

# Vocal-tract Influence in Trombone Performance

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## ABSTRACT

Control of sound production in brass instruments requires the player to accurately adjust the mechanical properties of the lips and the applied intra-oral air pressure. The vibration of the lips involves an acoustical coupling with the air column and results in an auto-oscillation phenomenon similar to that in reed instruments. Recent studies conducted on clarinets and saxophones [2, 3, 4] showed that for specific tasks, the player's vocal-tract can be used to significantly influence the vibration of the reed. This was especially observed in the extended register and for specific effects such as bending. In this study, we conducted experiments on trombone players using a customized mouthpiece and two calibrated pressure transducers in order to measure the acoustical pressure near the input of both the air-column and vocal-tract. This setup allows an estimation of relative influence of downstream (air-column) and upstream (vocal-tract) systems in driving the lip oscillations. Results show different behaviours according to subject, though most players appear to use their vocal-tract to support notes in the extended register (D5 and F5). These observations suggest different strategies according to performers, possibly linked to variations in vertical tongue position, vocal-tract physiology and embouchure management.

## INTRODUCTION

Mastery of brass instrument playing is a lifelong endeavour that involves an accurate control of many different physical and physiological parameters, especially those of the player's lips and their acoustic coupling with the instrument air column. By varying the stiffness and vibrating mass of the lips, as well as the intra-oral pressure within the respiratory system, the performer is able to adjust the lip vibration frequency to a given resonance frequency of the instrument. The lip oscillations are therefore supported through an acoustical coupling with the air column (downstream system). While much is known about the excitation mechanism of brass instruments, questions remain about the possible acoustical contribution of the vocal tract on lip oscillations.

There have been a number of previous studies to evaluate the possible influence of the vocal tract in reed instrument playing, with most concentrating on the analysis and comparison of resonances in a player's vocal tract (the upstream system) and in the instrument [1-4, 6]. Two main measurement strategies are found in these previous works: (1) a measurement of the impedance of the player's upstream windway while they hold a fixed vocal-tract shape used during performance (either simulated or while playing); or (2) a real-time measurement of the relative contribution of the downstream and upstream system during normal performance situations. Results obtained in recent studies are in general agreement that players can create and adjust a strong upstream resonance in the range 500–1500Hz, which likely corresponds to the second vocal-tract resonance [2, 3, 4]. In the case of single-reed instruments, this resonance appears to have significant influence in the extended register where the downstream system

only offers weak support to the reed oscillations. Moreover, vocal-tract influence was also observed in particular tasks such as pitch bending and timbre variations [3].

In the case of brass instruments, the influence of upstream windway resonances remains unclear despite some previous analysis [5]. Brass players often mention the importance of vocal-tract adjustments for a given musical task and in particular, a raising of the tongue when reaching the high register, which reduces the volume of the mouth-cavity. Another consideration includes the posture of the head, which may affect the degree of constriction and vertical position of the larynx. That said, vocal-tract influence in brass instrument playing might be expected to be less important than for single-reed instruments because the vibrational parameters of the lips are more readily controllable than those of a cane reed.

The aim of this study is to evaluate the possible influence of the upstream windway on the oscillations of the lips in brass instrument performance. The measurement system used here allows a real-time evaluation of the relative influence of the upstream and downstream systems during normal performance. In this work, experiments were performed on trombone players only.

## MEASUREMENT APPROACH

In this study, we use a method first developed for the measurement of vocal-tract influence in single-reed instruments [3]. This approach is based on the assumption of continuity of volume flow  $U$  at the reed junction. Considering  $Z_d$ , the input impedance of the downstream system,  $Z_u$ , the input

impedance of the upstream system,  $P_d$  and  $P_u$ , respectively the acoustic pressure at the input of the downstream and upstream systems, and  $Z_r$  the impedance of the lips, Benade & Hoekje [6] derived the following expressions:

$$U = \frac{P_d}{Z_d} + \frac{P_d - P_u}{Z_r} \quad (1)$$

$$U = \frac{P_u}{Z_u} + \frac{P_u - P_d}{Z_r} \quad (2)$$

Assuming that  $Z_r$  is very large compared to  $Z_d$  and  $Z_u$ , we derive formula (3) from (1) and (2):

$$\frac{P_u}{P_d} = \frac{Z_u}{Z_d} \quad (3)$$

Therefore, it is possible to evaluate relative values of the downstream and upstream impedances from the values of the acoustic pressure at the input of both systems; if the values of  $P_u$  are close to or larger than  $P_d$ , we expect that the upstream system will be influential on the oscillations of the lips. Indeed, the lips are assumed to be driven by the pressure difference ( $P_u - P_d$ ) across them. This method allows for the real-time measurement and observation of vocal-tract influence under normal playing conditions because  $P_u$  and  $P_d$  can be acquired using small pressure transducers and their spectra displayed using efficient signal processing techniques.

## EXPERIMENTAL SET-UP

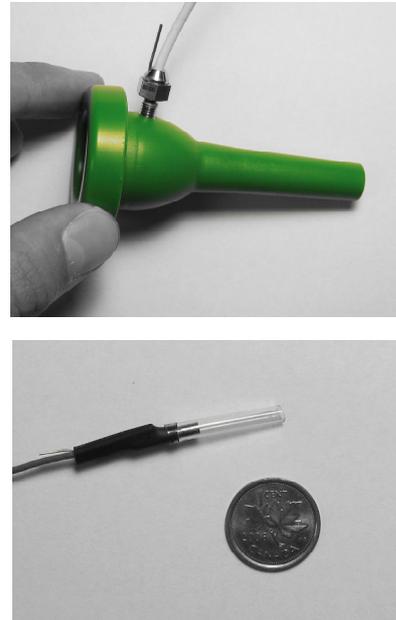
This measurement approach requires the acquisition of the acoustic pressure on both sides of the player's lips. For the downstream pressure, a customised mouthpiece was used through which an Endevco 8510B-1 pressure transducer was inserted to measure the acoustic pressure in the cup, about 5 millimetres from edge of the lips (Figure 1).

For the upstream pressure, an Endevco 8507C-1 miniature pressure transducer of 2.34 mm diameter was mounted in a small silicone tube (2 centimetres long) and inserted into the mouth of a subject. A short calculation shows that this tube induces a resonance around 4000Hz, which is significantly greater than the range of frequencies investigated here. Initially, the microphone was mounted on a stiff wire fixed to the mouthpiece so that its position would be constant for all subjects. However, this set-up was too uncomfortable for some subjects and they were instead allowed to more freely place the tube in their mouth with the condition that the end of the tube be above the tongue and relatively close to their teeth (roughly 5-10 mm from their lips). Ideally, the microphones would be located at the inner and outer edges of the lips. That being impossible, our solution provides valid results at least up to 2000Hz, as estimated in a similar study [3]. Considering that in this study we focus on a frequency range between 200–1500Hz, we assume the error induced by the position of the microphones to be negligible in our set-up.

## EXPERIMENTAL PROCEDURE

Measurements were performed on 5 subjects from the music performance program in the Schulich School of Music of McGill University in Montreal, Canada. Two subjects (Subjects B and C) were primarily bass-trombone players, though they were comfortable playing the tenor trombone as well, while the three others were tenor trombone players. Measurements were conducted on the same tenor trombone (King 2102) with a custom plastic mouthpiece manufactured at University Lille 3, France.

The experimental protocol consisted of two tasks. In the first task, subjects were asked to keep the slide in the closed position and to play the corresponding overtone series from written F3 to the highest note the subject could comfortably reach and then back down to the initial tone (F5 was the highest note recorded). In the second task, they were asked to "pitch bend" the notes B3-flat, F3 and B2-flat down a semitone without changing the slide position.



**Figure 1.** Downstream microphone mounted on a plastic mouthpiece (top), upstream microphone inserted into a small silicone tube (bottom).

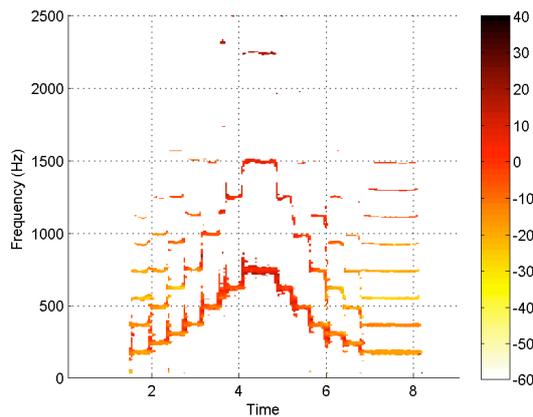
## RESULTS

### Overtones

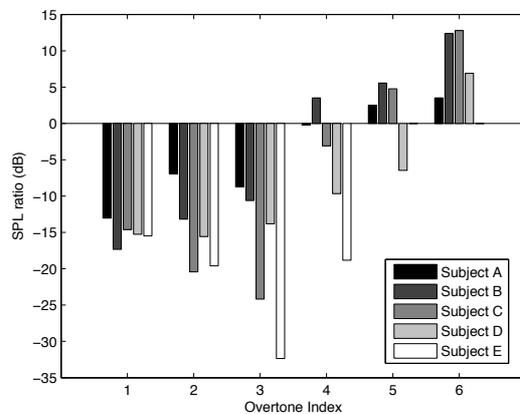
Brass instrument players must be able to sufficiently control the vibrational behaviour of their lips in order to initiate a particular tone from the overtone series of the air column. For example, when the tenor trombone slide is closed, the overtone series available is: B2-flat, F3, B3-flat, D4, F4, B4-flat, D5, F5. Common exercises involve the playing of the overtone series at different slide positions in order to develop embouchure flexibility and mastery of playing range. Therefore, the subjects were not unfamiliar with the first assigned task. Notes higher than F4 are more difficult to produce, primarily because they are an octave or less below the cutoff frequency of the air column (700Hz for the tenor trombone [7]) and thus weakly supported (acoustic feedback to help maintain the lip vibrations at the desired frequency is minimal and therefore requires more refined control of the lips by the performer). This is a situation in which vocal-tract influence might be important.

In Fig. 2, the spectrogram of the ratio of the sound pressure levels (SPL) in dB of the upstream and downstream pressures is plotted for an overtone series by Subject D from F3 to F5 and back to F3. The SPL ratios at the fundamental frequencies lower than B4-flat are below -12dB. Significant upstream pressures, which suggest vocal-tract influence in their production, become particularly apparent for higher notes (D5 and F5); the SPL ratio at the fundamental frequency for F5 reaches +6.8dB. SPL ratios greater than 0dB are also visible at higher harmonics from 700–2300Hz. This vocal-tract influence in the higher frequencies is not consistent across subjects; Subjects A, C and E show a contribution of the upstream system for harmonics in a range of frequencies

from 600 to 1000Hz. No clear contribution of the vocal tract was observed at higher harmonics for Subject B.



**Figure 2.** Spectrogram of the SPL ratios in dB of the upstream and downstream pressures for Subject D playing an overtone series from F3 up to F5 and back to F3.



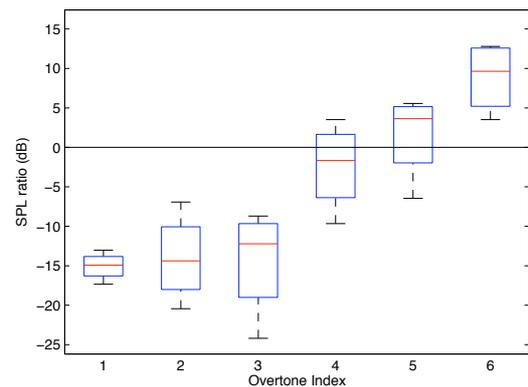
**Figure 3.** SPL ratios per subject in dB of the upstream and downstream pressures at the fundamental frequency of an ascending overtone series (1=B3-flat, 2=D4, 3=F4, 4=B4-flat, 5=D5, 6=F5).

If we compare the results across subjects, we observe different behaviours for the upstream contribution at the fundamental frequency of the sound. Figure 3 displays for all subjects the SPL ratios of the upstream and downstream pressures at the fundamental frequencies during the ascending part of the overtone series from B3-flat. Indices on the horizontal axis refer to overtone series notes (1=B3-flat, 2=D4, 3=F4, 4=B4-flat, 5=D5, 6=F5).

The highest SPL ratio, 12.8dB, was observed for Subject C playing F5 (index 6). The lowest SPL ratio, -32dB, was measured for Subject E playing F4 (index 3). A general tendency toward greater SPL ratios is evident as the subjects reach the higher, more difficult overtones. For two subjects (Subjects C and E), we observe decreasing SPL ratios up to F4. Subject C displays a clear break between a ratio of -24dB on F4 to a ratio of -3dB on B-flat4 (index 4), followed by increasing SPL ratios up to F5. No SPL ratios greater than about -15dB are observed for Subject E, though this subject could not reach the two highest notes (D5 and F5) of the overtone series.

Given a cutoff frequency of 700Hz for the tenor trombone, harmonics of notes starting at F4 (349Hz) will receive minimal support from the air column. It is interesting to note that a significant change in SPL ratios is observed in Fig. 3 for all subjects just after the F4 note. The four subjects able to reach

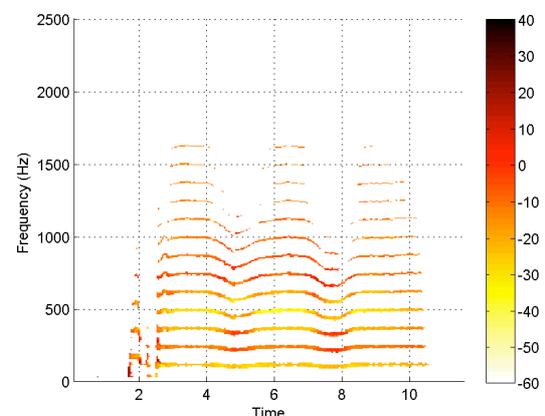
F5 all demonstrated SPL ratios greater than 0dB, while 3 of 4 had positive SPL ratios for D5 as well.



**Figure 4.** Boxplot of the SPL ratios in dB of the upstream and downstream pressures at the fundamental frequency of an ascending overtone series (1=B3-flat, 2=D4, 3=F4, 4=B4-flat, 5=D5, 6=F5). Subject D is not considered in the analysis.

Figure 4 displays a boxplot summary of the data represented in Fig. 3. As Subject D could not reach the highest two notes, his results are not included in this analysis. This representation confirms an increasing influence of the upstream system at the fundamental frequency with an increase in pitch. However, we observe a large variability in the results along the overtone series. Most consistent results are observed for the lower note (B3-flat) and the most variable data was found for F4 and B4-flat, located at the beginning of the higher register. This variability is not surprising given that, contrary to reed instruments, lip adjustments in brass instruments allow a significant degree of freedom in the strategy of a player. Embouchure settings are likely to vary across subjects and we assume that individuals find different combinations of either vocal-tract adjustments or embouchure settings in order to play a given note. This would explain results obtained for Subject D, who does not appear to take advantage of potential vocal-tract influence, even for B4-flat (see Fig. 3). We conclude that this performer relies predominantly on lip settings (maintaining a stiff embouchure) and that this strategy limits his use of the extended register (D5 and F5).

## Pitch Bending

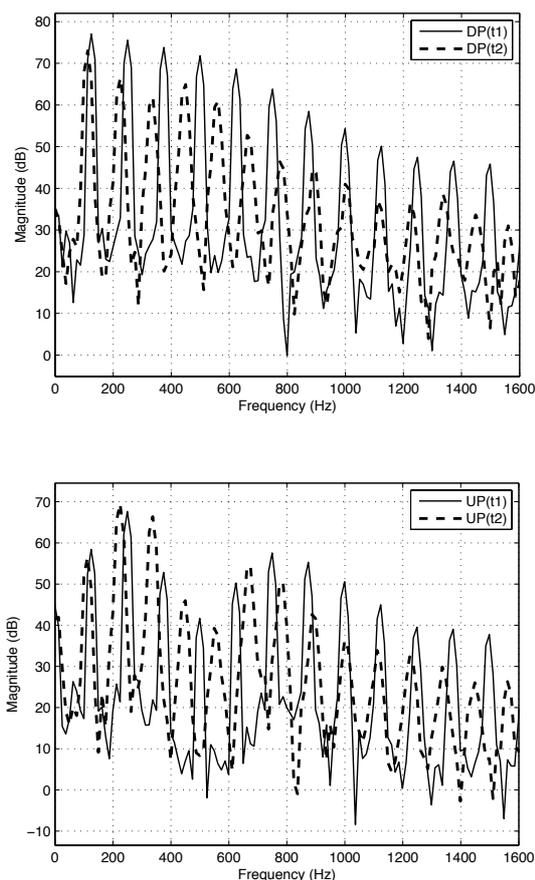


**Figure 5.** Spectrogram of the ratio of the SPL in dB of the upstream and downstream pressure for Subject E pitch bending down by a semitone from B2-flat.

Pitch bending is an effect that involves varying the sounding frequency of a note from its natural value for a given finger-

ing (which typically corresponds to a peak of the input impedance of the air column). For example, a trombone player can initially play an F3 with the slide in a closed position and then drop the sounding frequency via embouchure or vocal-tract manipulations to a C3 (or lower). This effect is commonly used by trombone players to play low notes that are not available in an overtone series for any slide position. Furthermore, some musicians report using pitch bending at higher pitches during practice for embouchure training or to relax the lips after a tiring playing session. In our study, musicians were asked to perform frequency bends from B3-flat, F3 and B2-flat down by a semitone and back. Although larger pitch bends are possible (up to a 5th for a performer trained to perform this exercise), current use of bending in a musical context does not involve greater pitch variations than a semitone.

Figure 5 shows the spectrogram of SPL ratios of the upstream and downstream pressures for two consecutive pitch bends performed by Subject E from B2-flat (116Hz) to A2. We do not observe any strong SPL ratios at the fundamental frequency of the sound. However, SPL ratios near 0dB are evident during the pitch bends at the first and second harmonics. The SPL ratio of the second harmonic during bending is between -2 and -1dB, whereas it lies around -20dB at the beginning of the B2-flat. As well, stronger SPL ratios are also evident for some harmonics located between 700–1200Hz.

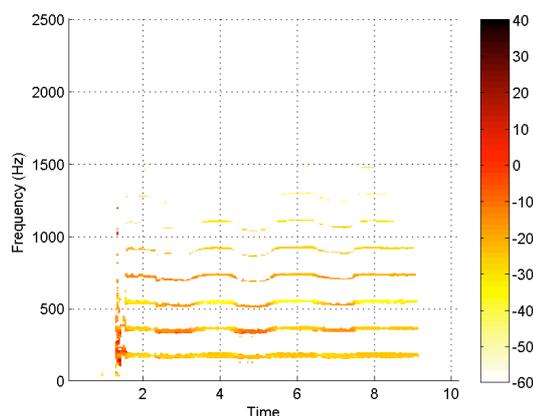


**Figure 6.** Snapshots of downstream (top) and upstream (bottom) spectra at time  $t_1=6.5$ s before bending and  $t_2=7.7$ s during bending for Subject E.

Snapshots of the mouth and mouthpiece spectra at time  $t_1=6.5$ s, before bending, and  $t_2=7.7$ s, during bending, for Subject E are shown in Fig. 6. The magnitude of every harmonic of the downstream spectrum is lowered during bending, while the fundamental frequency remains relatively constant. In the upstream spectrum, however, we observe a

slight increase during bending of the 3rd and 4th harmonic magnitudes in the frequency range 350Hz to 500Hz. The upstream spectral peaks increase in magnitude from a minimum around 500Hz to about 55dB around 800Hz. This range is consistent with an influence of the second resonance of the vocal tract. However, the effect of vocal tract on the first harmonics is quite unexpected.

Pitch bends from F2 and B3-flat show similar behaviour. Figure 7 shows the spectrogram of SPL ratios of the upstream and downstream pressures for two pitch bends performed by Subject B from F3 (174Hz) to E3. No strong influence is observed for the fundamental frequency but stronger SPL ratios appear at the first harmonic and increase with higher frequencies. In summary, subjects appear to make use of vocal-tract adjustments to support one or more harmonics of the sound during bending, however, no effect is clearly observed on the fundamental frequency.



**Figure 7.** Spectrogram of the ratio of the SPL in dB of the upstream and downstream pressure for Subject B pitch bending down by a semitone from F3.

## DISCUSSION

We have investigated possible vocal-tract support of lip oscillations in trombone performance. We observed SPL ratios of upstream to downstream pressures close to or greater than 0dB at the fundamental frequencies of high register notes (above 350Hz), where downstream support is weak. The four subjects who managed to reach the highest recorded note (F5) demonstrated SPL ratios above 3dB for this note. Moreover, these results are consistent with a frequency range that corresponds to the second vocal-tract resonance and that was shown to be influential in supporting reed oscillation in saxophone performance [3].

Nevertheless, variability in SPL ratios at fundamental frequencies was observed across subjects, especially just before reaching the higher register (F4, B4-flat). This result may be explained by differences in subjects' lip morphology and/or by different embouchure strategies. We suggest two hypotheses: (1) some individuals might vary the position of the tongue in different ways with increasing pitch, which would result in differences in vocal-tract resonance settings; and (2) some subjects may rely predominantly on embouchure adjustments instead of vocal-tract "tuning" when playing higher notes. The downstream air column resonances provide sufficient support for notes in the middle register, though some subjects appear to make use of vocal-tract adjustments to help stabilize some of them. Additional measurements of embouchure settings (perhaps the force applied by the lips on the mouthpiece to indicate relative lip tension) should be performed in the future to study possible correlations with vocal-tract influence. If the above mentioned hypotheses are

correct, we would expect to see lower lip forces for those subjects demonstrating higher SPL ratios and vice versa.

Results obtained for pitch bending from B2-flat show a possible upstream effect in two frequency ranges: one from 250–500Hz that supports the first harmonic of the sound and a second from 700–1200Hz. Although the influence of the vocal tract in the highest frequencies is consistent with upstream influence observed in overtone playing, the contribution that appears in the lower range (350–500Hz) is unexpected. This frequency interval might correspond to the first vocal-tract resonance, which was not reported to be influential in saxophone and clarinet playing [2, 3]. Furthermore, this phenomenon was observed across subjects with some instances of high SPL ratios within a very narrow frequency band around only the first harmonic ( $2*f_0$ ) of the bent note. Whether or not this effect results from a vocal-tract resonance is therefore unclear. In a future study, it would be interesting to ask subjects to perform bends of more than a semitone in order to better estimate vocal-tract influence for this effect.

A vocal-tract manipulation discussed by brass performers involves adjustments of the vertical position of the tongue when playing in the extended register. In fact, all our subjects agreed that they raise the tongue with increasing playing frequency, which qualitatively suggests a corresponding increase in a vocal-tract resonance frequency. Nonetheless, one subject suggested two strategies when varying the vertical position of the tongue. The first strategy involves raising the tongue as when pronouncing the syllable 's' (raising the front part of the tongue), and the second involves moving the back of the tongue up. In the second situation, the volume of the mouth cavity located just behind the teeth is larger than in the first condition. A comparison of upstream spectra in both conditions shows different envelopes: the first case provides a boosting of the energy in the upstream spectrum around 2000Hz for the B3-flat and between 1400–2100Hz when playing F5. These preliminary findings suggest that the tongue position has a strong influence on the upstream pressure spectrum. Future work will include recordings and analyses of the radiated sound in an effort to characterize performers' timbral choices and their correlation with vocal-tract adjustments.

Finally, it is important to address possible discrepancies in the results caused by procedural limitations. Indeed, these measurements involved the use of a microphone located in the player's mouth. The subjects reported a non-negligible difficulty performing normally with this setup, especially in the extended register. Therefore, subjects were asked to take time getting used to it and to freely find a suitable place for the microphone in order to minimise interference with normal playing conditions. Furthermore, a repeated control of the microphone location was verified after each trial in order to make sure the recording was performed above the tongue, as close as possible to the inside of the teeth. However, variations in the position and orientation of the microphone might have occurred from one subject to another and induced small discrepancies in the results across subjects.

## CONCLUSION

In conclusion, we have addressed a crucial question concerning the acoustical contribution of the upstream windway in the mechanism of trombone sound production. These results strongly suggest vocal-tract influence in the higher register and perhaps in pitch bending as well. These findings provide new perspectives in characterizing of the influence of tongue and laryngeal manipulations in brass instrument performance.

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