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Acoustical interaction between vibrating lips, downstream air column, and upstream airways in trombone performance

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This paper presents experimental results on the acoustical influence of the vocal tract in trombone performance. The experimental approach makes use of measurements at the interface between the player and instrument, allowing a relative comparison between upstream airways and the downstream air column impedances, as well as an estimation of the phase of the impedance of the upstream and downstream systems. Measurements were conducted over the full traditional range of playing, during sustained tones with varying dynamic, as well as in special effects such as pitch bending. Subjects able to play over the full range demonstrated significant upstream influence in the higher register of the instrument. These players were categorized in two groups according to their ability to control the phase of the upstream impedance and their ability to generate powerful downstream acoustic energy. Sustained tones played with varying dynamics showed a general tendency of a decrease in vocal-tract support with increase in loudness. Although pitch bends did not involve significant upstream influence at f_0, results suggest modification of the lip behavior during bending. Vocal-tract tuning at tone transitions was also investigated and found to potentially contribute to slur articulations. [http://dx.doi.org/10.1121/1.4823847]

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I. INTRODUCTION

In brass instruments, sound is produced by auto-oscillations of the lips resulting from an overpressure created by the player in the mouth cavity. These oscillations are sustained by a complex aero-acoustical coupling between the airflow generated at the lips, the lips themselves, the resonances of the downstream air-column and potentially, the resonances of the player's upstream airways.[1] Although the influence of vocal-tract resonances on woodwind instruments has been the object of significant interest over the last decades,[2–8] vocal-tract influence in brass instruments remains understudied and less well understood.

The objective of this study is to provide experimental results on the influence of the vocal-tract in trombone performance within the context of the linear theory of oscillation, and with the aim of characterizing how skilled players strategically tune their vocal tract during specific playing tasks.

Brass players usually agree on the importance of tongue placement in the control of intonation, timbre, and mastering of the upper register. According to some players, tongue placement is a crucial attribute in the control of the high register; a low tongue position is associated with the low register and a high tongue position with the high register.[9] Some famous brass players and pedagogues also refer to singing exercises as fundamental training practices.[10] These different testimonies lend support to the idea that vocal-tract adjustments may play an important role in the control of sound production in brass instruments.

Laryngoscopic measurements conducted on brass players showed some laryngeal and pharyngeal adjustments during performance, suggesting a strategic physiological control of the vocal-tract.[11–13] Although these observations were mostly discussed from a physiological perspective, they may also suggest underlying acoustical tuning of the upstream airways. Electroglottographic recordings conducted on French horn players showed electroglottographic activity during and prior to tone production, suggesting partial abduction of vocal-folds or ventricular bands during playing.[14]

A significant number of studies have focused on the influence of vocal-tract resonances in woodwind instruments. Overall, investigations agree on the ability of proficient players to precisely tune vocal-tract resonances in the range of 500–1500 Hz. These adjustments occur when the downstream impedance becomes weak enough so that a vocal-tract resonance may support or even override the effect of the downstream air column. This was particularly observed in saxophones and clarinets during altissimo playing and for special effects such as pitch bending.[4–8,15,16]

Regarding lip-reed instruments, experiments on the didjeridu[17] showed anti-resonances in the radiated sound induced by vocal-tract resonances. Wolfe *et al*. investigated the influence of upstream resonances in the didgeridoo and trombone performance using an artificial lip reed player.[18] This system enabled the characteristics of an upstream resonance to be varied (low or high tongue position) while maintaining a fixed reed setting. On both instruments, vocal-tract configuration had an effect on intonation as well as on transitions between two registers; an upstream constriction near

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the valve was able to slightly increase the playing frequency as well as facilitate transition to a higher bore resonance. These results were corroborated by more recent characterizations of the effect of vocal-tract resonances in trumpets,[19] although this study was only conducted on one subject. In this work, different upstream conditions were characterized from MRI imaging of a trumpet player's vocal-tract and tested through numerical simulations.[20] Vocal-tract configuration especially appeared to influence the minimum blowing pressure, as well as the natural lip frequency at which transitions between registers are observed. Although these studies appear to confirm a non-negligible influence of the vocal-tract in brass playing, they partly involved analog or numerical simulations of a brass player system and are limited to simple musical tasks, especially in terms of register. Chen *et al.* performed direct measurements of vocal-tract resonances on trumpet players.[21] Although this method allows for direct measurement of vocal-tract input impedance at the lips during performance, results did not show consistent tuning strategies from the players. One objective of the proposed study is, therefore, to develop or adapt a measurement technique for *in vivo* evaluation of vocal-tract influence in trombones allowing for investigation of a variety of playing tasks.

An important characteristic of brass playing relies on the degree of control from the player on the natural frequency of the lips. Lip-valves have been shown to be generally well represented by outward striking reed models.[22–27] Lip valves are able to oscillate only within a narrow frequency range around their natural frequency. This particularly highlights the fact that brass players must be able to adjust the mechanical properties of the lips and hence tune their natural lip frequency in order to excite the air column at a given frequency. This further suggests that vocal-tract tuning in brass performance may be particularly dependent on the nature of the lip-reed mechanism at the given playing frequency.[23] Therefore, it could be of great interest to consider both amplitude and phase of downstream and upstream system impedances at the frequency of interest. A second objective of this study is thus to adapt the principle of electroglottography[29] to the monitoring of lip transverse electrical impedance on trombone players in order to enable estimation of the phase of the downstream and upstream impedance at the playing frequency and provide further information on the modalities of the interaction between the downstream air-column, the lips, and the player's upstream airways.

II. THEORETICAL APPROACH

A. Upstream to downstream impedance ratio

Assuming continuity of the volume flow at the reed junction,[30] the following relations between upstream and downstream frequency domain quantities can be derived

$$\frac{Z_u}{Z_d} = -\frac{P_u}{P_d}, \tag{1}$$

where u and d subscripts denote upstream and downstream variables. P_d, therefore, corresponds to the downstream acoustic pressure created in the mouthpiece, and P_u corresponds to the upstream acoustic pressure created at the input of the vocal-tract (i.e., in the mouth cavity just upstream from the lips). Z_d and Z_u are the input impedance of the downstream air-column and the player's upstream airway, respectively.

B. Phase of upstream and downstream impedances

According to Elliot and Bowsher,[1] the downstream lip mobility G_d can be defined as

$$G_d = \frac{S_{\text{lip}}}{P_d}, \tag{2}$$

where S_{lip} is the alternating lip opening area. G_d is the response of the lip motion to the downstream pressure created in the mouthpiece of the instrument. This expression ignores P_u, the pressure at the input of the vocal-tract, and thus any influence of the upstream airway. Analogously, the upstream lip mobility G_u and the adjusted downstream lip mobility G can be defined as

$$G_u = \frac{S_{\text{lip}}}{P_u}, \tag{3}$$

$$G = \frac{S_{\text{lip}}}{P_d - P_u}. \tag{4}$$

G_u is the response of the lip motion to the upstream pressure P_u, ignoring the influence of the acoustic pressure created in the mouthpiece P_d, and G is the response of S_{lip} to the pressure difference across the lips $P_d - P_u$ and therefore takes into account both downstream and upstream interactions.

Assuming a quasi-static model of flow through the reed channel, the Bernoulli equation that relates the downstream acoustic flow $u_d(t)$ and $s_{\text{lip}}(t)$ in the time domain is given by the following expression:

$$u_d(t) = \pm\sqrt{\frac{2|p_0 + p_u(t) - p_d(t)|}{\rho}} \cdot s_{\text{lip}}(t), \tag{5}$$

where ρ is the average air density, p_0 represents the quasi-static blowing pressure, and $p_u(t)$ and $p_d(t)$, the time-dependent upstream and downstream acoustic pressures.

Under the assumption that the quasi-static mouth pressure p_0 is usually much greater than $p_u(t)$ and $p_d(t)$, Eq. (5) can be linearized to

$$u_d(t) \simeq \sqrt{\frac{2p_0}{\rho}} \cdot s_{\text{lip}}(t). \tag{6}$$

Equation (6) depicts a linear relationship between $u_d(t)$ and $s_{\text{lip}}(t)$, which implies that the two quantities oscillate in phase. The downstream phase condition of regeneration[1,22] (PCoR) can thus be derived at the fundamental frequency f_0 from Eqs. (2) and (6)

$$\angle G_d(f_0) + \angle Z_d(f_0) = 0. \tag{7}$$

Analogously, two other phase conditions of regeneration can be defined from Eqs. (3), (4), and (6)

$$\angle G_u(f_0) + \angle Z_u(f_0) = \pi, \tag{8}$$

$$\angle G(f_0) + \angle Z(f_0) = 0. \tag{9}$$

We refer to Eq. (8) as the upstream PCoR, and to Eq. (9) as the adjusted downstream PCoR, where $Z = Z_d + Z_u$ is the total impedance perceived by the lips.

In sum, Eqs. (7), (8), and (9) give the conditions under which auto-oscillations exist when coupled to both downstream and upstream systems: Eq. (7) alone amounts to neglecting acoustical interaction with the upstream airway, Eq. (8) alone amounts to neglecting the acoustical coupling with the downstream air column, and finally Eq. (9) amounts to considering both upstream and downstream interactions. Under the hypothesis that regeneration occurs on both sides of the lips, Eqs. (7), (8), and (9) show that $\angle G_d$, $\angle G_u - \pi$, and $\angle G$ can therefore be considered as estimates, respectively, of $\angle Z_d$, $\angle Z_u$, and $\angle Z$ at the fundamental frequency of the sound f_0.

In the low register, our results should be interpreted with care since the complex contact between the lips, as well as lip outward motion may induce a non-negligible non-linearity in the flow equation. However, this should not be the case when the pitch increases and the upward motion of the lips reduces the flow component arising from the lip longitudinal displacement.[20,25,31] Regarding the effect of collision, as supported by experimental and numerical investigations on vocal-fold vibration,[32,33] we may reasonably consider that given basic similarities in the behavior of both valve systems, the lip collision during closure does not significantly affect the linear relationship between the volume flow and opening area. During closure, we hypothesize that no volume flow occurs and only residual turbulence is present.[32] This assumption is supported by the observation of short closed phases in vibrating lips,[34,35] as well as potential simpler contact during the closed phase as shown by lip electrical impedance measurements.[35] Furthermore, as supported by Backus and Hunley,[36] as well as Elliot and Bowsher,[1] the small lip opening area in the high register increases the flow resistance of the lip orifice, the latter becoming potentially larger than the downstream impedance in the very high register. Consequently, the volume flow at the lips turns out to be proportional to the lip opening for high playing frequencies.

III. EXPERIMENTAL APPROACH

A. P_d and P_u recordings

A miniature Endevco pressure transducer (8510-B) was inserted through a hole in the cup of the mouthpiece in order to record the downstream acoustic pressure P_d (i.e., at the input of the downstream air-column). A second Endevco transducer (8507-C) was used to measure the acoustic pressure at the input of the vocal-tract P_u: The transducer was inserted in a small catheter and the subject asked to maintain the extremity of the catheter in the mouth, above the tongue, as close as possible to the internal wall of the teeth. We can then roughly estimate the distance between the catheter extremity and the lips at around 5 mm, which would cause a group delay of 14 μs, corresponding to a phase shift of about 3.6 deg at 700 Hz (close to the maximum sounding frequency). The small diameter of the transducer and catheter (about 2.5 mm) reduced the obstructiveness caused by the transducer. A relative calibration of the downstream and upstream microphones mounted in the catheter was performed over the frequency range of interest. As both transducers measure acoustic and quasi-static pressure, the low frequency component of the quasi-static mouth pressure p_0 was extracted by low-pass filtering the upstream transducer signal.

B. Electrical impedance measurement of the lips

As described in the previous section, our method involves the evaluation of the phase of the lip opening relative to the phase of the acoustic pressure measured on both sides of the lips. Similar measurements of lip motion were performed on French horn players using a strain gauge attached to the player's upper lip,[26] though this solution was quite invasive for the participant. Moreover, this technique requires a careful calibration in order to correlate the strain gauge signal with the opening and closing phases of the lip motion. Consequently, we propose an alternative approach by measuring the variations of electrical impedance across the lips during playing. This technique is based on the principle of electroglottography developed by Fabre[29] in 1957 and extensively applied to the monitoring of vocal-fold vibrations; a high frequency alternate current $i(t)$ is generated between two electrodes located across the larynx and variations of vocal-fold contact area during phonation cause amplitude variations of the alternating tension $u(t)$ recorded at the electrodes. After demodulation of $u(t)$, and according to Ohm's law ($u = R \cdot i$), the resulting signal is hence proportional to the varying amplitude of the electrical impedance $R(t)$ across the electrodes. A somewhat related approach was previously applied on the lips of a didgeridoo player by Wolfe and Smith[37] in order to simultaneously record vocal-fold and lip apertures in didgeridoo performance.

In our setup, two electrodes made of silver-plated copper shielding tape were glued on a Kelly plastic mouthpiece of dimensions equivalent to a Vincent Bach 6 1/2 AL (Fig. 1). The two electrodes were connected to a commercial electroglottogaph signal conditioner (Voce Vista) and the resistance of the electrode pair rose in order to fit with the signal conditioner requirements. The resulting tension recorded at the output of the conditioner is therefore proportional to the electrical impedance across the lips R_{lip}. As in the case of phonation, the oscillations of R_{lip} are due to periodic variations of the contact area between the lips. Thus, we can reasonably assume that R_{lip} and S_{lip} oscillate in phase at f_0; when the lips open, the contact area between the lips decreases and R_{lip} increases; on the contrary when the lips close, R_{lip} decreases since the contact between the lips becomes larger. Given the purpose of our sensing device, we propose to call it an "electrolabiograph." As far as we know, this term was first proposed by Krakow in 1994 for the study of articulatory lip motions in syllables.[38] In order to measure the latency of the

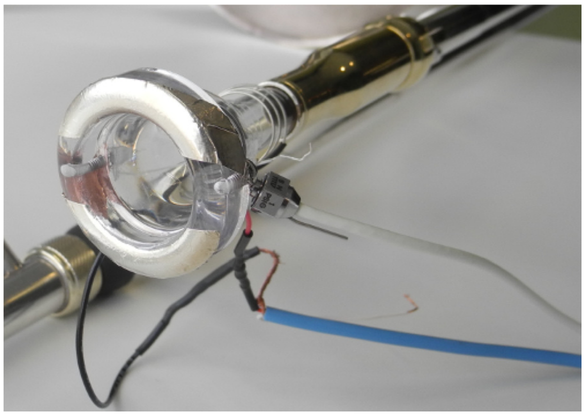

FIG. 1. (Color online) Kelly plastic mouthpiece 6 1/2 AL with two silver-plated electrodes mounted on the rim. The downstream microphone is mounted to record the acoustic pressure in the mouthpiece cup.

system (delay between actual variations of lip impedance and the output tension from the conditioner), a controllable variable resistance was mounted at the electrodes using a photo field effect transistor optocoupler. This calibration procedure enabled estimation of a group delay of 180 μs. Considering a sampling rate of 44.1 kHz, this latency results in a shift of eight samples which is not negligible in the context of phase analysis and is therefore taken into account in the analysis. The electrolabiograph signal, as well as P_d and P_u were recorded using a National Instruments I/O interface (sampling rate 44.1 kHz). After correction of the latency of the elctrolabiograph signal conditioner, $\angle G_d(f_0)$, $\angle G_u(f_0) - \pi$, and $\angle G(f_0)$ are computed by extracting the phase at the f_0 spectral peak from consecutive fast Fourier transforms of 1024 samples with an overlap of 256 or 512 samples depending on the playing task. Zero-padding was performed prior to Fourier transforming in order to increase the frequency resolution of computed spectra and refine the phase estimation at f_0.

C. Interpretation of the data

For convenience, we adopt the following notation: $\angle G_d = \angle G_d(f_0)$, $\angle G_{u-\pi} = \angle G_u(f_0) - \pi$ and $\angle G = \angle G(f_0)$. It is worth noting that from the definitions of G_d and G_u, the following relations can be deduced:

$$\angle G_d - \angle G_{u-\pi} = \angle P_u - \angle P_d + \pi = \angle Z_u - \angle Z_d \tag{10}$$

and, as described in the Appendix:

$$\frac{|\angle G_d - \angle G|}{|\angle G_{u-\pi} - \angle G|} = \frac{|\angle(P_d - P_u) - \angle P_d|}{|\angle(P_d - P_u) - \angle P_u - \pi|} \simeq \left|\frac{Z_u}{Z_d}\right| \tag{11}$$

when $\angle G_d(f_0) - \angle G_{u-\pi}(f_0)$ is relatively close to zero (see the Appendix for further clarification on this limitation).

Graphically, Eq. (10) indicates that the distance between $\angle G_d$ and $\angle G_{u-\pi}$ gives a representation of the distance between $\angle Z_d$ and $\angle Z_u$ at f_0. Second, Eq. (11) reveals that the relative position between $\angle G$, $\angle G_d$, and $\angle G_{u-\pi}$ is related to the relative acoustical coupling between the lips, the downstream air-column, and the vocal-tract; if the distance between $\angle G$ and $\angle G_d$ is smaller than the distance between $\angle G$ and $\angle G_{u-\pi}$, this indicates a predominant coupling with the downstream system at f_0, and vice versa. When $\angle G$ is equally spaced from $\angle G_d$ and $\angle G_{u-\pi}$, then both systems provide equal support to lip auto-oscillations.

Overall, our analysis scheme allows to combine time-domain visualizations of three attributes of the regenerative processes at the fundamental frequency of the sound: (1) the dominant regenerative system via the relative amplitude of P_d and P_u [see Eq. (1)], as well as relative proximities of $\angle G_d$, $\angle G_{u-\pi}$, and $\angle G$, as defined by Eq. (11); (2) the degree of "phase tuning" of upstream and downstream systems at the playing frequency via the phase difference between Z_d and Z_u, as defined by Eq. (10); and (3) an estimate of $\angle Z_d$, $\angle Z_u$, and $\angle Z$ via the values of $\angle G_d$, $\angle G_{u-\pi}$, and $\angle G$ [see Eqs. (7), (8), and (9)].

D. Player tests

Nine subjects took part in the experiments. Two of them are professional players performing in high level Canadian ensembles and teaching trombone at the Schulich School of Music at McGill University, five are young professional players who perform in classical and jazz ensembles in Montreal, one is an undergraduate student in jazz performance and one is an experienced trombone player and also first author of this article. All measurements were performed on the same tenor trombone (King 2B Silver Sonic) and same mouthpiece (Kelly 6 1/2 AL) on which the downstream microphone and electrolabiograph electrodes were mounted. The tuning slide was kept closed and subjects asked to avoid compensating for possible detuning of the instrument (which resulted in playing frequencies slightly above a 440 Hz reference). Participants were given some time to get accustomed to the trombone and mouthpiece setup prior to measurements. The amplitude and phase of the acoustical input impedance of the trombone and mouthpiece with the slide in the closed position are given in Fig. 2. The input impedance was measured using a two-microphone impedance measurement system.[39]

A real-time display of the electrolabiograph (ELG) waveform was provided to the subjects so they could identify when the lip impedance measurement was working or not; for some players, the electrodes needed to be humidified quite often to enable optimum electrical conduction. Subjects were presented each task prior to execution. Each task was recorded several times until the subjects were satisfied with their performance. At the end of the session, participants were asked to fill out a questionnaire about their trombone performance background and experience. After experiments, all recordings were reviewed by the experimenter. For each subject, the best execution of each task was selected for analysis, based on the sound and ELG signal quality.

IV. RESULTS

A. Arpeggios

The first task involved playing ascending and descending arpeggios in closed position from F3 (175 Hz) to F5

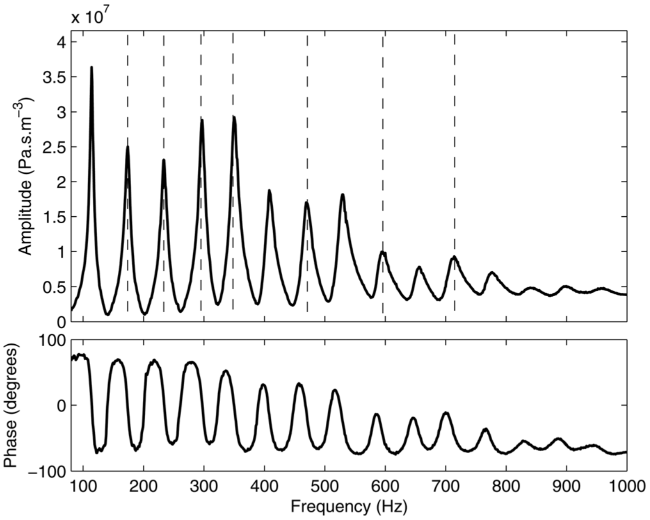

FIG. 2. Amplitude and phase of the input impedance of the King 2B Silver Sonic tenor trombone and Kelly 6 1/2 AL mouthpiece with the slide in the closed position (the first resonance located below 80 Hz is not measured). Vertical dashed lines indicate the resonances corresponding to the arpeggio series F3-B♭3-D4-F4-B♭4-D5-F5.

(710 Hz),[40] corresponding to the following tone sequence F3-B♭3-D4-F4-B♭4-D5-F5. The subjects were asked to slur the tone series (no tonguing articulation between tones). As a first example of collected data, results obtained from Subject A are presented in Fig. 3. Starting from the top of the figure, the first plot represents p_d and p_u waveforms normalized by the p_d maximum, the second represents the temporal evolution of $\angle G_d$, $\angle G_{u-\pi}$, and $\angle G$ at f_0, the third plot represents the evolution of the sound pressure level (SPL) ratio $|P_u/P_d|$ in dB at f_0, and the bottom plot the evolution of fundamental frequency f_0 as a function of time.

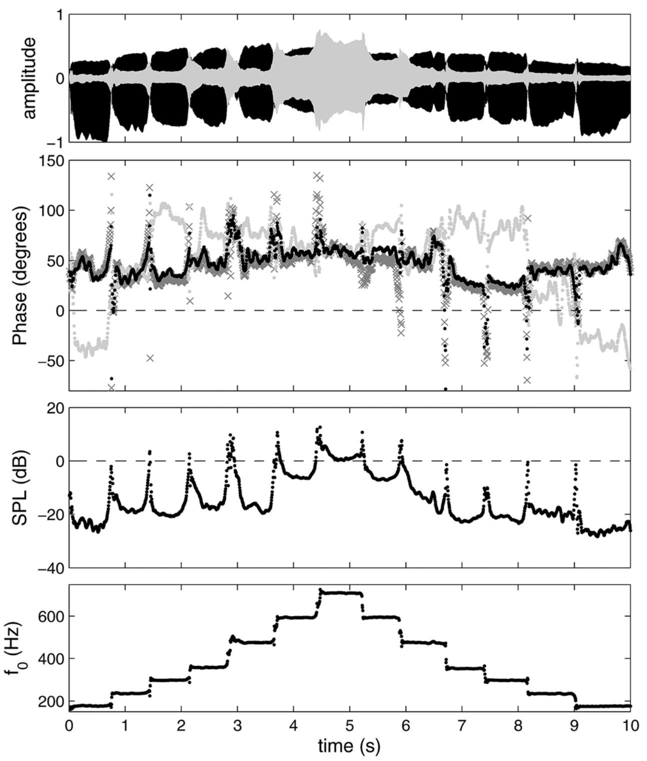

FIG. 3. Subject A playing ascending and descending arpeggio series: F3-B♭3-D4-F4-B♭4 -D5-F5. From top to bottom: waveforms of p_d (black), p_u (gray); $\angle G_d$ (dark gray), $\angle G_{u-\pi}$ (light gray), and $\angle G$ (black) at f_0; SPL ratio in dB of the upstream to downstream pressure; fundamental frequency.

During the sustained portions of the ascending tone series, the ratio $|P_u/P_d|$ remains low (around -20 dB) until B♭4 (475 Hz). It then reaches a maximum value around 0 dB at the highest tone F5 (710 Hz). Furthermore, tone transitions and onsets are marked by abrupt variations of $|P_u/P_d|$ with peak values around 10 dB at the onset of the three highest tones, this effect being less noticeable in the descending arpeggio portion. These first observations show that for the two highest tones, the input impedance of the upstream airways at f_0 becomes close to the magnitude of the downstream input impedance, suggesting a strategic vocal-tract tuning by the player in the high register. The peaks in the $|P_u/P_d|$ trace at tone transitions also suggest a possible upstream tuning at slurred transitions between tone registers. Although the characteristics of the volume flow at regime shifts between two tones may significantly deviate from a quasi-static Bernoulli flow model, the duration of these $|P_u/P_d|$ peaks (above 100 ms) suggest that an increase in $|P_u/P_d|$ occurs before and after the frequency shift during a time when steady-state oscillations are established. This potentially indicates occurrences of vocal-tract support at tone transitions. This is further discussed in Sec. IV D of this article.

Although $\angle G_d$ and $\angle G$ remain quite stable during the task, significant variations of $\angle G_{u-\pi}$ are observed, from $-50°$ at F3 (175 Hz) to $100°$ at D4 (295 Hz) and F4 (360 Hz). No strong hysteresis behavior is observed between the ascending and descending portions. The negative value of $\angle G_{u-\pi}$ at F3 (175 Hz) suggests a positive value of $\angle Z_u$ and therefore an inductive upstream impedance at f_0. However, all the other tones show a positive value of $\angle G_{u-\pi}$ and thus a capacitive upstream coupling. On the contrary, $\angle G_d$ remains positive for all tones indicating a capacitive downstream impedance at f_0. $\angle G$ seems to overlap with $\angle G_d$ for all notes and with $\angle G_{u-\pi}$ as well for the two highest tones, which is corroborated by the high SPL value of $|P_u/P_d|$ observed for these two tones. Therefore, the low register is characterized by a dominant downstream coupling, as well as relatively high distance between $\angle Z_d$ and $\angle Z_u$. An increase in pitch seems to correlate with an increase in $|P_u/P_d|$ as well as a decrease in the distance between $\angle Z_d$ and $\angle Z_u$, suggesting a constructive phase tuning of the downstream and upstream systems at f_0 in the higher register.

Figure 4 presents results obtained for different participants during the ascending part of the arpeggio series. The left column displays the data from Subject A and Subject C. Subject C shows increasing values of $|P_u/P_d|$ with increase in pitch and a maximum value at E♭5 (not played by Subject A). The values of $|P_u/P_d|$ at D5 (595 Hz) and F5 (710 Hz) are about the same in both subjects. Analogously to Subject A, the same transitory peak variations of the ratio are observed in Subject C. In both subjects, the abrupt sign change of $\angle G_{u-\pi}$ between the two first tones is observed. Although $\angle G_{u-\pi}$ stays greater than $\angle G_d$ in Subject A, it becomes smaller than $\angle G_d$ while remaining positive in Subject C from the 5th tone. As in Subject A, $\angle G$ follows the variations of $\angle G_d$ in Subject C, except for the last and highest tone where $\angle G$ lies in between $\angle G_d$ and $\angle G_{u-\pi}$. We observe that $\angle G_d$ shows more variability in Subject C while $\angle G_d$ and $\angle G_{u-\pi}$ are smoothly converging toward the same value with increase in pitch in Subject A.

The right column of Fig. 4 displays the data from Subject B and Subject D. In both subjects $|P_u/P_d|$ values are higher than Subjects A and C in the high register with less pronounced peaks at tone transitions. Subject B shows a change in the sign of $\angle G_{u-\pi}$ at the third tone while $\angle G_{u-\pi}$ stays negative along the entire ascending series for Subject D. In both subjects, $\angle G$ tends to decrease with increase in pitch, as opposed to the tendency observed in Subjects A and C. This trend is even more pronounced in Subject D. In Subject A, $\angle G$ and $\angle G_d$ overlap until the two last tones while in Subject D, $\angle G$ smoothly moves from $\angle G_d$ to $\angle G_{u-\pi}$ as the pitch increases. No clear constructive phase tuning of Z_d and Z_u is therefore observed in Subject B and D. Although $\angle G_d$ remains positive in both subjects for the entire task, it shows quite unstable behavior at the highest tones.

In order to compare experimental results from all the subjects, all extracted variables are averaged over stable sections of each tone. For each subject, stable portions are extracted based on fundamental frequency standard deviation criteria; for a given playing frequency f_0, a section of the tone is considered stable if the standard deviation of f_0 is below a threshold of 4 Hz within the observation window. Using this approach, values of $|P_u/P_d|$, $|P_d|$, $|P_u|$, p_0, $\angle G_d$, $\angle G_{u-\pi}$, and $\angle G$ are extracted for each tone of the arpeggio series and for each subject.

Figure 5 represents the SPL ratio $|P_u/P_d|$ in dB, as well as dimensionless variables $\gamma_d = |P_d(f_0)|/p_0$ and $\gamma_u = |P_u(f_0)|/p_0$ for all subjects and for each tone of the ascending arpeggio series (1:F3, 2: B♭3, 3:D4, 4:F4, 5: B♭4, 6:D5, 7:F5). While all the subjects were able to play the ascending tone sequence until B♭4, only the first six subjects were able to play up to D5 (595 Hz) and only the first five subjects were able to play up to F5 (710 Hz). If we assume that the amplitude of Z_d at f_0 does not differ significantly between subjects despite some small differences in individual playing frequencies, we can reasonably assume that the dimensionless parameter γ_d provides a representation of the mechanical ability of the lips to respond to the static blowing pressure. We therefore use this variable as a descriptor of what can be referred to as the "lip mechanical efficiency."

The low register is marked by negative values of $|P_u/P_d|$ SPL suggesting a predominant influence of the downstream

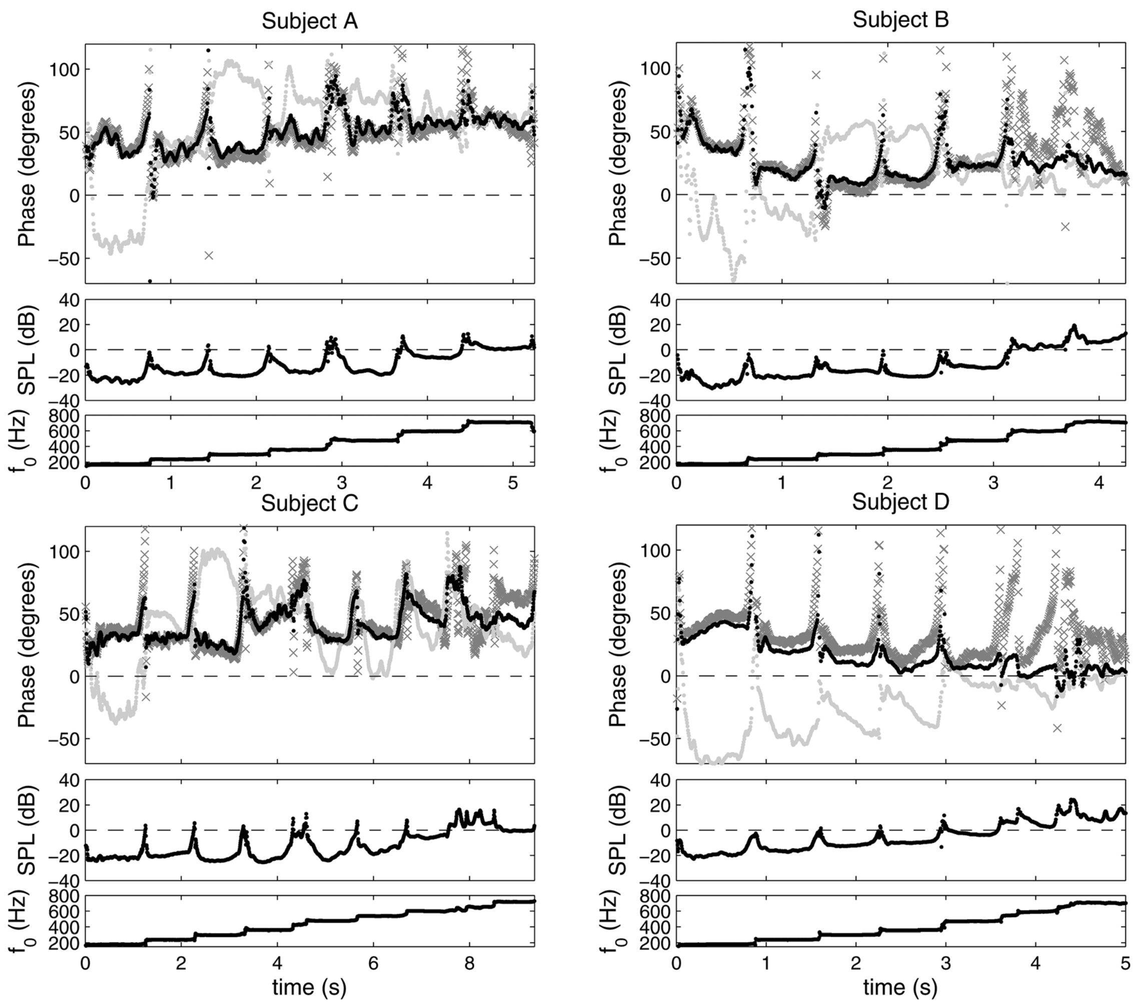

FIG. 4. Subjects A, B, C and D playing ascending arpeggio series F3-B♭3 -D4-F4-B♭4-D5-F5. From top to bottom: $\angle G_d$ (dark gray), $\angle G_{u-\pi}$ (light gray), and $\angle G$ (black) at f_0; SPL ratio in dB of the upstream to downstream pressure; fundamental frequency. Note that Subject C played additional overtones [C5 (535 Hz) and E♭5 (640 Hz)] in the tone series.

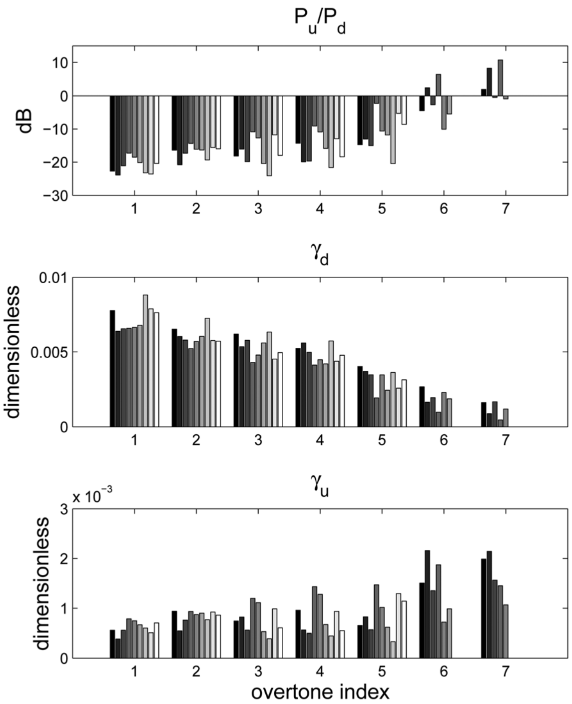

FIG. 5. SPL ratio in dB of upstream to downstream pressure at f_0, downstream and upstream pressure magnitude at f_0 normalized to the quasi-static blowing mouth pressure as a function of arpeggio index for all subjects (index refers to the ascending series F3-B♭3-D4-F4-B♭4-D5-F5).

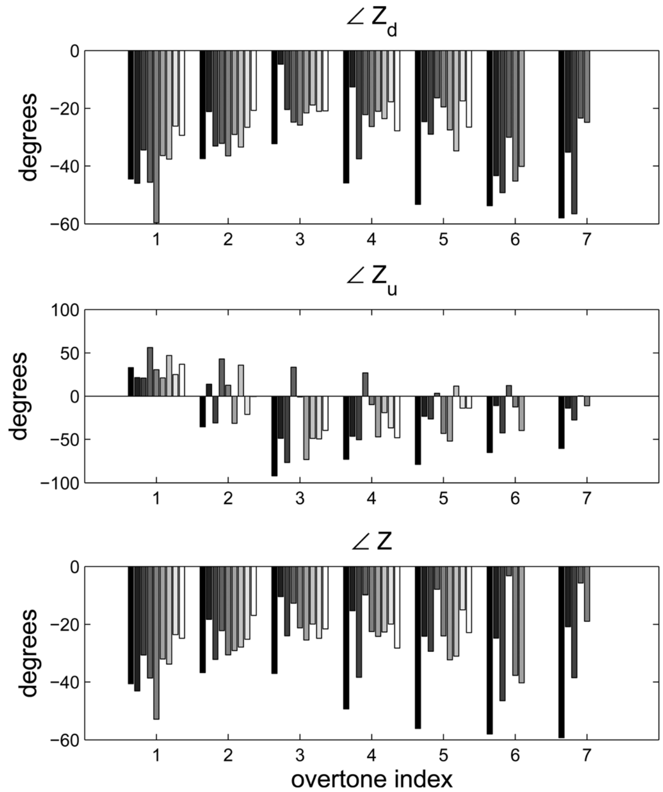

FIG. 6. Estimated $\angle Z_d$, $\angle Z_u$, and $\angle Z$ at f_0 as a function of arpeggio index for all subjects (index refers to the ascending series F3-B♭3-D4-F4-B♭4-D5-F5).

air-column. A clear change is observed at D5 (595 Hz) where Subjects B and D show positive SPL ratios indicating a predominant coupling with the vocal tract at the playing frequency. This tendency is confirmed by negative but small values of the SPL ratio in other subjects at D5 (595 Hz). At F5 (710 Hz), Subjects A, B, and D exhibit positive SPL ratios whereas Subjects C and E show ratios close to zero. This suggests a significant influence of upstream impedance in all subjects. γ_d values decrease with increasing playing frequency, which correlates with a decrease in Z_d amplitude with frequency in brass instruments (as $|Z_d|$ decreases, downstream support becomes weaker and more energy is needed to maintain lip oscillations). However, the opposite behavior is observed in γ_u, supporting the hypothesis of a growing amplitude of Z_u at f_0 with increase in pitch.

Estimation of $\angle Z_d(f_0)$, $\angle Z_u(f_0)$, and $\angle Z(f_0)$ from lip mobility measurements are represented in Fig. 6. $\angle Z_d(f_0)$ remains negative for all subjects suggesting a compliant downstream input impedance at f_0 along the task. $\angle Z_u(f_0)$ is positive for all subjects at F3 (175 Hz) supporting an inductive upstream impedance at f_0 for the lowest tone. At B♭3 (235 Hz), four subjects show a positive $\angle Z_u(f_0)$. Only Subject D maintains a positive or null $\angle Z_u(f_0)$ value for all tones with $\angle Z_u(f_0) \simeq 0°$ at F5 (710 Hz). Above B♭3 (235 Hz), all other subjects show negative values of $\angle Z_u(f_0)$, except Subject G who shows a positive value at B♭4 (475 Hz). These observations suggest a dominant inductive effect of players' vocal-tract in the low register with a rapid transition to a capacitive upstream coupling with increase in pitch.

Regarding the total impedance applied to the lips, $\angle Z(f_0)$ remains negative for all tones. Inter-subject variability grows with increase in pitch; Subject A shows the smallest values around $-60°$ for the three highest tones, while Subject D shows the greatest values between $-8°$ for B♭4 (475 Hz) and $-3°$ at F5 (710 Hz).

As vocal-tract adjustments appear to occur at high playing frequencies, we now focus our attention on the three highest tones of the arpeggio series. Looking particularly at $|P_u/P_d|$, γ_d, and γ_u for D5 (595 Hz) and F5 (710 Hz), we observe that Subjects B and D display the higher values of the SPL ratio and lower values of γ_d, indicating that although these two players were able to create high magnitude upstream impedances at f_0, the mechanical efficiency of the lips estimated from the dimensionless parameter γ_d remained low compared to other subjects. This correlation does not apply to γ_u; while the amplitude of Z_d is about the same for all subjects at the playing frequency, the magnitude of Z_u at f_0 significantly differs for each subject as shown by differences in $|P_u/P_d|$ (high for Subjects B and D, and lower for the others).

Subjects A and C show lower values of $\angle Z_d$ and $\angle Z_u$ than Subjects B and D. This may indicate that Subjects A and C were able to create an upstream resonance centered at a lower frequency than Subjects B and D, allowing oscillations to occur at a lower value of $\angle Z_d$. This tuning strategy results in a lower value of $\angle Z$ which means a value of $\angle G$ close to 90°. Therefore, if we assume that the lips oscillate according to an outward striking regime, one may hypothesize that the tuning strategy for Subjects A and C favors lip oscillations near a mechanical resonance of the lips. We thus distinguish two strategies: (1) strategy of Subjects B and D: high amplitude upstream resonance at f_0 overriding the downstream regenerative influence, and (2) strategy of Subject A and C:

careful tuning of Z_u phase at f_0 which might better support oscillations near a mechanical resonance of the lips.

Nevertheless, Subject E does not fit clearly in either of the two categories, especially for the highest tone F5 (710 Hz). Indeed, although this subject exhibits values of $\angle Z_d$, $\angle Z_u$, and $\angle Z_u$ similar to Subjects B and D at F5 (710 Hz), Subject E shows a slightly negative $|P_u/P_d|$ ratio and relatively high γ_d at this playing frequency, as in Subjects A and B.

In order to evaluate whether the observed increase in $|P_u/P_d|$ with f_0 results from an actual tuning of the vocal-tract or the overall reduction in the magnitude of Z_d resonances with increase in frequency, the value of Z_u is estimated from Eq. (1) at the fundamental frequency and first few harmonics for each tone of the ascending arpeggio series. It is then possible to characterize the evolution of $|Z_u|$ at particular frequencies appearing in the harmonic structure of specific tones. For instance, the frequency of the first harmonic of B♭3 located around 475 HZ corresponds to the fundamental frequency of B♭4 (475 Hz). Consequently, the magnitude of Z_u around 475 Hz can be calculated at these two steps of the arpeggio sequence and potential changes in $|Z_u|$ identified. The evolution of Z_u magnitude at 475, 595, and 710 Hz as a function of f_0 is presented in Fig. 7 during ascending arpeggios for the subjects able to play up to D5 (595 Hz) (Subjects A–F).

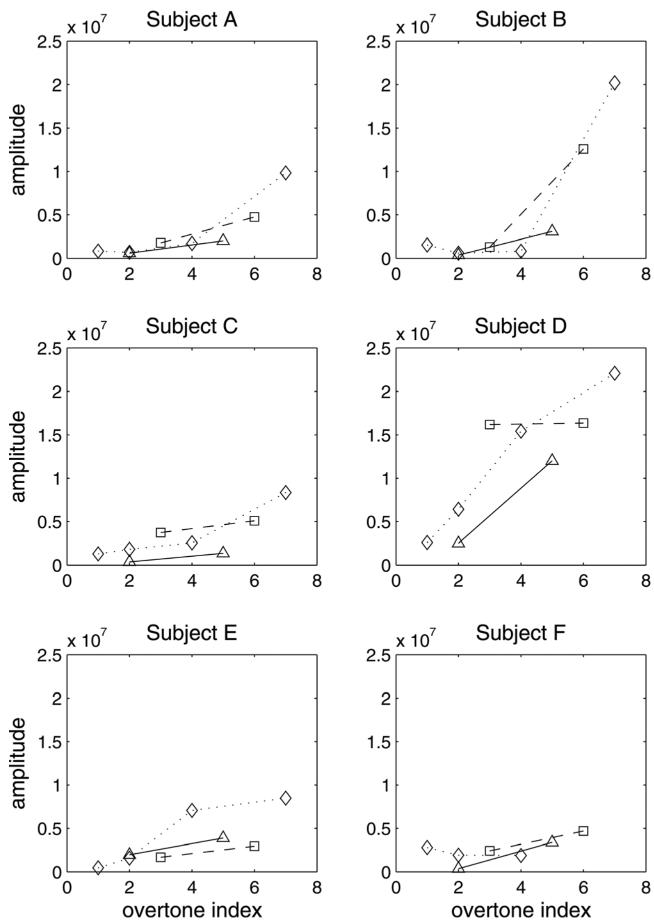

FIG. 7. Evolution of the magnitude of the upstream input impedance at frequencies of a B♭3 (475 Hz) (triangle solid line), D5 (595 Hz) (square dashed line) and F5 (710 Hz) (diamond dotted line) as a function of overtone index during ascending arpeggios for Subjects A to F.

In all subjects able to play over the full range (subjects A–E), the amplitude of Z_u around 710 Hz increases with increase in pitch, supporting the hypothesis of a tuning of the vocal tract in the higher register. Subject B shows significant variations in $|Z_u|$ around 595 Hz between overtone 3 (D4) and 6 (D5), while Subject C presents a constant but high amplitude of Z_u at 595 Hz and an increase in Z_u amplitude at 475 Hz between overtones 2 (B♭3 at 235 Hz) and 5 (B♭4 at 475 Hz). Moreover, in agreement with the categorization proposed, Subjects A and C show similar tuning patterns for the three frequencies observed, while subjects B and D show the highest values of $|Z_u|$ at both 475 and 595 Hz. Subject E presents a tuning trend closer to subjects A and C, although this subject is the only one showing a lower magnitude of Z_u at 595 Hz. Finally, Subject F does not present any significant tuning pattern and could not play the highest tone.

B. Influence of dynamics

In order to evaluate the influence of loudness on the characteristics of an upstream coupling, subjects were asked to play a sustained B♭4 (475 Hz) from *mezzo-piano (mp)*, *crescendo* to the maximum loudness they could comfortably reach and *decrescendo* to *mezzo-piano*. The choice of B♭4 was made since it is high enough to induce significant vocal-tract support and low enough to allow a clear crescendo and decrescendo to be produced comfortably. We propose a representation where $\angle G_d$ and $\angle G_{u-\pi}$ values are mapped onto a color scale extending from –30° to 140° and hence centered around 85°. According to this color scale, dark tonalities will be associated to a capacitive impedance whereas light tonalities will rather suggest an inductive input impedance. The boundary between the color arrays of $\angle G_d$ and $\angle G_{u-\pi}$ correspond to the SPL value of $|P_u/P_d|$ in dB. Results from Subjects A, B, C, D, E, and G are presented in Fig. 8. Results from other subjects showing a smaller *crescendo-decrescendo* effect are not shown. The top color area corresponds to $\angle G_d$ while the bottom area corresponds to $\angle G_{u-\pi}$. The black dashed lines represents the amplitude of $P_d(f_0)$ (considered as an index of loudness).

All subjects show a negative SPL ratio along the tone duration, indicating a predominant coupling with the downstream air-column. In all subjects, $|P_u/P_d|$ varies significantly with variations in P_d amplitude. All subjects, except B, show a maximum in P_d fitting with a minimum in SPL ratio. In Subject B, both extrema do not exactly match although the SPL ratio shows a low-value plateau around the peak of downstream energy. The lowest minimum value of the SPL ratio is found in Subject C around -40 dB whereas Subject D shows a minimum at -14 dB. The greatest variations of SPL ratio are observed in Subjects B, C, and G, for which higher dynamics are associated with a plateau of low SPL ratio. This phenomenon is not as visible in Subjects A, D, and E.

From color area observations, we notice that $\angle G_d$ remains relatively constant along tone duration for all subjects compared to variations in $\angle G_{u-\pi}$. The values of $\angle G_d$ are quite similar in all subjects (between 20 and 60°) suggesting a capacitive downstream input impedance at f_0. $\angle G_{u-\pi}$ remains positive and constant in Subjects A and E

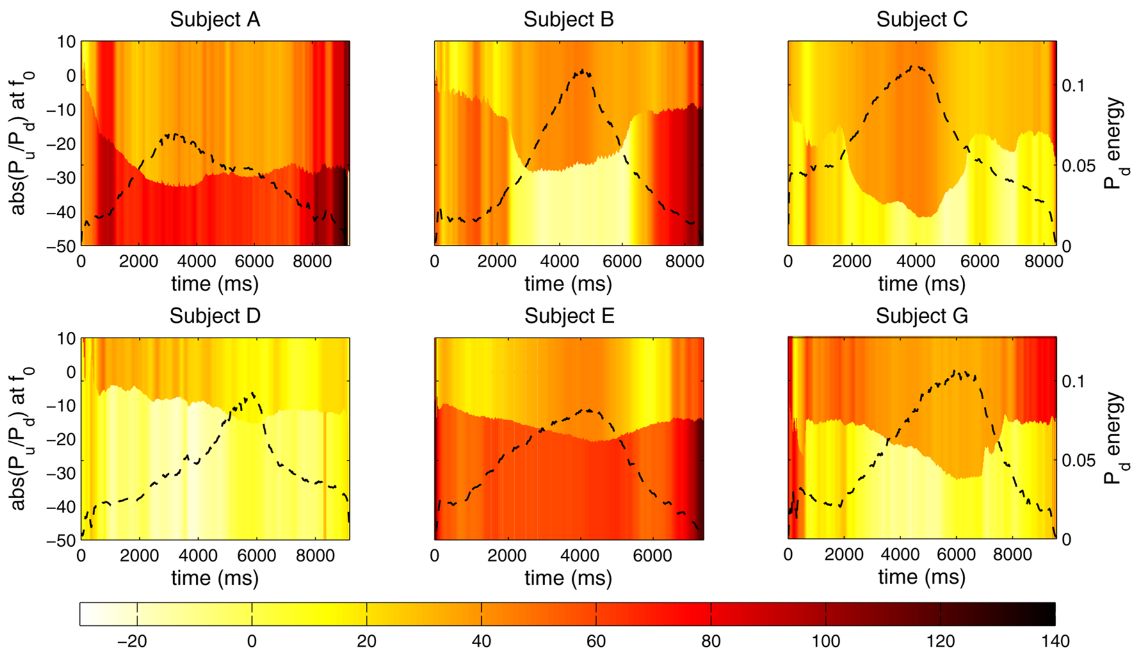

FIG. 8. (Color online) SPL ratio in dB of the upstream to downstream pressure (boundary between color areas), $\angle G_d$ (top color area), $\angle G_{u-\pi}$ (bottom color area), P_d amplitude (dashed black line) during sustained B♭4 (475 Hz) played following a *crescendo−decrescendo* dynamic pattern for Subjects A, B, C, D, E, and G. Color scale unit: degrees.

which supports a capacitive vocal-tract impedance along the tone duration. Analogously, $\angle G_{u-\pi}$ remains stable but closer to zero in Subjects D and G suggesting an inductive upstream impedance. More variability in the $\angle G_{u-\pi}$ value is observed in Subject B; Subject C shows small oscillations of $\angle G_{u-\pi}$ along the task while Subject B displays a clear change in $\angle G_{u-\pi}$ around the $|P_d|$ peak value. For this player, vocal-tract impedance varies from a capacitive to an inductive character and the value of $\angle G_{u-\pi}$ seems well correlated with variations in SPL ratio. To a lesser extent, variations of $\angle G_{u-\pi}$ around the minimum of $|P_u/P_d|$ are also observed in Subjects C, D, G, and somewhat in E, where a smooth variation of both $\angle G_d$ and $\angle G_{u-\pi}$ accompanies variations of loudness and playing frequency.

Overall, these observations suggest two categories of behavior: (1) a marked decrease in SPL ratio correlated with increase in dynamic, possibly associated with variations in $\angle G_{u-\pi}$ caused by changes in vocal-tract shape, and (2) rather stable upstream impedance, in amplitude and phase, with less marked minimum in SPL ratio at the downstream pressure peak. However, for high amplitude oscillations (as must be the case at the maximum loudness), it is difficult to formulate strong conclusions regarding the nature of $\angle Z_d$ and $\angle Z_u$ within the linear theory of oscillation.

C. Pitch bending

Although pitch bends are easy to produce on trombones by simply varying the slide length while maintaining a constant blowing condition, bent tones may also be produced by forcing lip oscillations below the frequency of a well sustained tone for a given slide position. This maneuver may be used in order to play, for instance, an E♭2 (77 Hz) at the 7th position of the slide for which the second input impedance peak is located at the frequency of an E2 (82 Hz). It therefore requires the player to maintain lip oscillations at a frequency not well supported by the downstream air-column. In contrast to woodwind playing, a brass player has a direct control on the mechanical resonance of the lips and may force oscillations away from a resonance of the air-column.[24,28] However, one may also hypothesize that players are capable of producing a significant vocal-tract resonance in the neighborhood of the playing frequency to support lip oscillations during a pitch bend.

In order to investigate this hypothesis, subjects were asked to perform a slow pitch bend starting from a B♭2 at 120 Hz (in closed position of the slide) to the lowest frequency they could maintain, and then back up to B♭2. Results from Subjects A, B, and D (who performed the largest bends) are represented in Fig. 9. The frequency range covered by the three subjects is quite identical and extends from 122 to 85 Hz for Subject A, from 122 to 87 Hz for Subject B, and from 122 to 93 Hz for Subject D. Subjects A and B were thus able to bend down to the frequency of an F2 around 90 Hz (a 4th below B♭2), while Subject D bent down to an F2♯ around 95 Hz (a major 3rd below B♭2).

In addition the value of $|Z_u|$ at f_0 is estimated for each subject during the task using Eq. (1) and presented in Fig. 9. In the three subjects, an increase of the ratio $|P_u/P_d|$ at f_0 is observed when bending down, but this increase seems to be due to the deflection of $|Z_d|$ at f_0 when the pitch is decreased, while Z_u remains constant. Peak values of the ratio are observed around −4 dB in Subject D, −14 dB in Subject B and −16 dB in Subject A. This variation in vocal-tract support occurs simultaneously with important alterations of $\angle G_{u-\pi}$: $\Delta\angle G_{u-\pi} = 130°$ in Subject A, $\Delta\angle G_{u-\pi} = 110°$ in Subject B, and $\Delta\angle G_{u-\pi} = 110°$ in Subject D. On the contrary, $\angle G_d$ remains more stable in

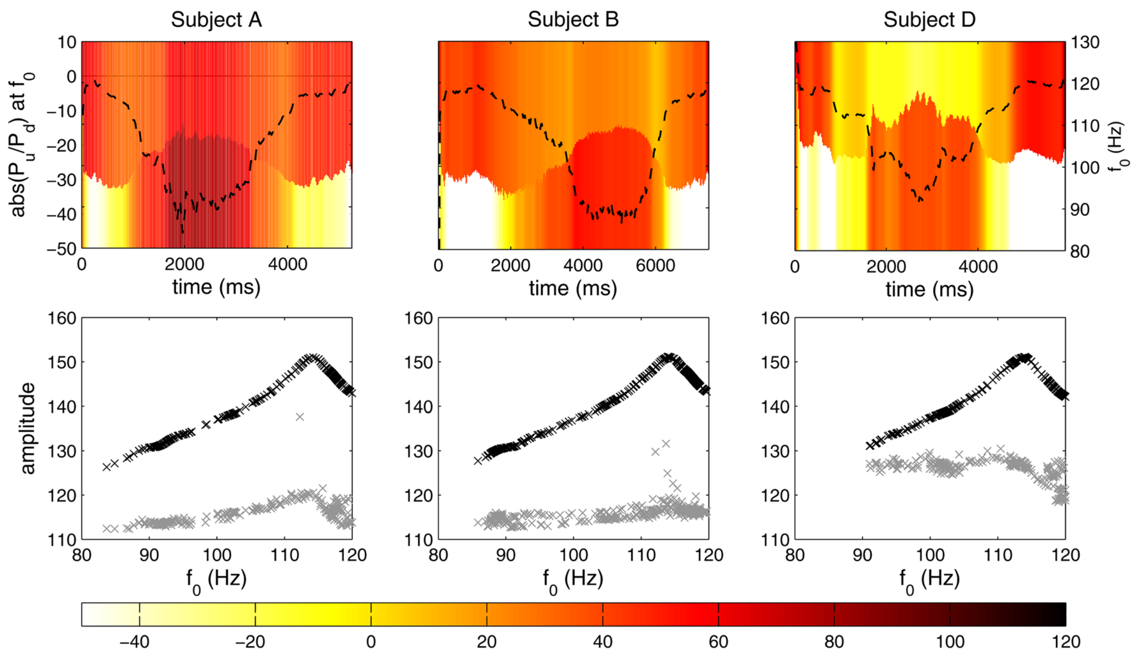

FIG. 9. (Color online) Top: SPL ratio in dB of the upstream to downstream pressure (boundary between color areas), $\angle G_d$ (top color area), $\angle G_{u-\pi}$ (bottom color area), f_0 (dashed black line) during bending from B♭2 (120 Hz) for Subjects A, B, and D. Bottom: magnitude of Z_d (black cross) and Z_u (gray cross) at f_0 during bending. Color scale unit: degrees.

Subjects A ($\Delta\angle G_d = 32°$) and B ($\Delta\angle G_d = 31°$), while it shows more fluctuations alongside f_0 variations in Subject D ($\Delta\angle G_d = 76°$).

These results suggest that a small contribution of the vocal-tract at f_0 accompanies the lowest frequency part of the pitch bends in all subjects, although this effect does not reflect any significant change in $|Z_u|$ at the playing frequency. Regarding the phase of G_d, the small variations observed in Subjects A and B are inconsistent with the important f_0 deviation that should result in a large variation of $\angle Z_d$ from observation of the trombone impedance curve in Fig. 2. Accordingly, we may hypothesize that the assumed linear relationship between the lip opening area and acoustic flow is no longer valid during this bending task. This could be further interpreted as suggesting that players A and B try to maintain a constant lip vibratory mechanism during bending by preserving the phase relationship between S_{lip} and P_d, thus forcing the lips into a particular regime of oscillation. Under this assumption, $\angle G_{u-\pi}$ can no longer be interpreted as an estimate of $-\angle Z_u$.

D. Tone transitions

Since the method proposed allows for a high temporal resolution tracking of $\angle G_d$ and $\angle G_{u-\pi}$, it particularly enables investigation of vocal-tract adjustments at tone transitions. Figure 10 shows extracted parameters near the end of a B♭4 (475 Hz) and the beginning of a C5 (535 Hz), therefore highlighting the slur transition between the two tones during the ascending arpeggio series played by Subject B. We notice that at the tone transition, and for a significant amount of time (about 100 ms), the SPL ratio in decibels becomes greater than zero. This is also visible in the p_d and p_u waveforms where a clear boost in p_u amplitude occurs during the transition.

Although the airflow at tone transitions may be turbulent and the continuity of the volume flow not valid at the frequency shift, this $|P_u/P_d|$ bump occurs within a significant amount of time (300 ms), well above the time required to reach a steady state of oscillation. We also notice an increase

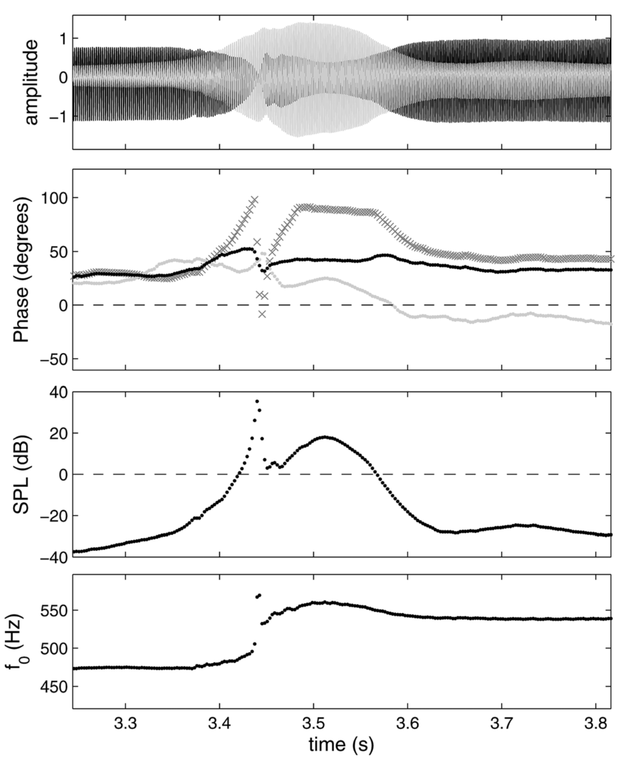

FIG. 10. Transition between B♭4 (475 Hz) and C5 (535 Hz) in Subject B playing an ascending slurred tone sequence. From top to bottom: waveforms of p_d (black), p_u (gray). $\angle G_d$ (dark gray), $\angle G_{u-\pi}$ (light gray), and $\angle G$ (black) at f_0; SPL ratio in dB of the upstream to downstream pressure; fundamental frequency.

in the SPL ratio before the frequency changes, which suggest an increase in vocal-tract support prior to tone transition. Moreover, $\angle G_{u-\pi}$ shows smooth and continuous variations during this transitory part, whereas $\angle G_d$ shows a discontinuous behavior. Regarding $\angle G_d$, this behavior is logically explained by the sign change in $\angle Z_d$ between two adjacent resonances. On the other hand, the continuous character of $\angle G_{u-\pi}$ may be attributed to a synchronous adjustment of the vocal-tract resonance around f_0 resulting in a smooth phase transition of $G_{u-\pi}$. As performers were asked to slur tone transitions (no tonguing articulation), this vocal-tract adjustment might be the result of slight variations in tongue position resulting in changes in vocal-tract resonances.

V. CONCLUSIONS

The experimental method proposed in this article allows for evaluation of the relative amplitude and phase of the downstream and upstream pressures, and thanks to theoretical developments, enables to estimate the relative amplitude and phase of the upstream and downstream input impedances at the playing frequency, as well as the absolute phase of the downstream and upstream input impedances at f_0. This approach involves measurements of lip electrical impedance which is assumed to be in phase with lip opening area.

During arpeggio sequences, a significant increase in vocal-tract support is observed in the higher register. A careful observation of the amplitude ratio and absolute phase of the downstream and upstream input impedances for the two highest tones suggests two categories of vocal-tract tuning: (1) Z_u amplitude large in comparison with Z_d amplitude and $\angle Z_u$ close to zero at f_0, suggesting a vocal-tract resonance located near the playing frequency and overriding the effect of the trombone impedance; (2) Z_u amplitude of the same order as Z_d and lower values $\angle Z_u$ phase, suggesting a vocal-tract resonance centered at a lower frequency and allowing lip oscillations at a lower value of $\angle Z$. This last tuning strategy is possibly favorable to an outward striking regime by allowing oscillations to occur closer to a mechanical resonance of the lips. This may also contribute to explain why the two players showing these characteristics were able to create higher acoustic downstream energy with lower mouth static pressure. However, this early classification may not apply to some subjects as illustrated by the results obtained for Subject E. Further investigations should be conducted in order to clarify the origin of these different strategies.

During sustained tones with variations of dynamic, a general trend involving a decrease in vocal-tract support with increase in dynamic is observed. Larger variations in $|P_u/P_d|$ ratio are observed in subjects showing highest variations in $\angle G_{u-\pi}$, which implies variations in the characteristics of the vocal-tract resonance at f_0 with increase in dynamic. Alternatively, the decrease in vocal-tract support with increase in acoustic energy produced may be explained by non-linear interactions between harmonics which participate to support lip oscillation and reduce the need for vocal-tract support at f_0.

Pitch bending tasks do not appear to involve any significant vocal-tract support at f_0. The stable phase of G_d observed in two subjects suggests a possible interruption of the assumed linear relationship between lip opening area and the input acoustic flow. A relatively greater vocal-tract support during bending may maintain this linear relationship as shown by significant variations of $\angle G_d$ in one subject.

During slurred tone transitions, variations of the amplitude ratio $|P_u/P_d|$ suggest a transitory vocal-tract influence, at least prior to tone transition, indicating that upstream acoustic support is possibly needed to achieve proper slurs. Smooth variations of $\angle G_{u-\pi}$ at tone transitions also support the hypothesis of a continuous adjustment of a vocal-tract resonance around f_0 during slurs. However, the nature of this transitory vocal-tract coupling should be interpreted with care as the nature of the volume flow at the frequency shift is quite uncertain.

Although these experimental results provide relevant insights regarding the potential importance of vocal-tract tuning in brass performance, they also require further investigation in order to better understand the nature of the interaction between an upstream resonance and the vibrating lips, as well as the influence of an upstream coupling on adjacent playing control parameters (static mouth pressure, lip tension, etc.) In this context, artificial player systems offer a great experimental platform to study different aspects of the sound production chain independently from each other. In particular, the influence of amplitude and phase of an upstream resonance around the playing frequency on the behavior of artificial lips has been the object of a recent study on an artificial trombone player system.[41]

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APPENDIX

$$\frac{|\angle G_d - \angle G|}{|\angle G_{u-\pi} - \angle G|} = \frac{|\angle(P_d - P_u) - \angle P_d|}{|\angle(P_d - P_u) - \angle P_u - \pi|} \tag{A1}$$

Define ϵ such that $\angle P_d(f_0) = 0$ and $\angle P_u(f_0) = \epsilon - \pi$, calling $p_d(t)$ and $p_u(t)$ the fundamental harmonics of the downstream and upstream pressures of amplitude a_d and a_u, respectively,

$$\begin{aligned}\Delta p(t) &= p_d(t) - p_u(t)\\ &= a_d \cos(\omega_0 t) - a_u \cos(\omega_0 t - \pi + \epsilon).\end{aligned}$$

For ϵ small, applying the cosine Taylor series we obtain

$$\begin{aligned}\cos(\omega_0 t - \pi + \epsilon) &= -\cos(\omega_0 t + \epsilon)\\ &\simeq -\cos(\omega_0 t) + \epsilon \sin(\omega_0 t).\end{aligned}$$

Consequently,

$$\Delta p(t) = (a_d + a_u)\cos(\omega_0 t) - a_u \epsilon \sin(\omega_0 t),$$

which leads to

$$P_d(f_0) - P_u(f_0) = \Delta P(f_0) = \frac{a_d + a_u}{2} + j\frac{a_u\epsilon}{2}.$$

Therefore, for ϵ small, applying the arctangent Taylor expansion,

$$\angle\Delta P(f_0) = -\text{atan}\left(\frac{a_u\epsilon}{a_d + a_u}\right) \simeq \frac{a_u\epsilon}{a_d + a_u} \simeq \frac{\epsilon}{1 + \frac{a_d}{a_u}}. \quad \text{(A2)}$$

Substituting Eq. (A2) into Eq. (A1) leads to

$$\frac{|\angle(G_d(f_0)) - \angle G(f_0)|}{|\angle(G_{u-\pi}(f_0)) - \angle G(f_0)|} = \left|\frac{\frac{\epsilon}{1 + (a_d/a_u)}}{\frac{\epsilon}{1 + (a_d/a_u)} + \pi - \epsilon - \pi}\right| = \left|-\frac{a_u}{a_d}\right| = \left|\frac{Z_u(f_0)}{Z_d(f_0)}\right|$$

when ϵ is close enough from zero, which implies that $\angle P_d(f_0) - \angle P_u(f_0)$ is close to π. For the measured data presented in this paper, $\angle Pd(f_0) - \angle Pu(f_0)$ ranges between 80 and 180°, which corresponds to an estimation accuracy of between 70% and 100% (as determined by direct comparison of the estimated and exact expressions). Thus, this approximation is satisfactory to give a visual estimation of the amplitude ratio by looking at the relative distance between $\angle G_d$, $\angle G_{u-\pi}$, and $\angle G$. For Figs. 3 and 4, this approximation can also be directly compared to measurements of the $|P_u/P_d|$ ratio.

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