An acoustic and perceptual evaluation of saxophone pad resonators

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Abstract

On some woodwind instruments, the key pads are often covered with what musicians and artisans refer as resonators. These are flat or domed disks made of metal or plastic fixed in the middle of the pad with a rivet. This article provides several analyses of the measured and perceptual behaviour of these pad resonators. In terms of their acoustic influence, resonators tend to lower the absorption coefficient of pads and when the tonehole is open, resonators can have an impact on the radiated sound. Input impedance measurements on an entire saxophone confirm that, when the holes are closed, pads without a resonator increase the damping, while the effect on open holes seems negligible. A perceptual study as well as in-vivo measurements are performed on four new alto saxophones of the same model (Yamaha YAS-480), the input impedances of which were found to be identical within the precision of the measurement setup. Two were kept in their original condition (provided with plastic resonators), while the other two were re-padded, one with metal resonators and one without resonators. In a first part of the study, 13 experienced musicians were asked to compare the saxophones on three criteria: *brightness*, *ease of play* and *evenness*. In a second part, musicians were asked to play an arpeggio while the pressure was recorded inside their mouth and at the bell of the saxophones. Results showed that the pad resonators increased the perceived *ease of play* and *brightness* of the saxophones. This is in agreement with a higher efficiency measured on saxophones with resonators as well as a higher harmonic spectral centroid in the radiated sound.

1 Introduction

Toneholes have an important role in the acoustics of woodwind instruments. When opened or closed, toneholes change the effective length of an instrument and allow musicians to play a wide range of different notes. As well, their position or geometric features can be adjusted during construction to modify the playing frequencies and the timbre of an instrument.

Toneholes can have a complex geometry (e.g. conical shape, undercutting) and involve several elements such as chimneys, keys, pads, and fingers. In his thesis, Lefebvre [14] gives a large overview of what is already known about toneholes and what remains to be investigated. The simple unflanged tonehole (i.e. a tonehole with a chimney that can be found in modern metal instruments such as concert flutes or saxophones) is now well described [8, 13, 14, 17]. This is also the case for the tonehole directly drilled in the wall (i.e. a tonehole without a chimney that can be found in many instruments made of wood, such as classical flutes or recorders) [6,14]. Moreover, Dickens [7] provides fit-formulae that match his experimental results for drilled holes that are closed. Dalmont et al. [6] give an analytical formula for keys positioned above a hole with a chimney that is valid for a range of key heights excluding very small values [9, 14, p. 80-85]. Some studies have been carried out on undercut holes [3, 5, p. 321] but no models are given.

An aspect that players find important, but which is not addressed by the studies cited above, is the influence of the material properties of the pad[1]. Indeed pads of different materials are used, some with flat disks made of metal or plastic affixed in the middle. These are called pad resonators by makers and musicians, a term that should not be taken literally in the acoustic sense of the word. The acoustic role of pad resonators has received little attention in the scientific literature, aside from previous work by the authors [10]. This paper investigates both the measured and perceptual behaviour of pad resonators on the saxophone, which is the instrument on which they were first introduced (likely due to their large hole sizes).

In order to evaluate the influence of pad resonators, measurements of the input impedance of a cylinder terminated by a key with interchangeable pads (with and without resonators) were performed. Open and closed situations were investigated. Then, four otherwise identical saxophones but with different pad resonator conditions were measured in order to quantify the influence of the different types of pads (with plastic resonator, metal resonator or without a resonator) on the impedance of the instrument. They were then used for a perceptual study and in-vivo measurements with musicians.

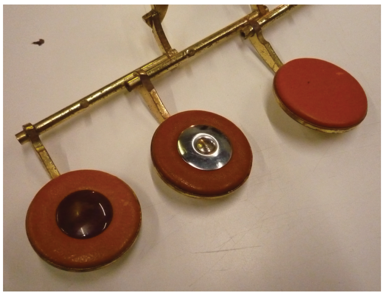

Figure 1: (Color online) Three kinds of pads: with a plastic resonator on the left, with a metal resonator in the middle, and without a resonator on the right.

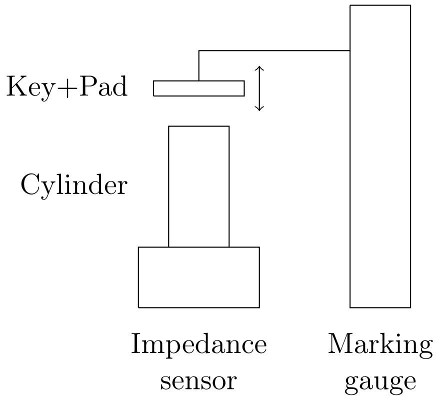

Figure 2: Technical sketch of the experimental protocol used for the measurements of the cylinder input impedance.

2 Acoustical influence of the pad at a pipe end

In order to investigate the role of a single pad, the input impedance of a pipe of diameter equal to that of a side hole and terminated by a key (which may or may not completely close the pipe end) was measured with the experimental set-up [20] developed jointly by the LAUM[2] and the CTTM[3]. This impedance sensor provides measurements with a relative error of ±3 cents [15]. All impedances reported throughout this paper are dimensionless (divided by the characteristic impedance $Z_c = \rho c/S$ with S the inner cross section of the pipe). The pipe was 100 mm long, with an inner radius of 12.8 mm and an external radius of 15 mm. Three identical keys of diameter 36 mm, provided with three different pads (see Figure 1) were measured:

[1] See for example: `http://bit.ly/1fR4b5S` or `http://bit.ly/1hbxh43`

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one with a plastic resonator, one with a metal resonator and one without a resonator. The pads are generally constructed of cardboard covered with leather. If they have a resonator, it is typically fixed at the middle with a rivet. A marking gauge was used to move the key, whose position is measured with a tenth of a millimetre precision. Closed and open situations with different heights were investigated. A sketch of the experimental setup is provided in Figure 2.

2.1 Closed tonehole

The input impedance of the pipe terminated with the three types of pads was measured, from which the absorption coefficient of each type of pad can be deduced. Figure 3 shows that the pads with resonator have a low absorption coefficient, circa 0.1, and that the pad without a resonator has a significantly higher absorption coefficient, circa 0.4. Moreover, Figure 3 shows some pad resonances. For the pad without a resonator, a first resonance with a low Q-factor appears around 1700 Hz and a second resonance with a larger Q-factor around 2500 Hz. Pads with resonators also present resonances, but they are shifted to higher frequencies. These results suggest that the input impedance of a saxophone might be significantly influenced by the presence or absence of a pad resonator. This issue is investigated in Section 3.1.

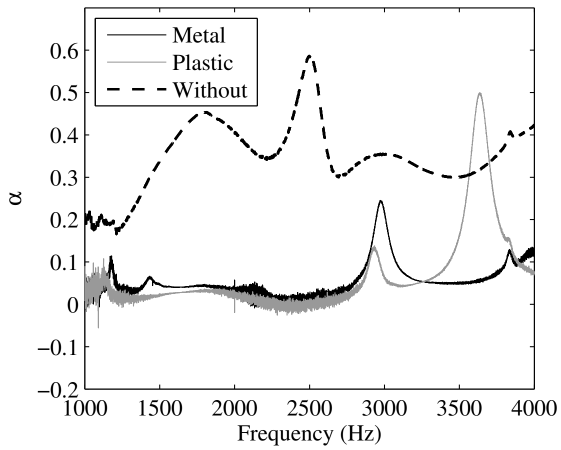
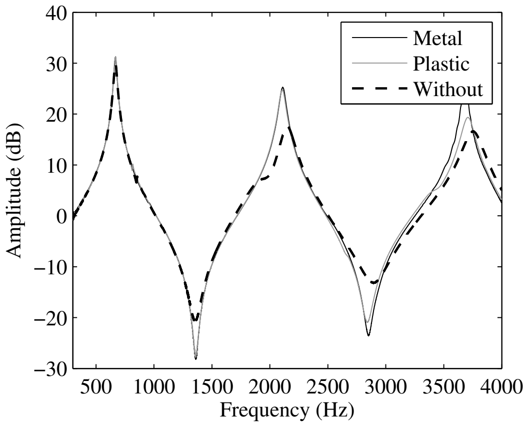


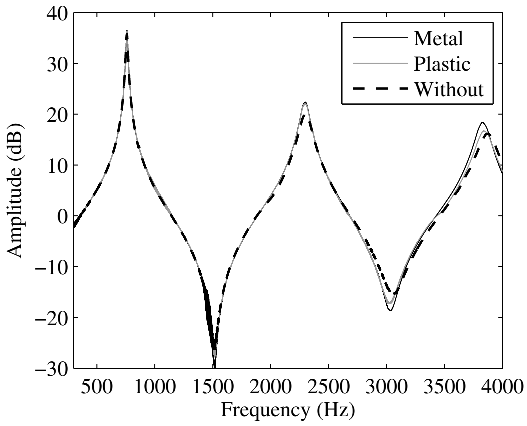
Figure 3: Absorption coefficient of the pads as a function of frequency. Pad with metal resonator (in black), with plastic resonator (in grey) and without a resonator (in black dashed line).

2.2 Open tonehole

When the key pad sits some distance away from the pipe end, the pad might also have an influence on the radiation impedance of the hole. Therefore,



(a) 1 mm



(b) 5 mm

Figure 4: Input impedance (dimensionless) of the pipe terminated by the three pads (pad with metal resonator in black, with plastic resonator in grey and without a resonator in black dashed line) at a height of (a) 1mm and (b) 5mm.

the input impedance of the pipe terminated by the pad was measured for different values of the distance between the pipe and the key. Figure 4 shows this impedance for the different pads and for two key heights: 1 and 5 mm. The effect of the pad is clearly visible when the key is close to the pipe end. Indeed, Figure 4 (a) shows that the second and third impedance peaks are damped for the pad without a resonator. This effect is also visible for the pad with a plastic resonator but only for the third peak. Furthermore, there is an abrupt dip in the impedance curve around 2000 Hz for the pad without a resonator which also appears for the pad with plastic resonator around 3500 Hz. In practice, a distance of 1 mm might only occur in a transitory state. The 5 mm case (Figure 4 (b)) corresponds more to the case where a key is at rest in an open state. In that case, the difference in the input impedance is much lower but it still might be detectable. These results suggest that the pads with plastic resonator and without a resonator have a resonant behaviour for some specific frequency ranges. The abrupt dips mentioned above appear to be caused by pad resonances, as deduced from mechanical vibration measurements reported in [10].

3 Effect on a complete saxophone

Now that we have highlighted the impact of the different pads on the input impedance of a tube, it is interesting to evaluate the influence of such pad resonators on an entire instrument, both for open and closed holes.

Four Yamaha model YAS-480 alto saxophones with consecutive serial numbers were used in this study. First, input impedance measurements were carried out in order to make sure that the four instruments could be considered as identical. Then, two saxophones (numbers 37 and 39) were kept in their original condition (provided with plastic resonators) while the pads of the other two were changed. Saxophone number 38 was reconditioned using pads without resonators and number 40 with metal resonators.

The effect of these different pads was investigated with measurements of the input impedance, a perceptual study and in-vivo measurements. A single neck from one of the saxophones was used for all reported measurements and the perceptual study. This helped minimize measurement discrepancies associated with slight variations of neck position on the impedance sensor, as well as avoided the need to move the mouthpiece during the perceptual study.

3.1 Input impedance measurements

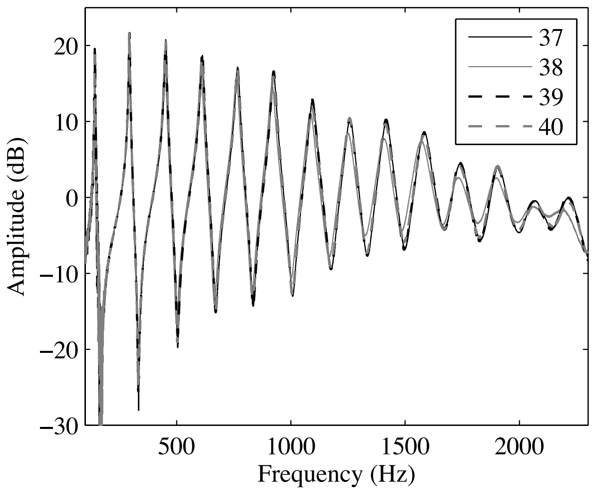


Figure 5: Comparison of the input impedance amplitude of the four saxophones for the fingering of B♭3 (all toneholes closed). 37 and 39 are the saxophones with plastic resonators (black continuous and dashed lines), 38 is the one without resonators (grey continuous line) and 40 the one with metal resonators (grey dashed line).

The input impedance of the four saxophones was measured for nine fingerings corresponding to the nine notes of the arpeggio that musicians were asked to play for the in-vivo measurements (see Figure 11).

A first session of impedance measurements was made on the four new saxophones provided with plastic resonators directly from the factory. We found that these saxophones were quite similar as the differences were less than 1 dB in amplitude and 5 cents in frequency, which is about the accuracy limits of the measurement system.

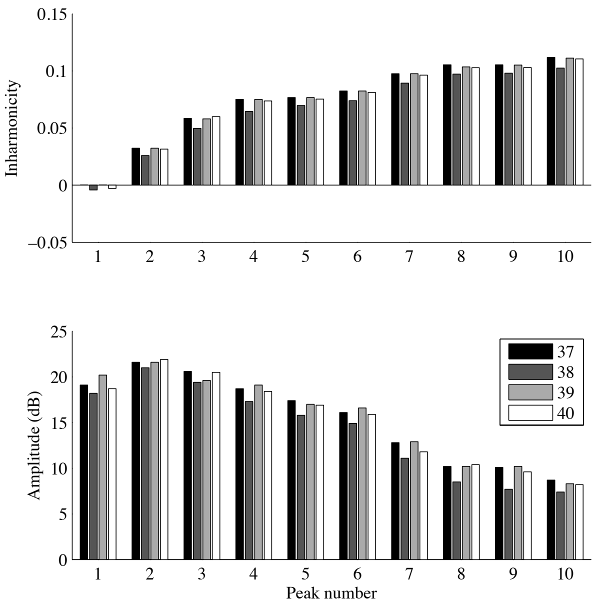
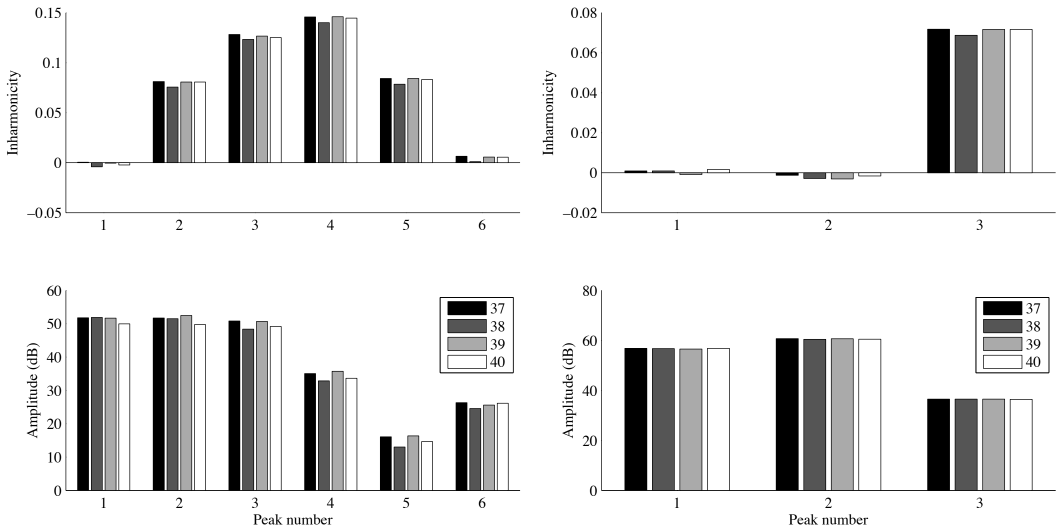


Figure 6: At the top, inharmonicity (with the fundamental frequency $f_0 =$ 142.4 Hz of saxophones 37 and 39 taken as reference) and at the bottom, amplitudes of the maxima of the 10 first input impedance peaks for the B♭3 fingering (all the holes closed) on the four saxophones.

Then, another set of measurements was carried out after the pads were changed. Figure 5 shows, for example, the comparison of the input impedance amplitude of the four saxophones for the fingering of B♭3 (all toneholes closed). By looking globally at this figure, the impedances of the four saxophones are very close, except at high frequencies for the saxophone 38, which is the saxophone without resonators. Figure 6 provides more detailed results by showing the inharmonicity and the amplitudes of the 10 first impedance peaks of Figure 5. The inharmonicity is defined as $(f_n - f_0)/nf_0$, where f_n is the frequency of the n^{th} peak and f_0 is the fundamental frequency of reference. We can see that saxophone 38 has resonance frequencies lower than the frequencies of the three other saxophones. The amplitude is also weaker by about 1 to 2 dB starting from the 4th peak.

Figure 7 (a) displays the inharmonicity and the amplitude of the first 6 input impedance peaks for the F4 fingering, where about half of the toneholes are closed. Here, the resonance frequencies of saxophone 38 are still lower than for the other saxophones, but the differences are less obvious than in Figure 6. In Figure 7 (b), the F6 fingering, in which case all but one of the



(a) F4 (b) F6

Figure 7: (a) At the top, inharmonicity (with the average fundamental frequency $f_0 = 218.1$ Hz of saxophones 37 and 39 taken as reference) and at the bottom, amplitudes of the maxima of the 6 first input impedance peaks for the F4 fingering (about half of the holes closed) on the four saxophones. (b) At the top, inharmonicity (with the average fundamental frequency $f_0 = 548.5$ Hz of saxophones 37 and 39 taken as reference) and at the bottom, amplitudes of the maxima of the 3 first input impedance peaks for the F6 fingering (all but one keys raised) on the four saxophones.

keys are raised, shows almost no differences. That proves that the pads have a cumulative impact over the number of closed holes.

3.2 Perceptual study

3.2.1 Participants

Thirteen skilled saxophone players took part in this experiment (1 female, 12 males; average age=30 years, standard deviation=8 years, range=22-48 years). They had at least 10 years of saxophone experience (average years of saxophone playing=17 years, standard deviation=7 years, range=10-35 years; average hours of saxophone practice per week=15 hours, standard deviation=10 hours, range=0-35 hours). They were paid for their participation. Five participants described themselves as professional musicians and six had higher-level degrees in music performance (MMus, MA, DMus, DMA). Nine were used to playing the alto saxophone, seven the tenor, four the baritone and four the soprano. Five normally played Yamaha saxophones, three normally played Selmer instruments, while the others normally played on

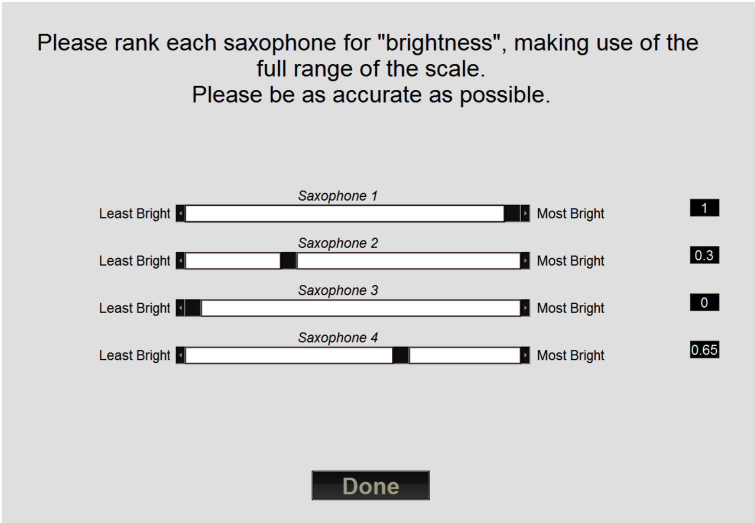


Figure 8: Matlab GUI used for the perceptual study.

different brands such as Keilworth, Phil Barone or Martin. They reported playing a wide range of musical styles: classical (60%), jazz (50%), contemporary (40%) or pop (20%).

3.2.2 Procedure

The experimental session lasted between 90 and 120 minutes and the experimenter was constantly present in the room to facilitate the procedure. First, participants were presented with the four saxophones previously described, randomly ordered on a table by the experimenter. They were asked to play all instruments for up to 15 minutes in order to familiarize themselves with the set. Then, for 10 minutes, the participants were asked to rate the *brightness* of the instruments, by using a Matlab GUI presented in Figure 8. The rating range was fixed between 0 and 1 with a step of 0.05 and the participants were obliged to use the whole scale, so they had to rate the saxophone they found the least bright at 0 and the most bright at 1. Then, they had to follow the same process and rate the *ease of playing* and the *evenness* (how similar is the timbre over the full range of the instrument) of the saxophones. Subsequently, in-vivo measurements were performed for about 20 minutes, after which the experimenter randomized the saxophones, and the participants were asked to repeat the rating of the saxophones.

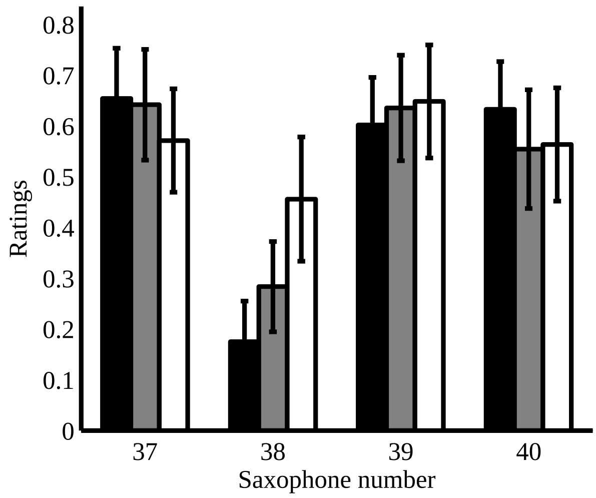


Figure 9: Average ratings of the *brightness* (in black), *ease of playing* (in grey) and *evenness* (in white) for the four saxophones. The error bars represent the standard error of the mean: $\sigma/\sqrt{n}$, where σ is the standard deviation of the data and n is the number of samples (13 here).

3.2.3 Results

Figure 9 presents the average of the two trials of ratings for the 13 participants[4]. It is clear that saxophone 38, which is the one without pad resonators, is perceived as the least *bright* and least *easy to play.* It is also rated as the least *even*, but the difference with the other saxophones is less obvious for this criterion. The three other saxophones have quite similar ratings, so it appears that participants did not find any significant difference in *brightness*, *ease of playing* and *evenness* between saxophones with plastic or metal resonators.

We performed a repeated-measures analysis of variance (ANOVA) to estimate the effect of two independent variables, saxophone (4) and repetition (2) on each of the three dependent variables (*brightness*, *ease of playing*, *evenness*) [4,22]. For effects with two or more degrees of freedom, Mauchly's test of sphericity was conducted [16]. No violations of sphericity assumptions were found for any condition.

The ANOVA was computed using SPSS[5]. The only significant results occur with the "saxophone" factor for the criteria *brightness* [$F(3,36)=8.08$, $p<0.001$] and *ease of play* [$F(3,33)=4.47$, $p=0.01$], indicating that there was a statistically significant variation of these two criteria across the saxophones.

In order to have more details on the impact of each saxophone, we com-

[4]There was a problem with the *Ease of Play* interface for the first participant, and so for that dependent variable there are only 12 participants

[5]`http://www-01.ibm.com/software/analytics/spss/`

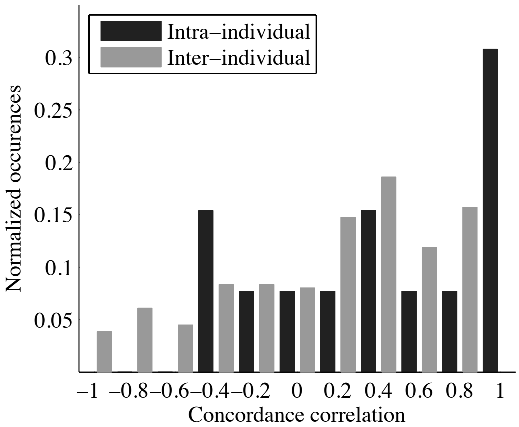
puted a paired-samples t-test [19, 23] to compare the ratings for the two significant criteria (*Brightness* and *Ease of play*) across the different saxophones. p-values obtained with this test are tested at the 5% significance level with the Holm-Bonferroni method [12]. For *brightness*, there were significant differences in the ratings of three saxophone pairs:

- saxophones 38 (M=0.175, SD=0.243) and 37 (M=0.654, SD=0.261); t(12)=3.955, p=0.002
- saxophones 38 and 39 (M=0.602, SD=0.243); t(12)=-4.002, p=0.002
- saxophones 38 and 40 (M=0.633, SD=0.235); t(12)=-4.217, p=0.001.

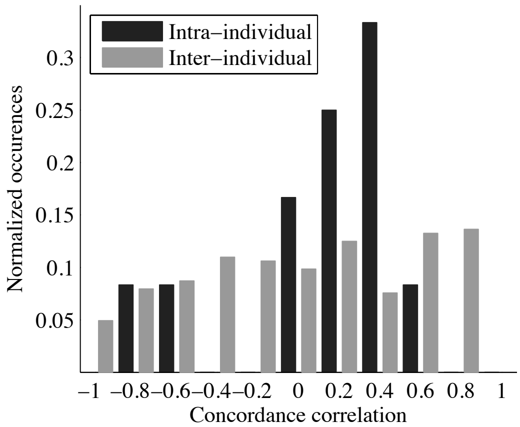
These results suggest that pads with no resonator have an impact on the perception of the *brightness* by the musicians. Specifically, when a saxophone does not have resonators, the sound is perceived as less *bright* than when it is provided with resonators. For the *ease of play*, there was a significant difference in the ratings of saxophone 38 (M=0.283, SD=0.235) and saxophone 37 (M=0.642, SD=0.147); t(11)=4.101, p=0.002. These results suggest that musicians found the saxophone without resonators more difficult to play than saxophone 37 with plastic resonators. Nevertheless, the differences in the *ease of play* for the other pairs were not significant. That suggests that the type of pad does not have a significant impact on the *ease of play* of the saxophone.

We also evaluated the consistency of the subjects using the concordance correlation between the ratings from the two trials. The Pearson's correlation matrix is a good way of studying the intra- and inter-individual consistency [21]. The Pearson's coefficients range from -1 to 1, where 1 corresponds to a perfect positive correlation, 0 is when there is no correlation and -1 is for a perfect negative correlation (which means that when a variable increases, the other decreases). The first step involved computing a 26x26 symmetric matrix of Pearson's coefficients between the ratings on each of the 2 trials for each of the 13 participants. One matrix is computed for each rated criteria: *brightness*, *ease of play* and *evenness*. Across the 325 cells of the lower triangular part of this correlation matrix, there are 312 correlations between trials from different participants and 13 correlations between trials from the same participant. The distributions of these correlations is shown in Figure 10. The intra-individual distribution is highly dependent on the rated criteria. Indeed, musicians were more consistent while rating the *brightness* (almost all the Pearson's coefficients are positive and a lot are equal to 1) than the two other criteria. The inter-individual correlation is also better for *brightness*. Moreover this figure shows that *evenness* was difficult to rate since participants were generally not consistent between themselves.

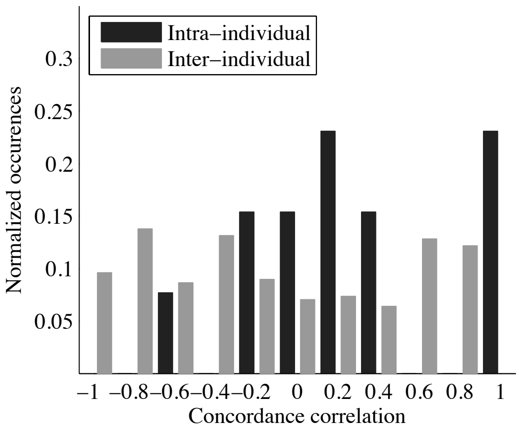
We tried to determine if some of the differences between the ratings could be explained by the level of practice of the instrument. Surprisingly, professionals (5 participants) were less repeatable than students (8 participants)



(a) *Brightness*



(b) *Ease of play*



(c) *Evenness*

Figure 10: Distribution of intra- and inter-individual concordance correlation coefficients, computed between all the ratings from the two trials from the same and different participants, respectively, for (a) *brightness*, (b) *ease of play* and (c) *evenness*. 1 corresponds to perfect consistency, 0 corresponds to no consistency and -1 corresponds to perfect anti-consistency (i.e., exactly opposite ratings given on different trials).

with an average intra-individual consistency on the three criteria of only 0.04 against 0.26. As well, the "weekly hours of practice" did not explain differences in intra-individual consistency because people playing less than 10 hours had an average of 0.19 while those playing more had an average of 0.16.

3.3 In-vivo measurements

Between the two rating sessions, the participants were asked to play the arpeggio given in Figure 11 using breath attack (not tonguing) at a mezzo forte dynamic.

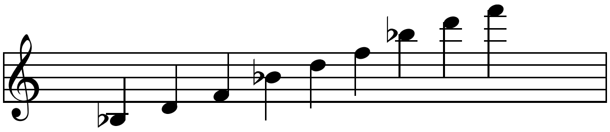


Figure 11: Arpeggio that participants were asked to play during the recordings.

(a)

(b)

Figure 12: (a) Differential pressure transducer Endevco 8507-C1 used to measure the static pressure in the mouth and (b) Microphone B&K 2669 located at 15 cm from the bell used to measure the radiated pressure.

The purpose of these measurements was to characterise the effect of the pads on the musician's playing parameters and on the radiated sound. The pressure in the musician's mouth and the radiated pressure at the bell were measured while the nine notes were being played on the four saxophones. These recordings were realised three times in order to get a meaningful average. Consequently we obtained, at the end of this study, 1080 observations to analyse (10 musicians * 4 saxophones * 9 notes * 3 repetitions)[6].

The pressure in the mouth was measured with an Endevco 8507-C1 differential pressure transducer. The radiated pressure at the bell was recorded with a B&K 2669 microphone located at approximately 15 cm from the bell,

[6]All 13 participants performed the same sequence of measurements but an incorrect transducer setting for the first 3 subjects prevented those results from being used in the analysis.

as shown in Figure 12. The data were collected using a National Instruments USB-4431 acquisition board, with a 44100 Hz sampling frequency. Figure 13 shows an example of the data collected while the musician was playing the arpeggio.

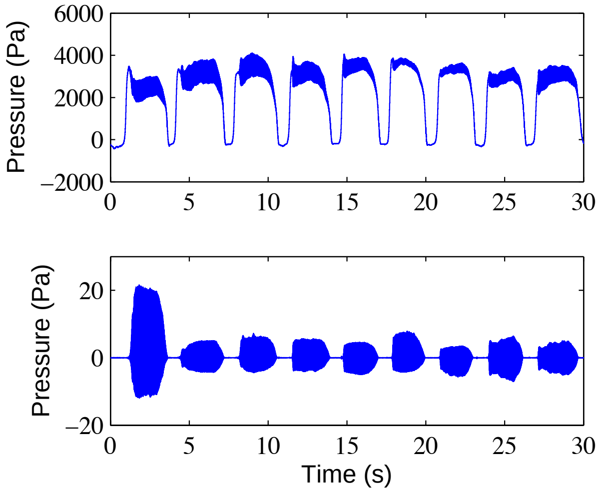


Figure 13: Example of the pressures recorded while the musician is playing the arpeggio: mouth pressure (top) and pressure at the bell (bottom).

Several physical descriptors characterising the timbre, the radiated sound and the musician's way of playing were chosen (as described in [1]). The following descriptors were calculated, as detailed in Appendix A, on the stationary part of the signal [11]:

- Harmonic Spectral Centroid (HSC)
- Tristimulus, 1st coefficient (TR1), which is the ratio between the fundamental component energy and the total energy
- Tristimulus, 2nd coefficient (TR2), which is the ratio between the energy of harmonics 2, 3, and 4 and the total energy
- Tristimulus, 3rd coefficient (TR3), which is the ratio between the energy of higher-order harmonics and the total energy
- Efficiency (E), which is the ratio between the average pressure at the bell and the mean mouth pressure (calculated on the stationary part)

and the others were computed on the transient:

- Attack Time (AT)
- Threshold Pressure (TP)

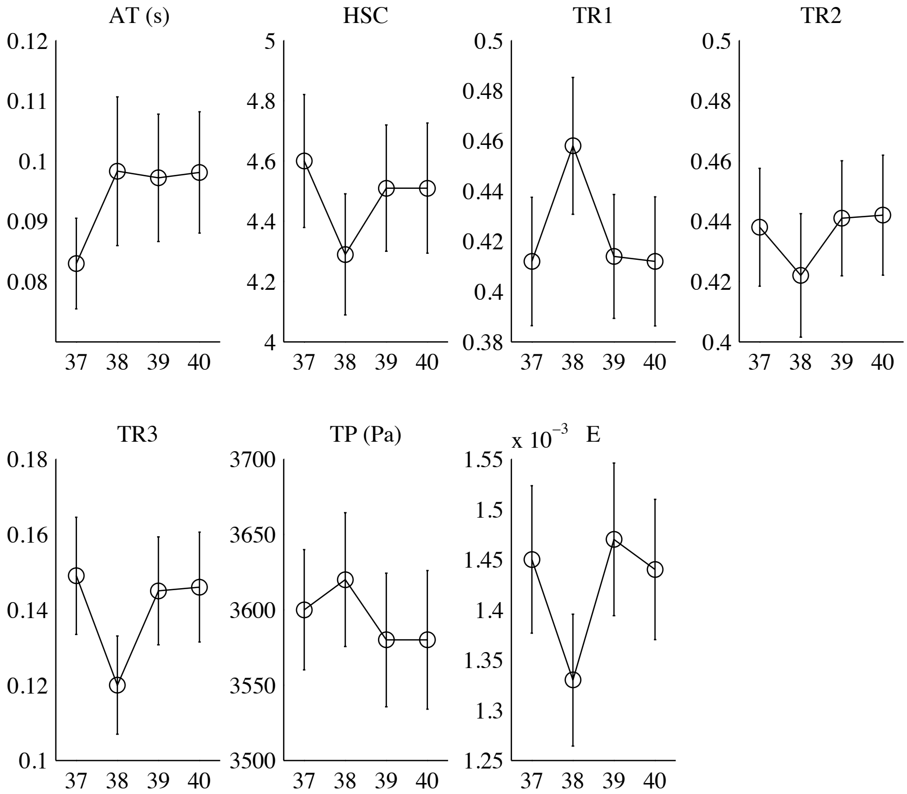


Figure 14: The mean and its standard error of the descriptors for each saxophone. The mean is calculated on 270 samples (10 musicians * 9 notes * 3 repetitions). All descriptors are dimensionless except AT which is given in seconds and TP which is given in Pa.

Figure 14 shows the mean and its standard error of all the descriptors for each saxophone. This figure first shows that the standard errors for the means are large because the average is calculated across all nine different notes tested. Indeed, the spectral content and the playing characteristics are very different from one note to another. The descriptors that are significantly impacted by the type of pad (in other words, descriptor values which are almost equal for the identical saxophones, 37 and 39, and are significantly different for at least one of the two other saxophones) are the Harmonic Spectral Centroid (HSC), and consequently the three Tristimulus coefficients (TR1, TR2 and TR3), and also the Efficiency (E). Pads without resonators have a lower HSC, a bigger TR1 and a smaller TR3: there are consequently more low frequencies and fewer higher harmonics in the spectral content of the radiated sound from a saxophone whose pads do not have resonators. The Threshold Pressure (TP) is a little higher for the saxophone without resonator, which means that, on average, the musician needs to blow a bit harder into that saxophone to get the reed to oscillate. The Attack Time (AT) is smaller for saxophone 37 than for the other three, which have almost identical AT values. This cannot be explained by the resonator type. This may be due to a small difference in the key adjustments.

By looking note by note at the Harmonic Spectral Centroid in Figure 15, we can see that the difference between the saxophone without pad resonators and the others can be mostly heard in the low register (B♭3, D4 and F4). In that register, the saxophone without pad resonators has a lower HSC than the saxophone with resonators (pads with metal or plastic resonators give essentially the same results). That correlates with a less *bright* ("darker") sound as rated by the musicians. For the higher register (B♭5, D6 and F6), the type of pads does not seem to have an impact on the radiated sound, which has almost the same spectral content for all the saxophones.

Finally, saxophones without resonators are less efficient than saxophones provided with metal or plastic resonators. This is in agreement with the perceptual study where the musicians rated the saxophone without pad resonators as the least easy to play. It is also consistent with the impedance measurements, where the impedance peak amplitudes were lower for the saxophone without pad resonators. We would intuitively expect that the efficiency of saxophone 38 would be more different from the saxophones with pad resonators for fingerings involving a lot of closed toneholes (like B♭3 or D4) and much closer for fingerings with a lot of open holes (B♭4, D6 or F6). In Figure 16, the efficiency of saxophone 38 for B♭3 is indeed much lower than for the other saxophones. Nevertheless, the difference is quite constant over all the played notes. The efficiency is in fact calculated with an average pressure level over the whole frequency range, measured at the bell of the saxophone. This measurement at the bell is less representative of the overall radiated sound as more and more side holes are opened, since significant energy radiates from the side holes.

4 Conclusion

The pad resonators have a measurable effect on the acoustical characteristics of the saxophone. Their main role is to stiffen the pad, so that the resonator might be called a "stiffener" or "reflector". The reflection coefficient is increased by the presence of a resonator when the tonehole is closed and the amplitudes of the saxophone input impedance peaks are consequently increased by several dB. The effect appears to be greater with more closed tone holes. It has been observed that pad vibrations can influence the acoustic radiation coming out of open toneholes. Nevertheless, this effect is small and is significant for small key heights only.

A perceptual study performed on 13 musicians shows that they find a saxophone without pad resonators less *bright* and less *easy to play*. Results

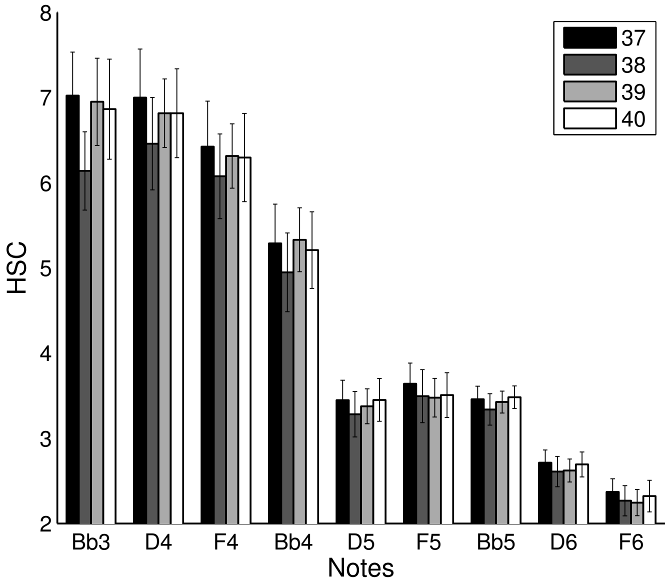


Figure 15: The mean and its standard error of the Harmonic Spectral Centroid for each note and each saxophone. The mean is calculated on 30 samples (10 musicians * 3 repetitions).

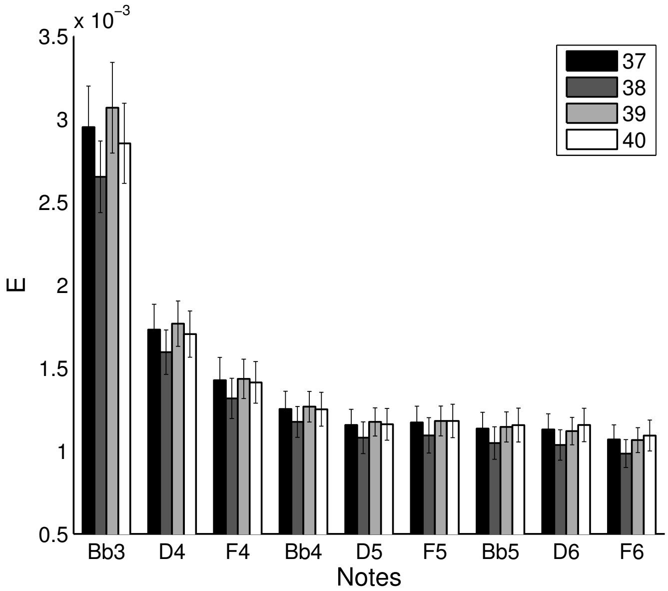


Figure 16: The mean and its standard error of the efficiency for each note and each saxophone. The mean is calculated on 30 samples (10 musicians * 3 repetitions).

for *evenness* are not significant enough to link the perception of *evenness* to a certain type of pad. Furthermore, there is no significant difference in ratings between the saxophone with metal resonators and those with plastic resonators for the three criteria. These results suggest that the absence of a resonator is perceived by the musician but that the material of the resonator does not affect the perceived *brightness*, *ease of play* or *evenness*.

The impact of the pad resonators can also be seen on the radiated sound of the instrument. Indeed, saxophones without resonators tend to have a spectrum with less higher harmonics than saxophones with resonators. This result seems in agreement with the musicians who perceived the saxophone without resonators as the least *bright* since the *brightness* is often linked to a high HSC. Moreover, measurements show that the pad resonators tend to increase the efficiency of the instrument. That is also in agreement with what the musicians perceived since they rated the saxophone with no resonators as the least *easy to play*. It is likely that the effect of the pad increases for instruments with larger pads (such as tenor or baritone saxophones), though this was not investigated in this study.

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A Description of the descriptors from Section 3.3

The estimation of the HSC is performed on the first 45 harmonics of the signal:

$$\mathrm{HSC} = \frac{1}{f_1} \frac{\sum_{k=1}^{45} A_k f_k}{\sum_{k=1}^{45} A_k}, \qquad (1)$$

where f_k is the frequency of the k^{th} harmonic and A_k the amplitude of this spectral component.

As only the stationary part of the signal is kept to compute this descriptor, the b_0 parameter, described in [2] which forces the descriptor to decrease at very low amplitudes when noise predominates, is not used here.

The descriptors TR1, TR2 and TR3 are estimated as follow:

$$\mathrm{TR1} = \frac{A_1^2}{\sum\limits_{k=1}^{45} A_k^2}, \quad \mathrm{TR2} = \frac{\sum\limits_{k=2}^{4} A_k^2}{\sum\limits_{k=1}^{45} A_k^2}, \quad \text{and} \quad \mathrm{TR3} = \frac{\sum\limits_{k=5}^{45} A_k^2}{\sum\limits_{k=1}^{45} A_k^2}. \tag{2}$$

The threshold pressure TP is found at the time where the acoustic pressure measured at the saxophone bell starts to show a periodic component at the fundamental frequency of the played note, this frequency being a priori known by analysing the whole signal over the note duration. In order to find this time t_p, the following detection function is used:

$$D = \frac{\sqrt{G^2 + H^2}}{\max\sqrt{G^2 + H^2}}, \quad \text{with} \tag{3}$$

$$G = \frac{1}{F_s} \sum_{i=0}^{N-1} p_a(t_i) \cos 2\pi f_1 t_i \tag{4}$$

$$H = \frac{1}{F_s} \sum_{i=0}^{N-1} p_a(t_i) \sin 2\pi f_1 t_i, \tag{5}$$

where p_a is the acoustic pressure, f_1 is the estimated fundamental frequency, F_s is the sampling frequency and N is the number of samples. The comparison between indicator $D(t)$ and a threshold value allows the threshold pressure time t_p of the note to be determined.

The Attack Time is given by $\mathrm{AT} = t_{ae} - t_{ab}$ where t_{ab} and t_{ae} are respectively the start and end of the attack times. They are defined, as described in [18], as the times at which the Root Mean Square (RMS) envelope reaches respectively 10% and 90% of its maximum value. For real signals, these parameters can be difficult to estimate because of the shape of the envelope which can be different from a monotonic increase.

References

[1] M. Barthet, P. Guillemain, R. Kronland-Martinet, and S. Ystad. From clarinet control to timbre perception. *Acta Acustica United with Acustica*, pages 678–689, 2010.

[2] J. W. Beauchamp. Synthesis by spectral amplitude and brightness matching of analyzed musical instrument tones. *J. Audio Eng. Soc.*, 1982.

[3] A. Chaigne and J. Kergomard. *Acoustique des instruments de musique.* Belin, 2008.

[4] R. Christensen. *Plane answers to complex questions: The theory of linear model.*, chapter Ch. 7. Multifactor Analysis of Variance, pages 156–195. Springer Texts in Statistics, Springer, 2002.

[5] M. Curtit, P. Bolton, and F. Masson. Accord d'un instrument à vent : quelques stratégies du facteur illustrées par une analyse de l'impédance d'entrée (in english: Tuning of a wind instrument: some makers' stategies illustrated by an input impedance analysis). In *Proceedings of the 10th Congrès Français d'Acoustique, Lyon*, 2010.

[6] J.-P. Dalmont, C. J. Nerderveen, and N. Joly. Radiation impedance of tubes with different flanges : numerical and experimental investigation. *J. Sound Vib.*, 244(3):505–534, 2001.

[7] P.A. Dickens. *Flute acoustics: measurement, modelling and design.* PhD thesis, School of Physics, University of New South Wales, 2007.

[8] V. Dubos, J. Kergomard, A. Khettabi, J.-P. Dalmont, D. H. Keefe, and C. J. Nederveen. Theory of sound propagation in a duct with a branched tube using modal decomposition. *Acustica*, 85:153–169, 1999.

[9] P. Eveno. *L'impédance d'entrée pour l'aide à la facture des instruments de musique à vent : mesures, modèles et lien avec les fréquences de jeu (The input impedance for the support of the musical instruments making: measurements, models and link with the playing frequencies).* PhD thesis, Univ. Pierre et Marie Curie (Paris VI), 2012.

[10] P. Eveno, M. Curtit, J.-P. Dalmont, and R. Caussé. Influence of pad "resonators" on saxophone. In *Proceedings of SMAC 2013, Stockholm, Sweden.*

[11] B. Gazengel and J.-P. Dalmont. Mechanical response characterization of saxophone reeds. In *Proceedings of Forum Acusticum 2011, Aalborg, Denmark.*

[12] S. Holm. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, 6(2):65–70, 1979.

[13] D. Keefe. Theory of the single woodwind tonehole. *J. Acoust. Soc. Am.*, 72(3):676–687, 1982.

[14] A. Lefebvre. *Computational Acoustic Methods for the Design of Woodwind Instruments.* PhD thesis, Computational Acoustic Modeling Laboratory, McGill University, Montreal, Quebec, Canada, 2010.

[15] C. A. Macaluso and J.-P. Dalmont. Trumpet with near-perfect harmonicity: design and acoustic results. *J. Acoust. Soc. Am.*, 129(1):404–414, 2011.

[16] J.W. Mauchly. Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics*, 11(2):204?209, 1940.

[17] C. J. Nederveen, J. K. M. Jansen, and R.R. van Hassel. Corrections for woodwind tone-hole calculations. *Acustica*, 84:957–966, 1998.

[18] G. Peeters. A large set of audio features for sound description (similarity and description) in the cuidado project. Technical report, Ircam, 2004.

[19] J. Rice. *Mathematical Statistics and Data Analysis.* Third Edition, Duxbury Advanced, 2006.

[20] J.-C. Le Roux, J.-P. Dalmont, and B. Gazengel. A new impedance tube for large frequency band measurement of absorbing materials. *Proceedings of Acoustics'08*, 2008.

[21] C. Saitis, B. Giordano, C. Fritz, and G. Scavone. Perceptual evaluation of violins: A quantitative analysis of preference judgments by experienced players. *J. Acoust. Soc. Am.*, 132:4002–4012, 2012.

[22] H. Scheffé. *The Analysis of Variance.* New York: Wiley, 1959.

[23] D.W. Zimmerman. A note on interpretation of the paired-samples t test. *Journal of Educational and Behavioral Statistics*, 22(3):349–360, 1997.