

3.2 Oscillation regimes

The outward striking reed reported here was found to vibrate at frequencies determined by the fundamental or a higher resonance of the instrument-tract system when the frequency of the latter exceed that of the reed by a limited range, as predicted by standard models [8,9]. We call this an instrument-determined regime. Outside this range, the reed vibrates near its own resonant frequency, almost independently of the length of the instrument (a reed-determined regime). For constant reed parameters, gradual lengthening of the pipe produces a pitch falling smoothly as the frequency of the mode of the instrument decreases: an instrument-determined regime. Once the latter falls below the reed frequency, there is a range of lengths over which there is little variation in playing frequency: a reed-determined regime. Beyond this length there is a regime over which the instrument plays at the next higher mode frequency. However, the precise playing frequency depends upon the vocal tract (Figure 2). Depending upon the relationship of the sounding frequency to the maxima and minima of the vocal tract impedance, the imaginary part of the tract impedance $\mathbf{Z}_t$ may be either positive or negative, and thus may either slightly increase or slightly decrease the imaginary part of the dominant bore impedance $\mathbf{Z}_b$.

Figure 2 shows that both the pitch and the regime transition depend upon the tongue position. For both tracts, the reed dominates at small pipe lengths L, but the pipe fundamental dominates above L = 550 mm for the high tongue, and above 650 mm for the low tongue. At L ≅ 1100 mm the reed begins to dominate again, but for the high tongue alone the second resonance begins to dominate above L = 1300 mm.

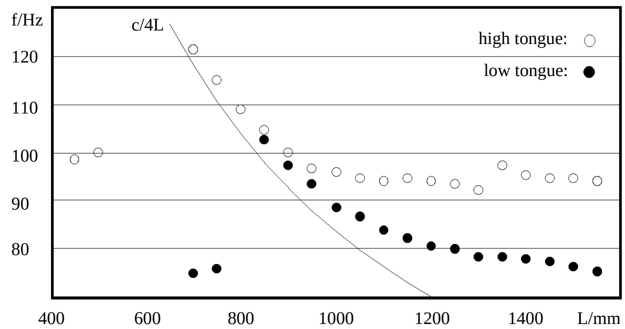

Figure 2. *Playing frequencies* f *for 'didjeridu' pipes of different lengths* L *played by an artificial playing system with simple vocal tract shapes.*

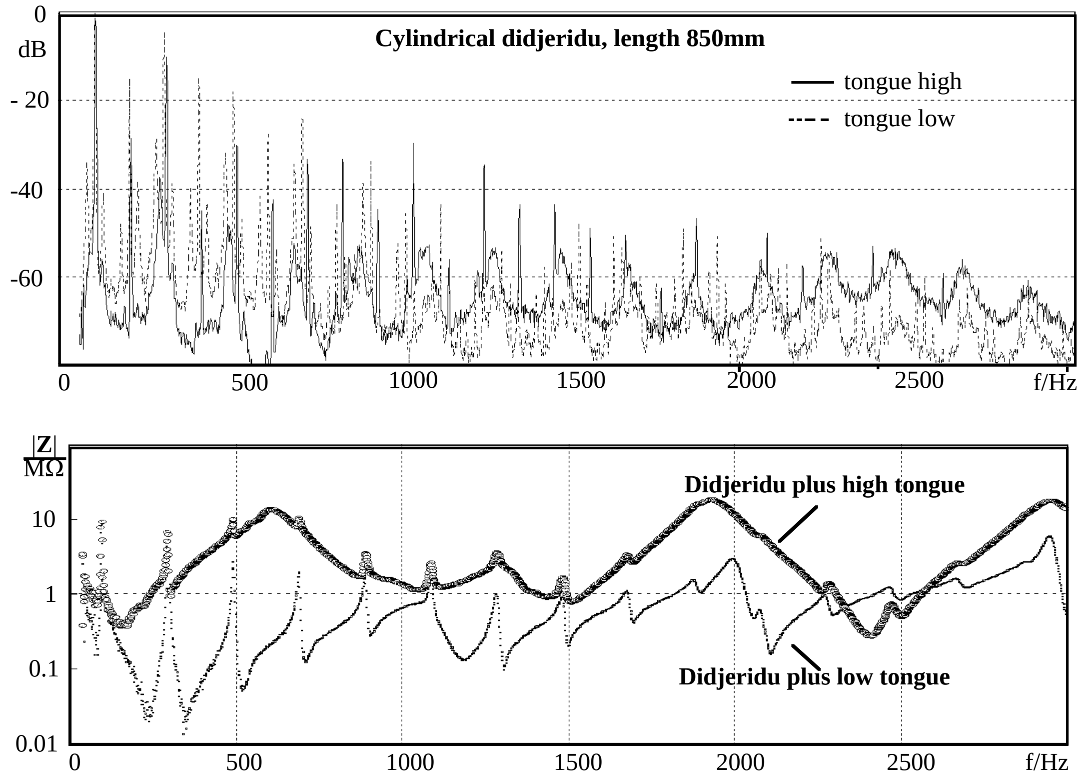

Figure 3. *Sound and impedance spectra of a didjeridu played with vocal tracts corresponding to high and low tongue.*

3.3. Vocal tract dominates didjeridu timbre

Figure 3 compares sound and impedance spectra in an instrument-determined regime for a didjeridu of length 850 mm. On the same axes are shown the sound spectrum and the series impedance $\mathbf{Z}_t + \mathbf{Z}_b$ for the two chosen vocal tracts.

The impedance of the bore (not shown separately) is the same for the two, and is a regular series of maxima and minima, spaced at approximately 100 Hz, the frequency of a wave about four times the length of the didjeridu. The minima are not symmetrically spaced with respect to the maxima because $\mathbf{Z}_b$ is measured with a small head, representing the small moving area of the lips. The envelope of the impedance curves is determined by the impedance of the tract. For the raised tongue tract, the maxima are sharper and have higher values of Z than do those of the low tongue tract.

The spectrum of the note played using the raised tongue shows a stronger formant around 2 kHz, near the frequency of the maximum in $\mathbf{Z}_t + \mathbf{Z}_b$. Qualitatively, this corresponds to the experience of didjeridu players: by raising the tongue close to the roof of the mouth, one can produce a strong formant in the 1–3 kHz range (its exact frequency depends on the detailed shape) [10]. The low tongue sound lacks this formant. (Sound files available at [11].)

As expected, the spectra show strong odd harmonics, with the even harmonics produced due to nonlinear effects in the reed. The sound files show that Phyl's timbre is breathy due to turbulence at the reed edge, so the resonances (which are not quite harmonic, especially at high frequencies) are excited by this broad band signal, as well as by the strictly harmonic partials of the reed. This is a simple example of the impedance matching effect of the tongue.

Other geometries (results not shown) give comparable effects: for example, a model tract consisting of a cone, narrow at the teeth and widening to meet the lower tract, produces both a strong impedance maximum and a corresponding formant. In this case, the tip of the tongue alone acts as an impedance matcher.

Note too the effect on the pitch (discussed in more detail below): on the one hand, this effect (among others) may be used by musicians for fine pitch adjustment. On the other hand, this effect can explain the intonation problems sometimes produced by double tonguing. In sufficiently rapid staccato passages, players initiate successive notes by alternating the articulations used in speech for [t] and [k]. Unless care is taken to keep the tongue tip high for the [k], the notes tend to alternate slightly in pitch.

3.4. Vocal tract influences trombone pitch

Figure 4 shows the spectrum of the sound played on a trombone by the artificial player using the two vocal tracts, in an instrument-determined regime. The shift in pitch, over

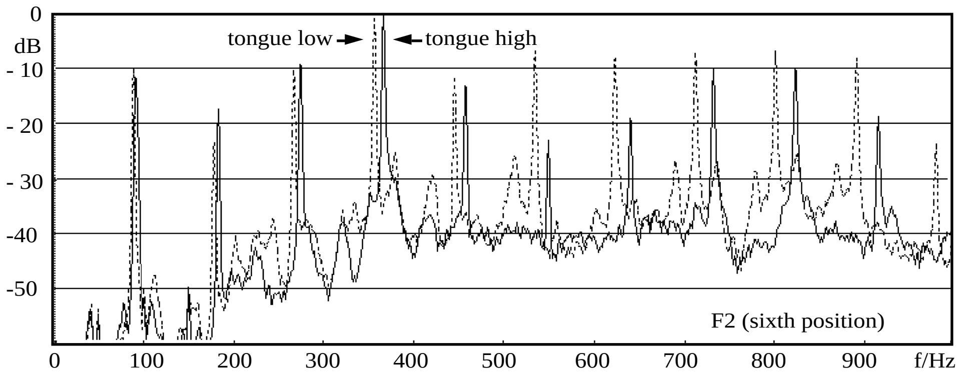

Figure 4. *Sound spectra. 'Phyl' plays F2 on the trombone with vocal tracts corresponding to high and low tongue.*

the range studied, is typically 20 cents: a musically important effect for intonation. Preliminary measurements on experienced brass players showed a comparable shift in pitch when they were asked to lower the tongue, keeping all else constant. A live brass player can compensate for this with lip tension of course—that she cannot is indeed one of Phyl's few advantages... to physicists.

The two tract configurations give timbres that are distinctly different, but less dramatically so than on the didjeridu (sound files at [11]). This is because the peaks in $\mathbf{Z}_b$ for the trombone are much higher than those for the didjeridu. Not only is the overall bore of the upper part of the instrument narrower than that of the didjeridu, but there is also a constriction in the mouthpiece that produces a formant near the ‘pop’ frequency of the mouthpiece [1].

4. CONCLUSIONS

In this study of a model player of wind instruments:

1. Vocal tract geometry dominates the timbre of the sound of the didjeridu, and less strongly affects the timbre of the trombone.

2. The tract geometry affects the played pitch by typically 20 cents over both instrument-dominated and reed-dominated regimes in both instruments. It can also cause a transition between different playing registers.

3. Raising the tongue, or the tongue tip, increases the height of peaks in the vocal tract impedance, and so more effectively couples it to the instrument resonances and to the reed or lips. This gives wind players a method of fine pitch adjustment, by variably coupling a largely imaginary impedance. It also explains the intonation problem sometimes introduced by double tonguing.

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