CrossMark
click for updates

'Warming up' a wind instrument: The time-dependent effects of exhaled air on the resonances of a trombone

Henri Boutin,[1,a)] John Smith,[2] and Joe Wolfe[2]

[1]*Sciences et Technologies de la Musique et du Son (UMR9912), Sorbonne Université, Ircam, CNRS (Centre National de la Recherche Scientifique), 1, place Igor Stravinsky, 75004, Paris, France*

[2]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*

ABSTRACT:

To study the effect of 'warming up' a wind instrument, the acoustic impedance spectrum at the mouthpiece of a trombone was measured after different durations of playing. When an instrument filled with ambient air is played in a room at 26–27 °C, the resonance frequencies initially fall. This is attributed to CO_2 in the breath initially increasing the density of air in the bore and more than compensating for increased temperature and humidity. Soon after, the resonance frequencies rise to near or slightly above the ambient value as the effects of temperature and humidity compensate for that of increased CO_2. The magnitudes and quality factors of impedance maxima decrease with increased playing time whereas the minima increase. Using the measured change in resonance frequency, it proved possible to separate the changes in impedance due to changes in density and changes in acoustic losses due to water condensing in the bore. When the room and instrument temperature exceed 37 °C, condensation is not expected and, experimentally, smaller decreases in magnitudes and quality factors of impedance maxima are observed. The substantial compensation of the pitch fall due to CO_2 by the rise due to temperature and humidity is advantageous to wind players. © *2020 Acoustical Society of America.* https://doi.org/10.1121/10.0002109

I. INTRODUCTION

Players of wind instruments "warm up" their instruments by playing or breathing into them before tuning: they know that, all else being equal, a cold, dry instrument usually plays at a lower pitch than it does when filled with warm, humid, exhaled air. During extended sections of rest in ensemble music, they often breathe quietly into the instrument to warm it to ensure that, on reentry, they will be playing an instrument already filled, at least partly, with warm, humid, exhaled air.

The speed of sound in air increases with increasing temperature and humidity, and decreases with the increasing concentration of CO_2. (The expansion of the instrument itself over the small temperature change produced by playing is negligible.) Consequently, and all else being equal, increased temperature and humidity raise the frequencies of resonances and thus the pitch of notes played. Increases in playing pitch of 1.2 to 2.6 cents per °C increase in temperature are reported for brass instruments (Young, 1946). The increase in CO_2 during playing of a phrase would be expected, all else being equal, to lower the pitch, while humidity is expected to increase it (see calculations by Fuks, 1996; Balasubramanian and Kausel, 2015). Measurements on an (already warmed) oboe and bassoon show decreases in pitch of order 10 cents (0.6% in frequency) in the 10 s of playing following inhalation; these are attributed to increased CO_2 concentration (Fuks, 1997).

To a non-musician, effects of less than one percent (the size of the effects reported here) may seem small, but to a musician, one percent is a sixth of a semitone and, for a sustained note, an important error in intonation.

By adjustment of blowing pressure and other control parameters that players would include in the term "embouchure," players of modern brass instruments can "lip up or down," i.e., raise or lower the pitch over a total range of roughly two semitones (Boutin *et al.*, 2020), and thus can usually correct quickly for expected or heard errors in intonation. (Trombonists also have the slide available.) Consequently, simple measurements of the played pitch, especially for experienced musicians, are not expected to reveal the effects of breath composition or temperature in the absence of compensation. Nevertheless, it is interesting for both scientists and musicians to know the magnitude of these effects.

There have been several previous measurements of the input impedance of a trombone filled with cool, dry air (e.g., Backus, 1976; Caussé *et al.*, 1984; Braden *et al.*, 2009). One of the motivations for the present study is that knowledge of the impedance in playing conditions can allow determination of the acoustic flow into the instrument (Boutin *et al.*, 2015, 2020).

This paper reports measurements of the impedance spectrum of the bore of a trombone, initially filled with dry, ambient air, but then played for differing durations. A preliminary set of measurements was briefly reported previously (Boutin *et al.*, 2013) as part of a different study. Those results are reanalyzed here, as are a more detailed set of

a)Electronic mail: boutin@ircam.fr, ORCID: 0000-0002-4895-6453.

results over a larger range of conditions. All but one set of measurements were made at room temperature (between 26 °C and 27 °C). The other set was made in a laboratory heated to 39 °C so as to avoid the effect of condensation of water in the bore of the instrument.

II. MATERIALS AND METHODS

A. The instrument

The trombone (Yamaha YBL 321) and a modified mouthpiece were used and described in a previous study (Boutin *et al.*, 2015). The mouthpiece had the same volume and rim diameter as a normal mouthpiece but was modified for other experiments conducted at the same time. The B♭-F "trigger" mechanism was used in its shorter configuration and the main slide had its minimum length throughout. Players call this "first position": it is used to play notes in an incomplete harmonic series, including B♭2 (nominally 117 Hz at A440), F3, B♭3, D4, etc. The tuning slide was maintained at 18 mm from its shortest position (a typical position for playing at A440). The player for the detailed study was the first author, who has very limited experience playing the trombone, but has no unusual respiratory issues and plays with an air flow rate typical of experienced players (Boutin *et al.*, 2015). For the larger preliminary study, measurements were made on three more additional players, two of whom had orchestral or band experience on brass and one of whom was a beginner. For the data reported here, no measurements were made of the players—only of the instrument, after different periods of being played.

B. The trombone input impedance

The input impedance of the trombone bore, called Z_{bore}, was measured using an impedance head mounted in a plane plate that was sealed to the rim of the mouthpiece with petroleum jelly (Boutin *et al.*, 2015). An acoustic current source was located next to a microphone (4944 A, Brüel & Kjær, Denmark) connected to a pre-amplifier and a FireWire audio interface (MOTU 828, Cambridge, MA), see Fig. 1. This impedance head (Smith *et al.*, 1997) was calibrated by measuring the impedance of an acoustically infinite duct, 142 m long and 7.8 mm in diameter. The broadband signals used for calibration and measurement were sums of sine waves between 50 Hz and 1.8 kHz, with a spacing of 0.67 Hz (=44.1 kHz/2^{16}) corresponding to a time window lasting 1.49 s. This was a compromise between resolution in frequency and time; the 0.67 Hz frequency resolution allowed accurate determination of the maxima and minima, while the 1.49 s time resolution was needed for the extrapolation of measurements back to the cessation of playing. Measurements were conducted in a lab at temperature of 26.3 ± 0.3 °C and 55 ± 6% relative humidity, except for one series. That series was conducted with the temperature of the laboratory, and the trombone raised to 39 ± 2 °C with relative humidity 45 ± 6%. This temperature was chosen to avoid water condensation in the bore of the instrument when played.
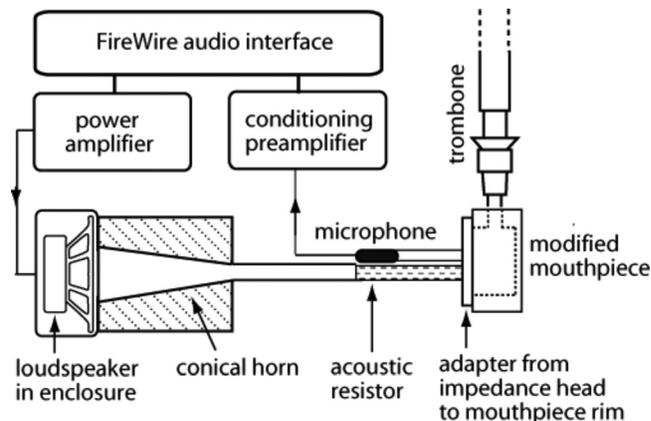

FIG. 1. Schematic (not to scale) of the impedance spectrometer used to measure $Z_{bore}(f)$ for the trombone.

The instrument was initially at ambient temperature, then flushed with ambient air and equilibrated in the lab at ambient temperature and humidity. The impedance head was connected to the mouthpiece and the input impedance was measured before each note was played. The trombone was then played for a predetermined duration. For the 3 s and 10 s measurements, a single sustained note was played. For the 30, 60, 120, and 240 s measurements, the player played long notes but briefly inhaled as needed. The slide was left in first position, and the player mainly played the first two notes of the harmonic series (B♭2 and F3). The impedance head was then connected and an impedance measurement started within 3 s of the cessation of playing; each impedance measurement comprised 32 cycles of 2^{16} samples at 44.1 kHz, consequently each cycle lasted 1.49 s and the total measurement lasted 48 s. The instrument was then flushed with ambient air. This protocol of a measurement before and after each playing was repeated three times for each note duration. Thus 36 impedance measurements were obtained at 26.3 °C and another 28 at 39 °C.

The measurement of each cycle took 1.49 s, which limits the frequency resolution. Because the proportional change is of interest here, the resulting uncertainty has a greater effect on the low-frequency impedance peaks. On the other hand, the eighth and higher peaks are weaker and so less sharp, see Fig. 3(a), which introduces uncertainty at high frequencies. Analysis showed that peaks three to seven gave least variance among measurements. (These also fall toward the middle of the instrument's range: the first peak is not used, and those above the eighth are rarely used.) In the following analysis, averages over the third to seventh peaks are used.

Around each maximum and minimum of each impedance measurement, a cubic spline interpolation was used to achieve a frequency resolution of 0.1 Hz. The associated Q factor is estimated as the ratio between the peak frequency and its 3-dB bandwidth. A finer cubic spline interpolation with a frequency resolution of 0.001 Hz was used to achieve a precision lower than 0.01. The frequency and magnitude of each impedance maximum and minimum, and the Q
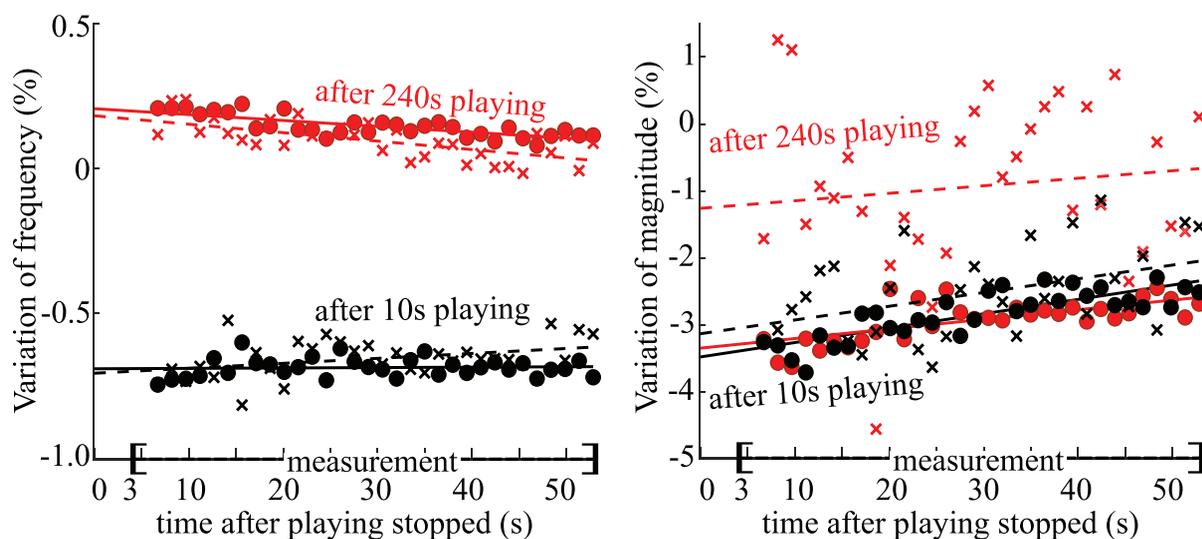
1818   J. Acoust. Soc. Am. **148** (4), October 2020

Boutin *et al.*

FIG. 2. (Color online) Examples of the extrapolation procedure used to estimate the percentage changes in the frequencies f_{max} and f_{min}, and the magnitudes Z_{max} and Z_{min} of the extrema in Z_{bore} at the moment playing ceased ($t = 0$). The percentage variations in frequency (left) and magnitude (right) of the impedance maxima and minima over the measurement period are relative to the values measured before playing started. Circles indicate the average values of maxima 3 to 7 (169–405 Hz) for each cycle, and the crosses indicate the average values of minima 3 to 7 (195–439 Hz). The black symbols correspond to a playing duration of 10 s and the red (gray) symbols to a playing duration of 240 s. The linear regressions for maxima and minima are shown as solid and dashed lines, respectively. The time for each point was taken as the middle of each cycle used to calculate $Z_{bore}(f)$. Data are for lab temperature $26.3 \pm 0.3\,°C$ and relative humidity $55 \pm 6\%$.

factor of each impedance maximum, were then calculated for each cycle of the measurement. The values at the moment when playing ceased (i.e., 3 s before the first cycle of measurement) were determined by linear regression over the following 32 contiguous cycles during the measurement period, as shown by the extrapolations to $t = 0$ in Fig. 2. Note that the magnitudes of the minima (especially those after 240 s of playing) are more scattered from cycle to cycle than the other data. This may be due to the difficulty of quickly measuring the magnitudes of the impedance minima with a variation less than 1% in a duct with water condensing on the walls. [The magnitudes of the minima and maxima are taken from the same measurement of $Z_{bore}(f)$, and the minima are typically about 30–40 times smaller than the maxima (see Fig. 3) with a corresponding decrease in measured precision].

III. RESULTS AND DISCUSSION

When the player commences playing an instrument that had previously been flushed with dry air and equilibrated in the lab at ambient temperature and humidity, the input impedance Z_{bore} of the instrument can be affected via the following three mechanisms.

The first is that the temperature T rises in the bore and the gas composition changes; this will change the density ρ of the air in the bore. (The gas composition and temperature will vary with time and also with distance along the bore.) The speed of sound is given by $c = \sqrt{\gamma P_0/\rho}$, where P_0 denotes atmospheric pressure and γ denotes the heat capacity ratio, whose variation with composition is shown later to be several times less than that due to changes in density. For a simple open cylindrical duct of effective length L, the

frequencies of impedance extrema are given by $f_{max} = (2n + 1)c/4L$ and $f_{min} = nc/2L$ where n = 0, 1, 2, 3, etc. Thus, all else being equal, an increase in ρ will decrease the resonance frequencies.

The characteristic impedance Z_0 of a simple cylindrical duct is given by $Z_0 = \sqrt{\rho\gamma P_0}/A$, where A denotes the cross-sectional area of the duct. An increase in ρ or γ will increase the magnitude of the characteristic impedance, Z_0, and consequently increase the magnitudes of the maxima and minima.

The second occurs when water vapour in the bore has begun to condense on the walls: this can increase the acoustic losses (Hickey *et al.*, 2000; Coltman, 2003). All else being equal, increased acoustic losses will decrease the magnitude of maxima, increase the magnitude of minima, and broaden the resonances (i.e., reduce their Q factors).

The third is a much smaller effect due to loss by sound radiation in air as a function of composition; this should be negligible in comparison with the wall losses (Morse and Ingard, 1968).

A. Measurements at ambient temperature: 26 to 27 °C

At constant atmospheric pressure, the effects of increasing T and water concentration in the bore would both on their own lower the density of air and so increase the speed of sound; this would tend to increase the frequency of each bore resonance. However, CO_2 concentration in the bore also rises, which tends to lower the speed of sound. (Oxygen concentration also falls, but because O_2 has a molar mass close to the average for air, the effect of falling O_2 concentration is expected to be modest.) Molar masses for water, air, oxygen, and CO_2 are 18, 29, 32, and 44 kg.kmol^{-1},

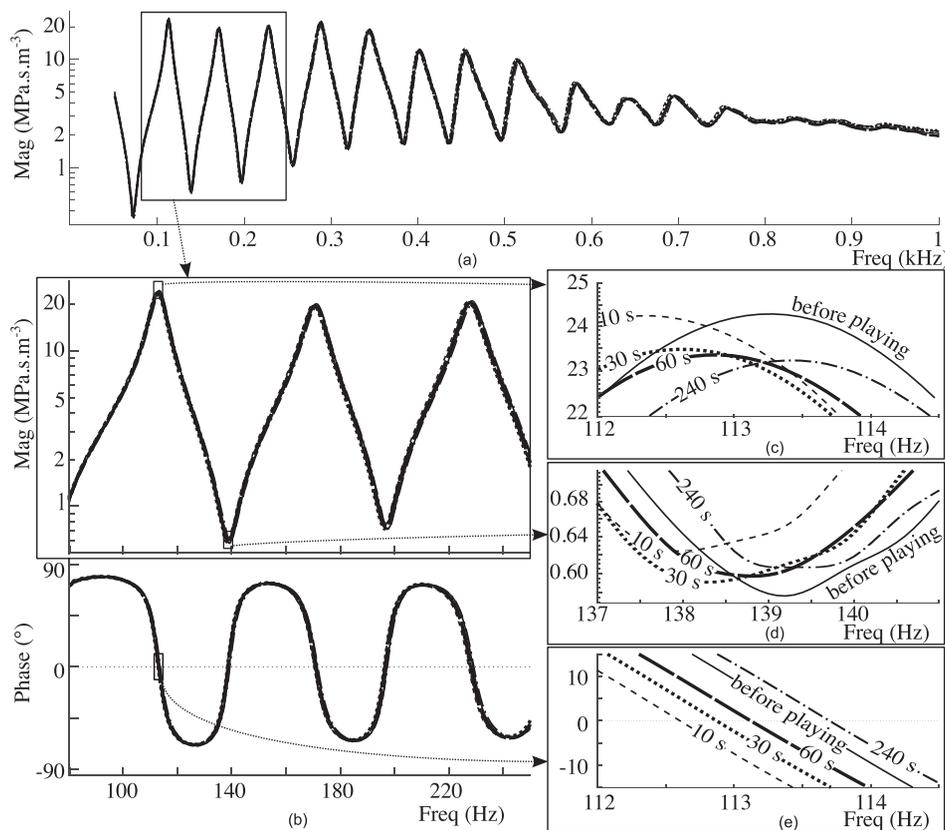J. Acoust. Soc. Am. **148** (4), October 2020

Boutin *et al.* 1819

FIG. 3. (a) $|Z_{bore}(f)|$ measured between 50 Hz and 1 kHz showing the second and higher resonances. (b) A zoom on the resonances two, three and four measured 3 s after different durations of playing by the same player. (c) The insets zoom in on the impedance magnitude maxima and (d) minima and on the (e) phase zero-crossing of the second resonance.

respectively. Figure 3 shows measurements on a section of the impedance spectrum of the trombone when played for 10, 30, 60, and 240 s. The lowest resonance, which is not played, does not occur in the frequency range of these measurements.

The resonance frequencies initially decrease for short playing durations, until they begin to increase; this is consistent with an initial increase in density produced by increasing CO_2 concentration until it is counteracted by increasing T and humidity. However, from consideration of gas density alone, a decrease in frequency produced by an increase in density would be accompanied by a corresponding increase in the magnitudes of Z_0 and hence Z_{max}. The measurements show that the Z_{max} actually decrease for longer playing duration, presumably as a consequence of increased losses. The increase in Z_{min} after 30 s is also consistent with increased losses. These losses are discussed below.

Figure 4 shows the average of the data at ambient room temperature obtained by the extrapolation procedure explained in Sec. II for the 36 measurements at 26.3 °C and the 40 measurements in a preliminary study at 27 °C, reported in a conference paper (Boutin *et al.*, 2013). It shows the mean percentage changes in the frequencies and magnitudes of the peaks in Z_{bore} after playing for 3, 10, 30, 60, 120, and 240 s.

Both f_{max} and f_{min} initially decrease when playing starts, the lowest frequency being produced after playing for 10 s [see Fig. 4(a)]. Over this short time, the effect of CO_2 on the speed of sound dominates over those of temperature and humidity. For the longer durations, the players inhaled at

least once. Consequently, the concentration and effect of CO_2 did not increase monotonically over time, while the effects of temperature and humidity presumably did increase and eventually more than compensated for the effect of CO_2. This is consistent with the observed slow increase in f_{max} and f_{min} after 10 s. (The fact that increased CO_2 concentration significantly cancels the effect of increased temperature and humidity is a fortunate one for wind players.) Changes in density should affect f_{max} and f_{min} equally; over all measurements, the ratio of the changes in f_{min} to the preceding f_{max} was 0.99967 ± 0.00126.

There is a nearly monotonic decrease in the magnitude of the impedance maxima with increasing playing time, and the magnitude of the minima increases in an almost monotonic fashion [see Fig. 4(b)]. After a 240-s duration of playing, the magnitudes of the extrema have changed by around 4%, in opposite directions. Assuming that the observed initial decrease in frequency is caused by an increase in density, a corresponding increase in Z_0, and hence Z_{max} and Z_{min}, would be expected. The change due to density can be calculated from Fig. 4(a), neglecting that due to specific heat ratio. The effect of density on Z_0 can then be removed from the measured magnitude of the impedance extrema, leaving only the changes produced by increased losses (see Fig. 5). Changes in the wall losses are expected to be roughly proportional to changes in the magnitude of the impedance; consequently, the wall losses have increased by around 4% after 240 s of playing.

Increased losses would increasingly broaden both maxima and minima, with increased time of playing
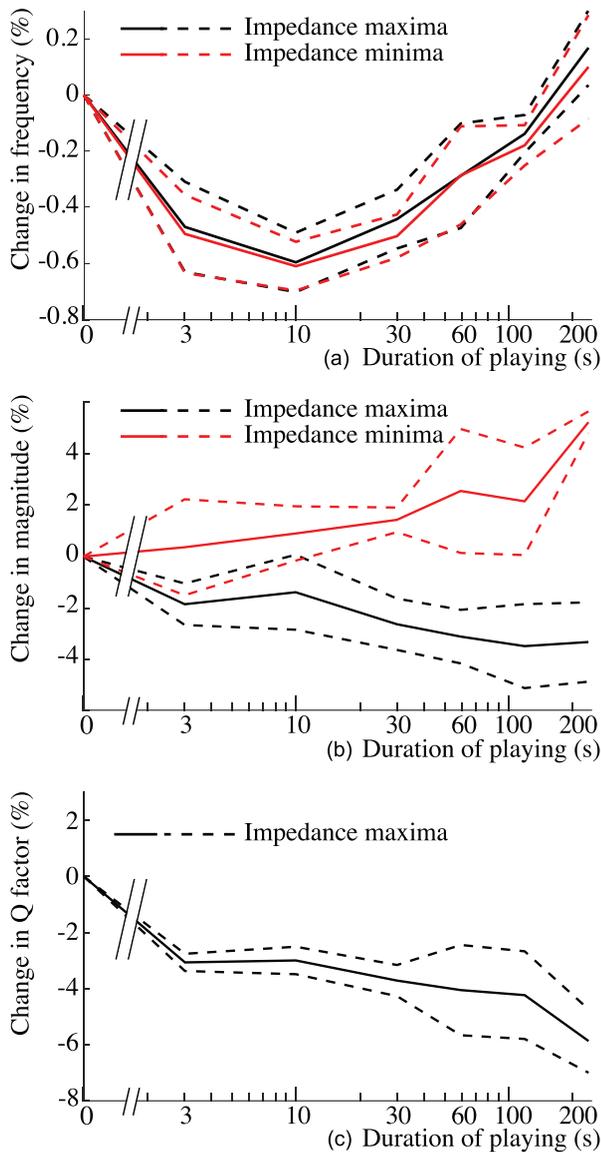
FIG. 4. (Color online) The mean percentage changes in the (a) frequencies, (b) magnitudes of the extrema in Z_{bore}, and (c) Q factors of impedance peaks 3 to 7 versus duration of playing (on a log scale) in a lab at ambient temperature and 55% relative humidity. The black and red (gray) lines (top and middle) show the variations of, respectively, the corresponding impedance maxima and minima. The dashed lines show ± one standard deviation.

FIG. 5. Separation of the percentage changes in the mean values of Z_{max} and Z_{min} into those caused by density changes and those caused by changes in the losses at ambient temperature.

had been heated to 39 °C, with the instrument equilibrated at that temperature.

B. Measurements at elevated temperature: 39 °C

The 39 °C measurements show that the mean frequencies of the maxima and minima are initially reduced only slightly, if at all, for most playing durations [see Fig. 6(a)]. However, the changes are generally not statistically significant at the 95% confidence level. In this experiment, a negligible change in temperature with playing time is expected. However, the fact that the initial decrease in frequency at 39 °C is smaller than that at ambient temperature can be explained by humidity: the water concentration at saturation is 1.83 times higher at body temperature (37 °C) than at 26.3 °C (Engineering Toolbox, 2020), so the humidity offsets the CO_2-induced fall in frequency to a greater extent at the higher temperature.

The rise in frequency toward 240 s might be explained if the player at this stage had reached his steady-state respiration, breathing more often at high temperature than he would for shorter phrases or lower temperature, and were thus keeping the CO_2 concentration lower than for shorter intervals.

The smaller changes in resonant frequencies also mean that changes in impedance magnitude due to density changes will be smaller than at ambient temperature (see Fig. 7).

However, for playing durations greater than 10 s, rather than decreasing as for ambient temperature, the mean of Z_{max} now slightly increases with increasing duration of playing, although this increase is not statistically significant at the 95% level. The air in the lungs at 37 °C is close to saturated at this temperature. The relative humidity of this air falls further below saturation when it enters the warmer instrument at 39 °C. So, no condensation is expected inside a trombone at 39 °C, and hence, unlike at ambient

consequently producing decreases in the quality factor Q of the resonances. Percentage changes in the average value of Q are shown in Fig. 4(c). From 380 peaks where Q and Z_{max} were both measured, a linear fit found the relationship between the change in Q factor and the change in Z_{max} due to losses was $\Delta Q = 0.76$ (m³s⁻¹MPa⁻¹)ΔZ_{max} − 0.02 at ambient temperature (r² = 0.57).

Hickey et al. (2000) and Coltman (2003) (see also Slaton, 2004) identify a significant energy loss mechanism in instrument bores when water is present and the humidity is at or close to saturation: water can condense and evaporate in each cycle of a standing wave. To eliminate condensation, a set of measurements were conducted in a lab that
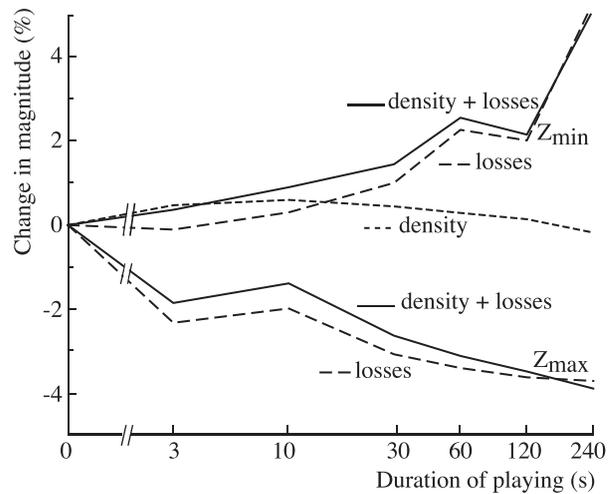
J. Acoust. Soc. Am. **148** (4), October 2020

Boutin *et al.* 1821

FIG. 7. Separation of the percentage changes in the mean values of Z_{max} and Z_{min} into those caused by density changes and those caused by changes in the losses at $39\,^{\circ}$C.
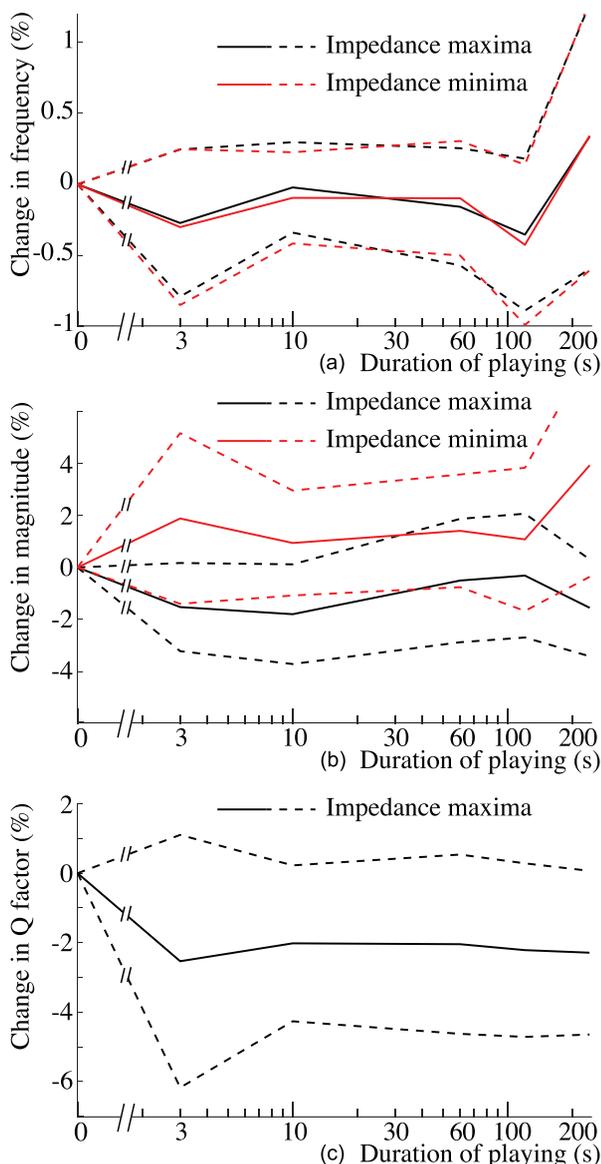
FIG. 6. (Color online) The mean percentage changes in the (a) frequencies, (b) magnitudes of the extrema in Z_{bore}, and (c) Q factors of impedance peaks 3 to 7 versus duration of playing (on a log scale) in a lab at $39\,^{\circ}$C and 45% relative humidity. The black and red (gray) lines (top and middle) show the variations of the corresponding impedance maxima and minima, respectively. The dashed lines show $\pm$ one standard deviation.

and H_2O have, respectively, 44/29 and 18/29 times the mass of a mole of air. O_2 has a molar mass (32 kg.kmol^{-1}) not far from the average for air (29 kg.kmol^{-1}), and so depleting oxygen concentration is expected to have relatively little effect. At constant temperature, the speed of sound is inversely proportional to the square root of the density of air, to a good approximation. The values of γ for CO_2, H_2O, and dry air are, respectively, 1.289, 1.330, and 1.400 (Bhattacharjee, 2020; Engineering Toolbox, 2020). The speed of sound is given by $c = \sqrt{\gamma P_0/\rho}$ or, for constant pressure,

$$1 + \frac{\Delta c}{c} = \left(1 + \frac{\Delta\gamma}{\gamma}\right)^{\frac{1}{2}} \left(1 + \frac{\Delta\rho}{\rho}\right)^{-\frac{1}{2}}.$$

At constant temperature and pressure, consider only small increases ΔC and ΔH in fractional molar concentrations of CO_2 and H_2O in the air, respectively, where these gases replace air in the usual mixture of nitrogen and oxygen. The adiabatic ratio is changed by

$$\Delta\gamma = \Delta C(\gamma_{CO_2} - \gamma_{air}) + \Delta H(\gamma_{H_2O} - \gamma_{air})$$

and the density by an analogous expression. From substitution and retaining only zeroth and first order terms, the speed of sound is increased by a factor $1 - 0.30\Delta C + 0.16\Delta H$. (If instead CO_2 and H_2O replace pure nitrogen or oxygen, the numerical results are only a little different.)

For inhaled and expired air under normal breathing, ΔC is typically about 4% by volume or mole (Buszewski *et al.*, 2007), which on its own would give a fall in the speed of sound of a little more than 1%. However, the difference is likely to be smaller on average in this experiment, because the players began exhaling into the instrument as soon as they finished inhaling, which would give exhaled gas whose initial CO_2 concentration would be lower than normal.

If the temperature change were ΔT and uniform, the speed of sound would increase by a factor of about $1 + \frac{\Delta T}{2T}$. Taking $T \sim 300$ K, and using ΔT for an effective, overall change in T, the speed of sound and so the frequency are

temperature, there is no expected loss due to condensation-evaporation cycles, even though the humidity rises.

The Q values for $39\,^{\circ}$C fall by about 2% in the first 3 s (as soon as the bore is largely filled with exhaled air) and then remain steady for longer durations [see Fig. 6(c)]. This is in contrast to the Q values at ambient temperature that continue to fall as playing time increases. This latter behavior is what the condensation-induced losses would predict as successively more of the bore walls acquired condensation.

The results of the experiments reported here are qualitatively explained above in terms of the known effects of gas composition and temperature on the speed of sound. Simple estimates allow the changes in Figs. 4 and 6 to be related to the underlying variables. CO_2 (molar mass 44 kg.kmol^{-1})

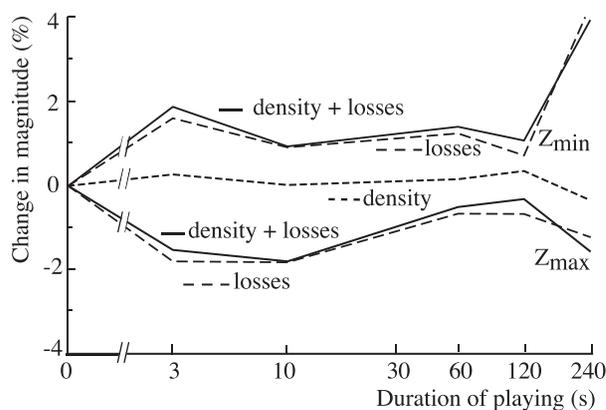Boutin *et al.*

proportional to $1 + \frac{\Delta T}{600\,\mathrm{K}}$. So the proportional change in frequency would be $\Delta f/f = \Delta T/600\,\mathrm{K} - 0.30\Delta C + 0.16\Delta H$. Thus a 1% increase in frequency would require either $\Delta T \cong +6\,°C$, $\Delta C \cong -3\%$, or $\Delta H \cong +6\%$, or some linear combination of these. For example, Fig. 4 could be explained by a CO_2 concentration of 2%–4% that is gradually offset by a combination of a few degrees of increase in effective temperature and a few percent increase in water concentration. Once there is condensation, a rise in T usually means a rise in absolute humidity, because the water content at saturation rises strongly with T.

IV. CONCLUSIONS

Playing the dry instrument at room temperature, the frequency of the impedance peaks of the bore fall by about 0.6% in the first 10 s as the density of the air in the bore increases. This is a result of CO_2 in the breath more than compensating for increased temperature and humidity. Over the next few minutes, the frequencies rise to close to or a little above their original values, as the effects of humidity and temperature overcome that of the CO_2. The magnitude and quality factors of impedance maxima decrease with increasing playing time, consistent with enhanced wall losses due to water condensing in the bore. This effect is attributed to losses associated with latent heat exchange between humid air and wet walls. Playing in a room at $39\,°C$, and therefore without condensation, the effect on the magnitudes of impedance extrema and the Q factor is substantially reduced.

ACKNOWLEDGMENTS

Backus, J. (**1976**). "Input impedance curves for the brass instruments," J. Acoust. Soc. Am. **60**(2), 470–480.

Balasubramanian, S., and Kausel, W. (**2015**). "Pitch shifts in wind instruments due to changes in air composition," in *Proceedings of the Third Vienna Talk on Music Acoustics*, Vienna, Austria, pp. 16–19.

Bhattacharjee, S. (**2020**). "Properties of various ideal gases (at 300 K)" (San Diego State Univ.), https://www.ohio.edu/mechanical/thermo/property_tables/gas/idealgas.html. Last accessed 19 July 2020.

Boutin, H., Fletcher, N., Smith, J., and Wolfe, J. (**2013**). "Lip motion, the playing frequency of the trombone and upstream and downstream impedances," in *Proceedings of SMAC Conference*, Stockholm, Sweden, pp. 483–489.

Boutin, H., Fletcher, N., Smith, J., and Wolfe, J. (**2015**). "Relationships between pressure, flow, lip motion and upstream and downstream impedances for the trombone," J. Acoust. Soc. Am. **137**, 1195–1209.

Boutin, H., Smith, J., and Wolfe, J. (**2020**). "Trombone lip mechanics with inertive and compliant loads ("lipping up and down")," J. Acoust. Soc. Am. **147**, 4133–4144.

Braden, A. C. P., Newton, M. J., and Campbell, D. M. (**2009**). "Trombone bore optimization based on input impedance targets," J. Acoust. Soc. Am. **125**, 2404–2412.

Buszewski, B., Kesy, M., Ligor, T., and Amann, A. (**2007**). "Human exhaled air analytics: Biomarkers of diseases," Biomed. Chromat. **21**(6), 553–566.

Caussé, R., Kergomard, J., and Lurton, X. (**1984**). "Input impedance of brass musical instruments: Comparison between experiment and numerical models," J. Acoust. Soc. Am. **75**, 241–254.

Coltman, J. W. (**2003**). "Acoustical losses in wet instrument bores," J. Acoust. Soc. Am. **114**, 1221.

Engineering Toolbox. (**2020**). "Ratio of specific heat of gases," https://www.engineeringtoolbox.com/specific-heat-ratio-d_608.html. Last accessed 19 July 2020.

Fuks, L. (**1996**). "Prediction of pitch effects from measured CO2 content variations in wind instrument playing," *KTH Dept Speech, Music and Hearing, Quarterly Progress and Status Reports*, Vol. 37, pp. 37–43.

Fuks, L. (**1997**). "Measurements of exhaled air effects in the pitch of wind instruments," *KTH Dept Speech, Music and Hearing, Quarterly Progress and Status Reports*, Vol. 38, pp. 7–11.

Hickey, C. J., Raspet, R., and Slaton, W. V. (**2000**). "Effects of thermal diffusion on sound attenuation in evaporating and condensing gas–vapor mixtures in tubes," J. Acoust. Soc. Am. **107**, 1126–1130.

Morse, P. M., and Ingard, K. U. (**1968**). *Theoretical Acoustics* (McGraw-Hill, New York, NY), pp. 270–300.

Smith, J. R., Henrich, N., and Wolfe, J. (**1997**). "The acoustic impedance of the Bœhm flute: Standard and some non-standard fingerings," in *Proceedings of Institute of Acoustics*, Vol. 19, pp. 315–320.

Slaton, W. V. (**2004**). "Comment on 'Acoustical losses in wet instrument bores' [J. Acoust. Soc. Am. **114**, 1221 (2003)] (L)," J. Acoust. Soc. Am. **115**(3), 971–972.

Young, R. W. (**1946**). "Dependence of tuning of wind instruments on temperature," J. Acoust. Soc. Am. **17**(3), 187–191.

J. Acoust. Soc. Am. **148** (4), October 2020

Boutin *et al.*   1823