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Objective characterization of saxophone mouthpiece playability

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Abstract

In single-reed instruments, the mouthpiece and reed have an essential effect on instrument playability, since they largely determine the range of lip force and blowing pressure required to produce notes. This paper quantitatively examines the effect of three different mouthpiece designs (Selmer S80, Concept, and Spirit) on the range of lip force and blowing pressure combinations in which tone can be produced on the alto saxophone for notes ranging from D3 to D5. Average lip force, blowing pressure, loudness, and tuning are investigated as functions of notes and for three different reed strengths. Characteristics such as lip-force/blowing-pressure playability area (total playability area, TPA) and correctly tuned playability area (CTPA) are determined for different reed strengths and note values, and change of tuning as a function of notes is investigated. Apparent differences were observed between mouthpieces of different designs and even between mouthpieces with extremely similar tip openings. The Spirit mouthpiece is louder but requires higher lip force and more adaptation of lip force and of blowing pressure over note ranges. The Concept, with a remarkably similar tip opening and facing length as the S80, allows for a smoother transition between the low and high registers of the instrument and has better tuning stability. The new parameters <TPA> and <CTPA> are introduced as summarizing indicators of mouthpiece characteristics, averaged over note range and reed strength range. Such parameters can be used to define mouthpiece playability objectively and can form important input for parameter-based design improvement or customization.

1. Introduction

Wind instrument sound results from self-sustaining airflow-driven oscillations. In the case of reed instruments, the reed acts as a valve that modulates the flow (Fabre et al., 2011; Fletcher, 1979; Fletcher and Rossing, 1998; Hirschberg et al., 1991; McIntyre et al., 1983; Van Zon et al., 1990). The reed is placed on a mouthpiece so that a small slit remains between the tip of the reed and the tip of the mouthpiece. Many different mouthpiece designs exist, mainly characterized by tip opening, facing, and internal shape (Lorenzoni et al., 2013; Lorenzoni and Ragni, 2012; Ozdemir et al., 2021). The tip opening is the distance, in the direction perpendicular to the reed backplane, between the tip of the reed and the tip of the mouthpiece. The facing length is the distance along the mouthpiece over which a separation exists between the reed and the top surface of the mouthpiece when the reed is mounted on the mouthpiece. When lip force is applied, the reed bends towards the mouthpiece so that the facing opening closes, except near the tip where the reed remains free to vibrate. The number of different mouthpiece designs for the saxophone is especially large, as the instrument is typically used in various music genres, ranging from classical to pop and jazz. The mouthpiece design has major implications both on instrument playability and timbre, and, until recently, mouthpiece characteristics were mainly described in subjective, lyric terms.

Playability and timbre are also influenced by the stiffness and shape of the reed, characterized by strength and cut. Reed strength is indicated by numbers and is linked mainly to the stiffness and thickness of the tip of the reed. Several studies have focused on objective and subjective characterization of reed quality (Gazengel et al., 2012, 2016; Munoz and Gazengel, 2014).

For a single mouthpiece and reed strength, it has been shown that the lip and blowing pressure play a significant role in triggering quasi-periodic vibration (Doc and Vergez, 2015). An instrumented mouthpiece was developed to measure the embouchure parameters (mouth pressure, mouthpiece pressure, and lip force) as musicians play (Guillemain et al., 2010). Dalmont et al. studied the influence of the embouchure parameters on the intonation for one mouthpiece–reed combination (Dalmont et al., 2012). They showed that lip force, related to reed opening, can significantly influence playing frequency. An artificial mouth with adjustable lips was constructed to study the embouchure of a bassoon to gain insight into the instrument's functioning in terms of correct tuning (Grothe, 2012). The blowing-pressure ranges of human players were measured for different instruments (Fuks and Sundberg, 1999). In that study, the saxophone's blowing pressure ranges were measured for two professional saxophonists, using different instruments, reeds, and mouthpieces.

For the single-reed instrument, such as the saxophone, the geometric design of the mouthpiece, in combination with the reed, has a considerable influence on timbre as well as on instrument playability. Both aspects have been studied, but little objective quantification exists. Lorenzoni et al. used a professional saxophone player to evaluate 11 modified 3D-printed mouthpieces (Lorenzoni et al., 2013). The work focused on the acoustic properties of mouthpieces and showed relationships between the aerodynamics of flow and geometrical modifications in the mouthpiece. Another study (Doubrovski et al., 2012) performed an experimental acoustic investigation on 3D-printed saxophone mouthpieces. Different changes were made in the chamber of an existing mouthpiece, and professional saxophonists evaluated the effects. Details on the assessment protocol were not given. None of the changed mouthpieces was favored above the participants' original mouthpieces, and no consistent findings were observed between musicians. A possible reason was that the musicians used their own reeds. Carral et al. conducted a study with human players on internal mouthpiece geometry modifications through sound and pressure measurements (Carral et al., 2015). The tests were performed by playing the C major scale from C4 to C6. An effort ratio was defined as the mouth pressure divided by the radiated sound pressure level. Differences between different mouthpiece designs were observed, but results were limited to one blowing pressure. Holding a constant blowing pressure is challenging for human players, and lip force was not measured.

A recent study investigated the link between mouthpiece design parameters and their playing characteristics in terms of resistance, loudness, brightness, and flexibility (Ozdemir et al., 2021). Flexibility was investigated using a combination of artificial blowing and results obtained with a single player. For playability, the onset of vibration and loudness were quantitatively measured using a pressure-controlled blowing machine. Only the neck of the saxophone was used, so results were limited to a single frequency of 410 Hz, and the range of blowing pressures in which sound can be produced was not investigated.

The entire playing range of different types of mouthpieces with different reed combinations has not yet been mapped quantitatively. No protocol exists for assessing playability ranges of saxophone mouthpieces. The aim of the current paper is to establish a well-defined quantitative protocol to test mouthpiece playability range and tuning and to define objective parameters to describe such characteristics. The method and its results will be demonstrated on three mouthpieces.

2. Methodology

The measurement method is based on the methodology used in a previous study (Ukshini and Dirckx, 2022). We will briefly describe its main features below.

Synthetic reeds (type “Signature,” Légère Reeds, Barrie, Ontario, Canada) with a stiffness of 2.00, 2.75, and 3.50 were used. These reeds consist of polyethylene fibers and have anisotropic material parameters as is the case in natural cane reeds but without the problem of humidity dependence. Fiber distribution and elasticity are far more homogeneous than in natural cane, leading to less inter-specimen variability and better measurements reproducibility. Using synthetic reeds avoids dehydration problems and differences in behavior between specimens (Casadonte, Donald Jay, 1995; Obataya and Norimoto, 1999). For beginning musicians, a reed strength of 2.00 is typically used. More advanced players generally use higher strengths in classical playing. The majority of alto saxophone reeds sold by Légère Reeds have strengths between 2.00 and 3.50.

Measurements were performed on three different mouthpieces (Henri Selmer, Paris, France): a standard beginner mouthpiece (S80 C*), a more recently designed mouthpiece aimed at classical music (Concept), and a mouthpiece aimed at jazz music (Spirit). To measure mouthpiece geometry, we performed X-ray tomography with a pixel resolution of 45 micrometers. Figure 1 shows a schematic representation of the central sagittal cross section obtained from these data. The gray line indicates the level of the reed backplane for the reed in rest position. For all three mouthpieces, the bore is cylindrical, since it needs to fit over the saxophone neck, except at the throat: the transition zone from the bore to the chamber. For the Concept and Spirit mouthpieces, the throat has a cylindrical shape, but the S80 has a rectangular shape. The main internal design parameters of a saxophone mouthpiece are the shape of the internal chamber and the height of the baffle. The main external shape aspects are the tip opening, the lay profile, and the facing length (the part where the mouthpiece's upper surface bends away from the reed). Simulations have shown that baffle height and tip opening influence the aerodynamics of the airstream passing along the bottom side of the reed (Da Silva et al., 2007, 2013). These simulations were done without acoustic feedback but showed that geometry substantially affects the hydrodynamic behavior of the mouthpiece and hence reed vibration. The S80 and Concept have extremely similar tip openings (1.55 mm and 1.47 mm respectively) and facing lengths (24 mm for both). The difference between the two mouthpieces is limited mainly to chamber shape and baffle height. The Spirit mouthpiece has a facing length of 27 mm, and a significantly larger tip opening of 2.1 mm, which is typical of mouthpieces designed for jazz performances.

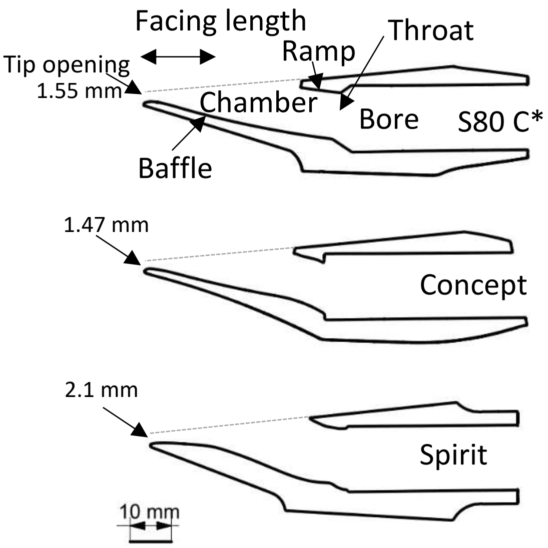


Figure 1: Sagittal sections for the three evaluated mouthpieces. From top to bottom: S80 C*, Concept, Spirit. The gray lines indicate the levels of the reed backplanes for the reeds in rest position.

A new reed was used for each mouthpiece, and reeds were preconditioned by playing a note on average loudness for 20 hours before starting actual measurements. In a separate preparatory experiment, the effect of reed behavior as a function of playing time was investigated. Reeds were set to continuously vibrate under 4 N lip force and 4 kPa blowing pressure, and measurements of playability range and loudness were performed after subsequent one-hour time lapses. The results showed relatively significant changes during the first hours of playing, but after 20 hours, behavior stabilized. Over the measurement time, the behavior remained sufficiently constant to obtain reproducible measurements.

The mouthpiece, with the reed mounted onto it, sits in a pressurized transparent square box with outer sides of 20 cm. An artificial lip is pressed against the reed, using a motorized stage. The lip is made of soft silicone rubber (Shore ≈ 0) and has an even thickness of 10 mm. It has an arc-like front, so that the free-vibrating part of the lip has an oval shape. The lip has a straight backplane that rests on the reed; in the center, it has a length of 10 mm. The shape of the lip was based on lip prints taken from several players.

Further details and a photo of the lip are shown in a previous paper (Ukshini and Dirckx, 2021). The force exerted on the lip is measured with a load cell (Honeywell FSS1500NSR). The lip can be positioned at various positions on the reed by a vertical translation stage, so that tests can be performed for different lip positions (details below).

A computer controls the air pressure in the box through a set of electromagnetically driven valves and a feedback regulation circuit. A pressure transducer (SCX 01, SenSym ICT) and a flow meter (Honeywell Zephyr HAF series) register the blowing pressure and airflow going to the box. The mouthpiece sits on the neck of a Selmer alto saxophone. The saxophone neck passes through the wall of the box with an airtight seal, so the rest of the instrument body is in ambient air. Since the instrument is designed to operate with the player's exhaled air and tuning is highly temperature-dependent, the air flowing through the mouthpiece is conditioned at 35°C. The mouthpiece was positioned on the saxophone neck so that after warming the instrument, the note F# (transposed notation) was precisely tuned to 440 Hz measured at medium blowing pressure and lip force. Sound pressure generated by the instrument was measured using a microphone (Bruel and Kjaer Type 2669, Denmark) positioned in front of the instrument bell at a distance of 15 cm. The entire setup was situated in a soundproof booth (volume 8 cubic meters) with reverberation-damping walls. Computer-controlled electromagnets actuate the instrument's valves, so that the entire measurement cycle is fully automated.

For each measurement cycle, blowing pressure was increased from 0 Pa to 8 kPa in steps of 0.2 kPa. This measurement was repeated for different lip forces. Lip force was increased from 1 N to 15 N in steps of 1N. At each step, actual lip force was measured. The airflow into the mouthpiece and sound pressure in front of the bell were measured. A digital flow meter was used to monitor the airflow into the artificial mouth. Values will be reported as Liters Per Minute (LPM), measured at actual blowing pressure. As the pressure in the artificial mouth can be up to 8 kPa, or 8 % higher than ambient pressure, values in Standard Liters per Minute (SLPM) would be slightly greater. At each pressure step, pressure was held constant for 3 seconds. The pressure regulation system takes about 1s to settle to a stable value, so only the final two seconds of each pressure step were used for data processing. The measurement cycle was repeated for musical notes D3, F#3, A3, C#4, D4, F#4, A4, and D5 (in the transposed notation for the alto saxophone, the instrument sound a major six lower than written). This measurement sequence was repeated for four different lip positions, leaving a distance of 10, 9, 8, and 7 mm between the reed tip and the line where the lip first touches the reed. These positions will be referred to as Positions 1, 2, 3, and 4.

3. Results and discussion

3.1. Playability area

Figure 2 shows the measurement results obtained for note A3 on the three mouthpieces for lip position 1. The rows provide results for the three mouthpieces; columns correspond to the different reed strengths. Sound pressure as a function of lip force and blowing pressure is shown. The note is easy to play, and an extensive range of lip forces and blowing pressures is found at which the note can be produced. Measurement points for which the tone is produced with a pitch that deviates more than 15 cents from correct tuning are indicated in semi-transparent color. In a previous paper (Ukshini and Dirckx, 2022), the surface area of all pressure and lip force combinations at which tone is produced, expressed in N.kPa, was called the total playability area (TPA). The area in which tuning within an interval of [-15, +15] cents is obtained is called the Correctly Tuned Playability Area (CTPA) (Ukshini and Dirckx, 2022). From similar graphs as those shown in Figure 2, the TPA and CTPA can be calculated for all notes, lip positions, and lip forces, and the ranges and averages of parameters such as loudness, lip force, and blowing pressure for points within the TPA and CTPA can be determined.

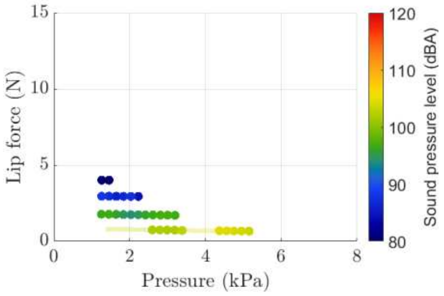
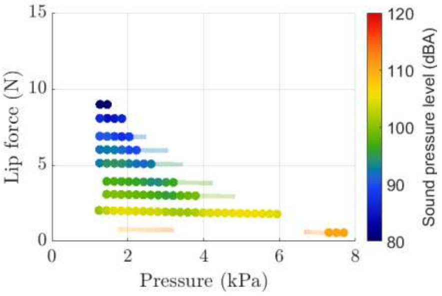
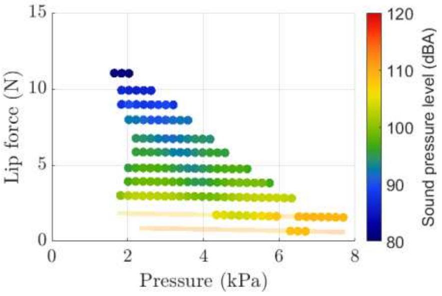
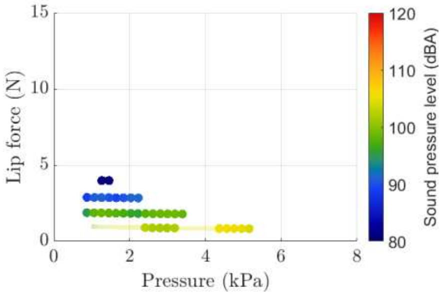
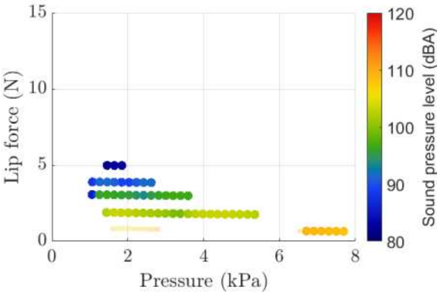
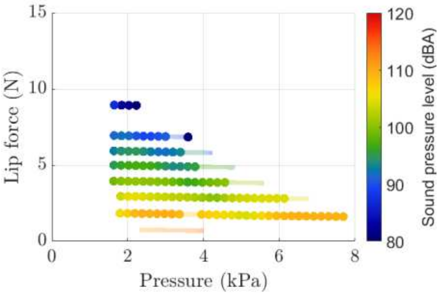
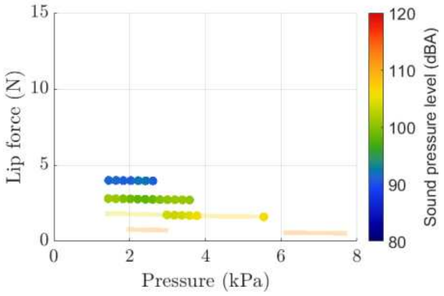
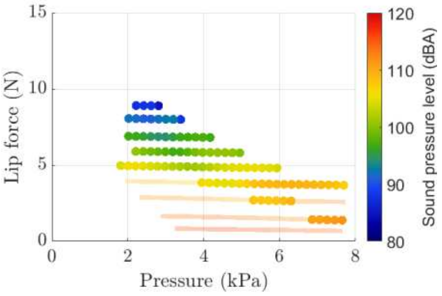
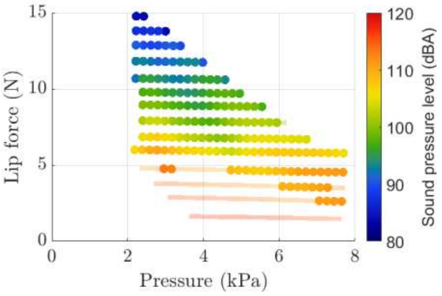
Pos.1 A3	**2.00**	**2.75**	**3.50**
S80			
Concept			
Spirit			

Figure 2: Sound pressure level as a function of lip force and blowing pressure for note A3. The colored dots indicate the region where the fingered note is heard. Different dot transparency distinguishes between the total playability range and the correct tuning range (tuning within [-15, +15] cents). Each colored dot with full opacity represents a measurement with correct tuning. The color of each dot indicates the corresponding SPL. Semi-transparent dots represent measurement points where the note is produced with a pitch deviation of more than 15 cents.

Figure 2 shows that the playability range is influenced mainly by reed strength rather than mouthpiece type. For a stiffer reed, the total playability area increases. Furthermore, it can be noticed that, for the same lip force, loudness increases as a function of reed strength. The median loudness at a lip force of 2 N for the Concept mouthpiece is 98 dB(A), 103 dB(A), and 109 dB(A) for the three reed strengths respectively. As reed strength increases, the useful range of lip force also increases. For the weakest reed, a slight difference in lip strength can make a substantial difference in loudness. Loudness as a function of lip force is much more stable for a stiffer reed. For most mouthpiece–reed combinations, sound can be produced, starting from the smallest measured lip force (1 N). For this lip force, the sound produced does not fall into the 15-cent interval of correct tuning. For the Spirit mouthpiece, this is most noticeable.

Compared with the entire range of blowing pressures, the minimum blowing pressure to initiate oscillation (without considering the correct pitch) differs little between mouthpieces. The Concept mouthpiece requires a smaller blowing pressure compared with the other two mouthpieces. For a reed strength of 2.00 at a lip force of 2 N, the minimal blowing pressure is 1.3 kPa, 0.9 kPa, and 1.4 kPa for the S80, Concept, and Spirit mouthpiece respectively. Lip force strongly influences the extinction threshold. For the S80 mouthpiece with a 3.50 reed, the extinction threshold decreases from 7.7 kPa to 2.0 kPa with increasing lip force.

The results of airflow for different blowing pressures and lip forces are shown in Figure 3. The rows show the different mouthpieces. For most reed–mouthpiece combinations, the airflow is less than 10 liters per minute (LPM) for measurement points inside the CTPA. The typical negative resistance of the reed is observed: as blowing pressure increases, the reed moves closer to the mouthpiece, and airflow decreases even though pressure increases. Further, Figure 3 shows a clear trend of increasing airflow as a function of reed strength, and airflow differs strongly between the jazz mouthpiece and the two classical mouthpieces. For example, the airflow measured at a lip force of 4 N and a reed strength of 3.50 is 7 LPM for the S80 and Concept mouthpieces, but it is 18 LPM for the Spirit mouthpiece. The airflow for the S80 mouthpiece at a lip force of 3N and for the smallest pressure value at which the reed vibrates is 1 LPM, 5 LPM, and 10 LPM for the three different reed strengths (ranging from weak to stiff). The maximum airflow measured on the S80, Concept, and Spirit mouthpieces (without considering correct tuning) is 20 LPM, 21 LPM, and 36 LPM for the stiffest reed. For measurement points inside the CTPA, the maximum airflow is 12 LPM, 15 LPM, and 18 LPM for the S80, Concept, and Spirit mouthpieces.

Légère reeds, with a strength of 2.00, are extremely soft, and the graphs show that the TPA is relatively small on all three mouthpieces and for all notes. The loudest producible sound with a 2.00-strength reed is limited to about 111 dB(A) for the classical mouthpieces and 116 dB(A) for the jazz mouthpiece. For the stronger reeds, maximal sound pressure is approximately 6 dB higher for the classical mouthpieces. On the Spirit mouthpiece, maximal sound pressure can be as high as 120 dB(A), using the stronger reeds. The lowest obtainable sound pressure level on S80 and Concept mouthpieces is approximately 76 dB(A) for all reed strengths and a correctly tuned note.

With a reed strength of 2.00, it is possible to play in tune starting from an extremely low lip force. A less stiff reed also makes it easier to vary between piano and forte playing. Initial blowing pressure differs relatively little between reed strengths.

The shape of the contour of the playability area is a good indicator of the difference between mouthpieces. For the 2.75 and 3.50 reeds, the lip force range and the maximum pressure at a given lip force can differ between the two classic mouthpieces. Figure 2 also shows that, for different reed–mouthpiece combinations, the sound was produced, starting from the smallest measured lip force of 1 N. For the softest reed, these measurement points fall in the range of the CTPA. On the other hand, lower lip force produces a sound outside the area of correct tuning for a stiffer reed. Other authors have also observed this for lip force on the clarinet (Almeida et al., 2013).

The minimum airflow required to produce sound is higher for a stiffer reed than for a less stiff reed. Figure 3 shows how flow depends on lip force and blowing pressure. For all mouthpieces and reed strengths, the flow for measurement points within the CTPA range lies between 1 and 18 LPM. Out-of-tune playing occurs when high flows are used. This occurs mainly on the Spirit mouthpiece with a harder reed. It should be noted that this by no means should be interpreted as a lack of mouthpiece quality. Especially in jazz playing, bending the note pitch can be desirable. The results show that the Spirit mouthpiece performs best in allowing this pitch bending, but only at higher sound pressures.

Finally, it should be highlighted that the acoustic impedance of the artificial mouth is different from the human mouth. To some extent, the acoustic impedance of the mouth may influence minimum blowing pressure and tuning, so that the measured playability clouds may be somewhat different from the clouds obtained in an actual player.

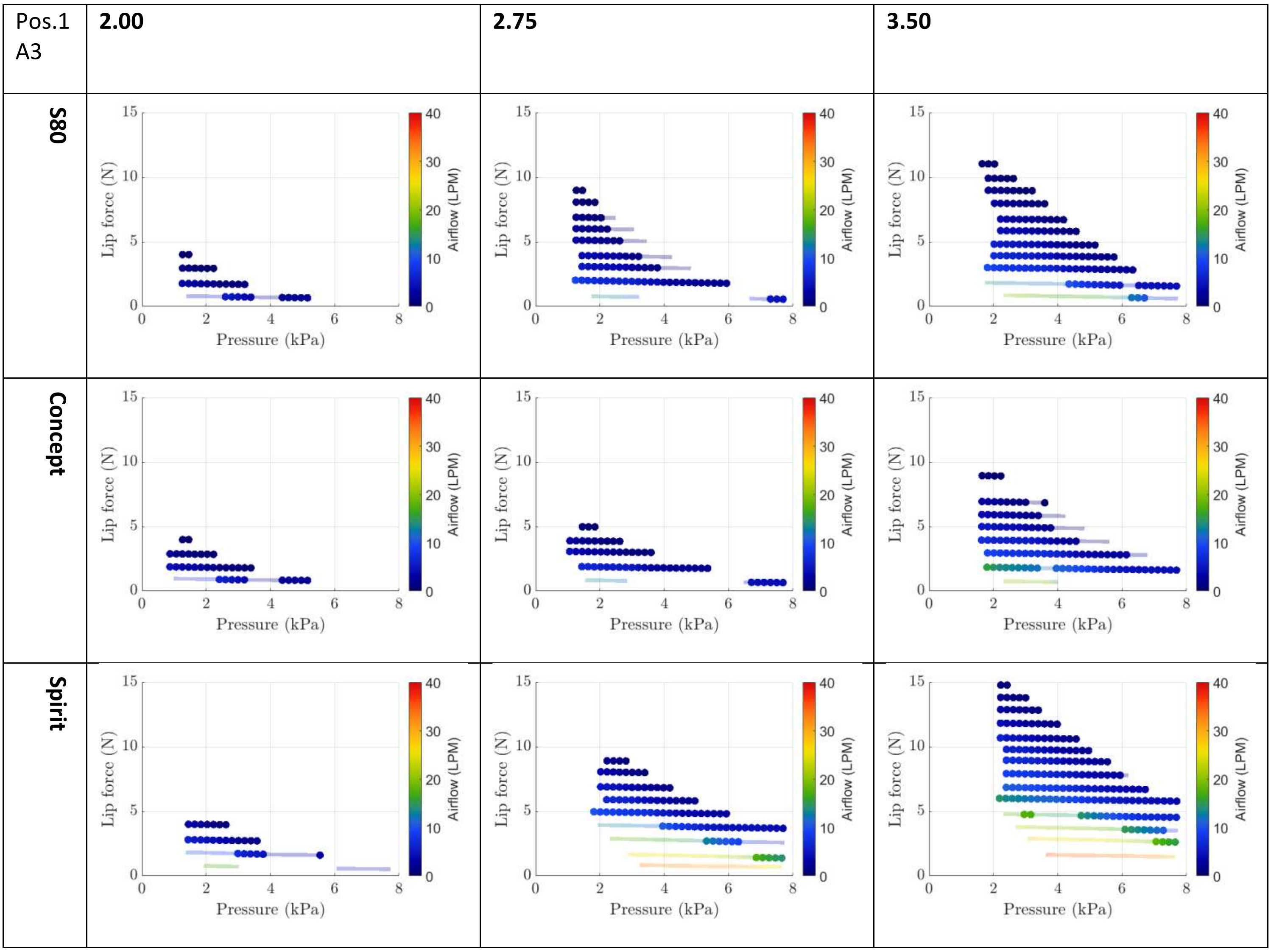


Figure 3: Airflow as a function of lip force and blowing pressure for note A3. The total area shows the region where the fingered note is correctly heard. Different transparency makes a distinction between the total playability range and the acceptable tuning range of [-15,+15 cents]. Each colored dot with full opacity represents a measurement with correct tuning. The color of each dot shows the corresponding airflow. Semi-transparent dots represent measurement points where the note is produced with a pitch deviation of more than 15 cents

3.2. *TPA & CTPA of C#4 and D4*

On the alto saxophone, C#4 is a rather difficult note to produce with good tone quality. Figure 4 shows, for all three mouthpieces, the tuning deviation for this note as a function of lip force and blowing pressure (again for lip position 1). The color scale is now used to indicate pitch deviations within an interval of -30 to +30 cents. For the softest reed, the note is flat on nearly all measurement points. A pitch deviation of more than 80 cents was measured for the lowest measured lip forces. When lip force is high enough, C#4 is approximately 20 cents lower than C#4 on the equal-tempered scale for a reed strength of 2.00. For the stronger reeds, the situation improves, but parts in the center of the playability area are mistuned for more than 15 cents. For the S80 mouthpiece and a reed strength of 3.50, the pitch deviation of the middle part of the TPA is not above 20 cents.

For the Concept mouthpiece, pitch deviation is less than 10 cents. For D4, the first note in the upper register where the octave key is used, the situation is the opposite: the note is sharp for nearly all combinations of lip force and blowing pressure for lip position 1. Only at low lip force, D4 is occasionally in tune for certain reed–mouthpiece combinations.

The results revealed no significant difference in the maximum pitch deviation for different reed strengths. The analysis also did not show significant differences in maximum pitch deviation between the different mouthpieces. For all reed–mouthpiece combinations, D4 is approximately 30–40 cents sharper compared with D4 of the equal-tempered scale. This indicates that this mistuning effect is an aspect of the instrument itself, not of the mouthpiece.

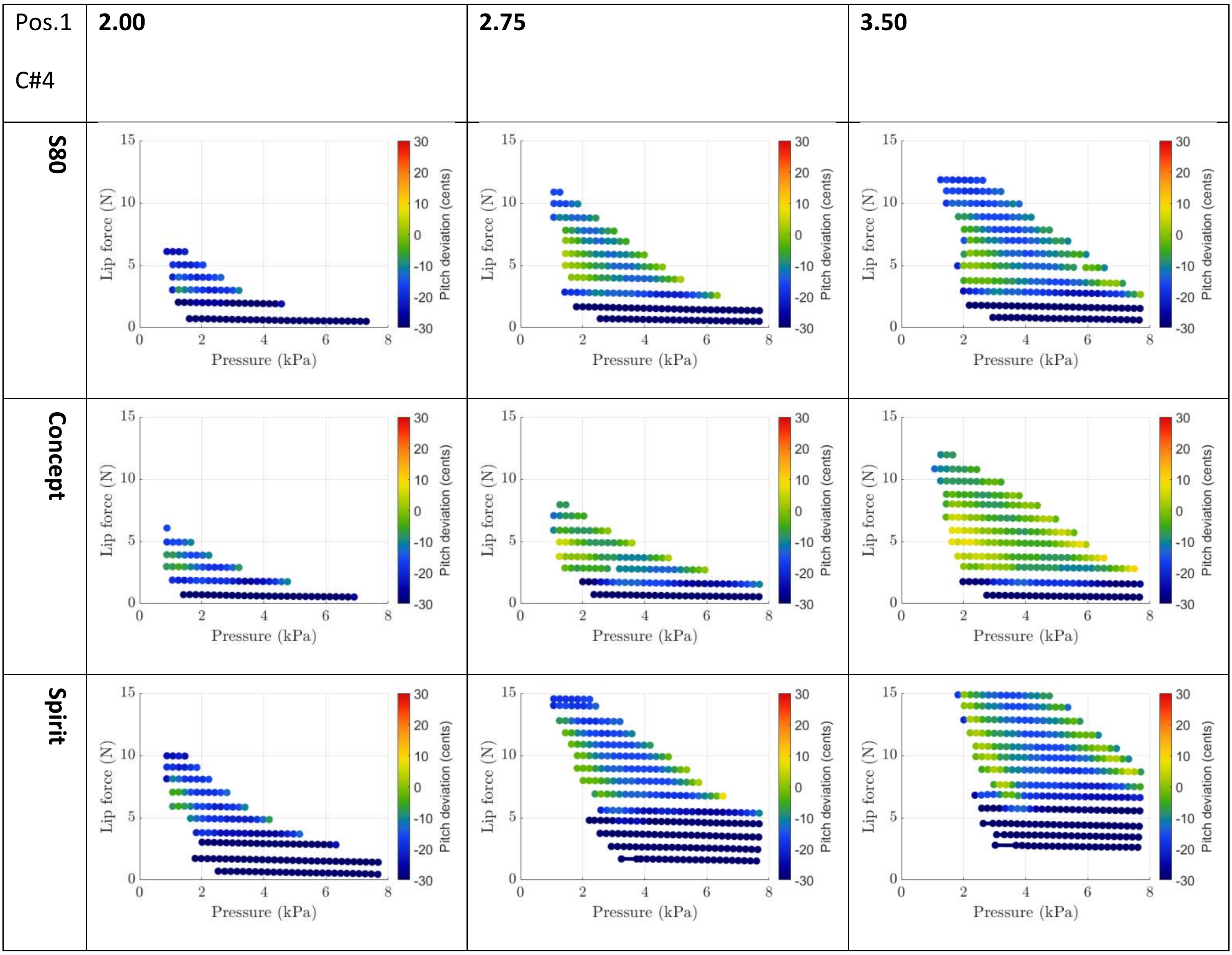


Figure 4: Pitch deviation as a function of lip force and blowing pressure for note C#4 and different reed–mouthpiece combinations. The total area shows the region where the fingered note is heard. The color of each dot shows the corresponding pitch deviation in cents.

Figure 5 shows the CTPA values for all notes measured with an S80 mouthpiece and a 3.50-strengh reed. For example, for lip position 1, the CTPA is 2 N.kPA, and the TPA is 10.8 N.kPa. Similar results were observed for the other reed–mouthpiece combinations. The CTPA value of D4 is the lowest of all notes in the second register. Unlike the TPA, where the calculated values are extremely similar between the notes of the second register, it is clear that the CTPA for D4 is much smaller.

In designing a wind instrument, compromises must be made to get all notes into correct tuning in as good as possible a way. On the alto saxophone, these compromises lead to a systematic flat tuning of C#4. One of the reasons is that, for this note, nearly all tone holes are open, so resonance occurs mainly in the top part of the instrument only. Figure 4 showed the TPA and CTPA for C#4: especially on the Spirit mouthpiece, but also on the S80 mouthpiece with a reed strength of 3.50, the center part of the TPA is mistuned. In other words, there is a missing vertical wedge in the CTPA due to a lower pitch. Of course, one could tune the instrument higher, but then all other notes would be sharp. Moreover, the TPA of C#4 would be in tune with the center blowing pressure values, but points would turn semi-transparent at the edge of the point cloud, so there would be no gain in overall CTPA. On the Concept mouthpiece, the problem is much less prominent: there is no missing wedge in the CTPA, and even with the softest reed, there is some choice of values where the note can be played in tune.

In the clarinet, frequency decreases as blowing pressure rises to between 4–5 kPa (Dalmont et al., 2012). The explanation of this phenomenon has been related to the reed's natural frequencies (Chaigne and Kergomard, 2016; Silva et al., 2008). This is similar to the missing vertical wedge shown in Figure 4, but the effect is not observed for all notes. The results demonstrate that mouthpiece design can substantially influence intonation. For the Concept mouthpiece, intonation is much more stable as a function of blowing pressure than for the S80 or Spirit mouthpieces.

In addition, Figure 4 shows that reed strength also substantially influences intonation. The vibrational surface of the reed adds an additional oscillating flow, which can be related to an extra length of the instrument, linked to a fictitious volume (Silva et al., 2008). The connection between this length and reed strength has been given by (Nederveen, 1969). Although this length is relatively small compared with the instrument dimensions, it has been shown that interaction between the acoustic resonator and the reed influences frequency (Silva et al., 2008). The current results show that softer reeds generally lead to flatter intonation.

D4 is the first note in the upper register. To play it, the octave key is used, opening a small tone hole on the upper part of the instrument. The hole aims to create a pressure node halfway between the pressured nodes of the note played in octave. As the same hole is used to put notes D to F# into an octave, positioning the hole is again a compromise. Consequently, D4 is tuned too high. For this note, the CTPA also has nearly no missing wedge. The note is in tune for the Spirit and S80 mouthpieces, using the stronger reeds for the lowest lip forces. For the Concept mouthpiece, the TPA for this note is terribly small for all reeds, and it is sharp under nearly all playing conditions.

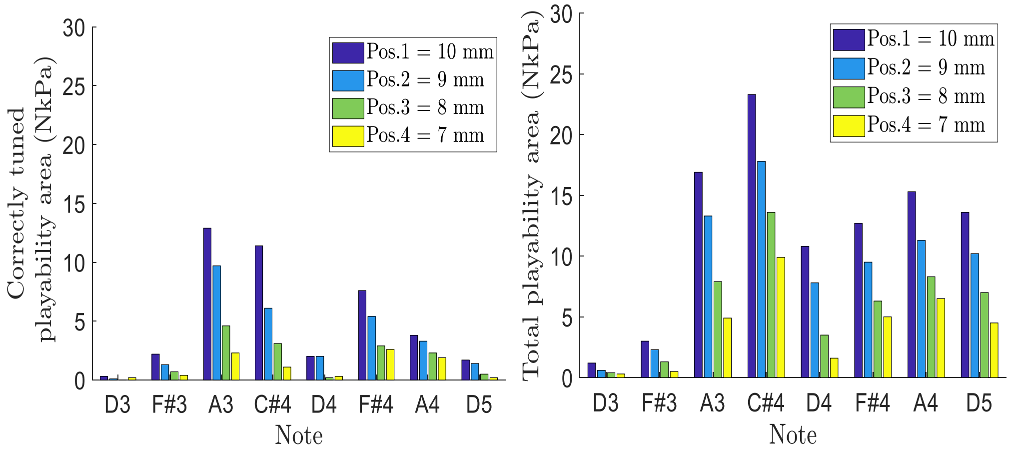


Figure 5: Values of correctly tuned playability area and total playability area for different notes and different lip positions calculated for an S80 mouthpiece with a reed strength of 3.50

3.3. General characterization

The average TPA is calculated to obtain an objective general characterization parameter, which will be indicated as <TPA>. The value is obtained as the total number of pressure and lip force combinations for which note sound is produced for all notes and lip positions, divided by the number of notes times the number of lip positions on which the tests were performed (in the current testing protocol 8X4). Similarly, the calculation was performed for the <CTPA>. The results of these calculations are presented in Table 1. Table 1 shows a clear trend of increasing <CTPA> with increasing reed strength. For the S80 mouthpiece and a reed strength of 2.00, the <CTPA> is 0.7 N.kPa. For the same mouthpiece and a reed strength of 3.50, the CTPA is 3.0 N.kPa. Table 1 shows a considerable difference between the <CTPA> values of the different mouthpieces. The CTPA of the S80 and Concept mouthpieces for the weakest reed strength is similar. The <CTPA> of the Spirit mouthpiece is slightly higher, with a value of 0.8 N.kPa. A significant difference of <CTPA> for the different mouthpieces is seen for higher reed strengths. For a reed strength of 2.75, the <CTPA> of the jazz mouthpiece is 1.9 times larger, compared with the <CTPA> of the classical mouthpieces. For a reed strength of 3.50, the <CTPA> of the Spirit mouthpiece is 1.8 times larger compared with the <CTPA> of the classical mouthpieces.

Though no significant difference was found between the <CTPA> of the classical mouthpieces and jazz mouthpieces for a reed strength of 2.00, there is a substantial difference here between the <TPA> of the Spirit mouthpiece and the classical mouthpieces. There are also differences between the classical mouthpieces (at the higher reed strengths). For example, the <TPA> value for a reed strength of 2.75 is 3.0 N.kPa for the Concept mouthpiece, whereas the value of the S80 mouthpiece is 4.4 N.kPa. The <TPA> for the jazz mouthpiece is at least twice as high as the classical mouthpieces.

In Table 1, the ratio between the <CTPA> and <TPA> is also shown.

Table 1: <TPA> and <CTPA> values for different reed–mouthpiece combinations. The <CTPA>/<TPA> ratios are shown in the last three rows.

Reed strength		**2.00**	**2.75**	**3.50**
<CTPA> (N.kPa)	**S80**	0.7	1.8	3.0
	Concept	0.6	1.5	3.2
	Spirit	0.8	3.1	5.5
<TPA> (N.kPa)	**S80**	1.8	4.4	7.8
	Concept	1.8	3.0	6.4
	Spirit	4.0	10.2	13.7
<CTPA>/<TPA> (%)	**S80**	38.3	41.2	37.6
	Concept	33.1	48.8	49.2
	Spirit	20.1	30.3	39.9

For the S80 mouthpiece, the ratio of <CTPA>/<TPA> is rather independent of reed strength. For the Concept mouthpiece, the ratio increases as a function of reed strength, and for the Spirit mouthpiece, it even doubles between the softest and the strongest reed. The Concept mouthpiece also shows the highest value of nearly 50% (when using a 3.50 reed). Table 1 shows that both <CTPA> and <TPA> increase by about a factor of two as reed strength increases from 2.00 to 3.50. For the less stiff reed, there is no significant difference between the <CTPA> of different mouthpieces. In contrast, a significant difference between the <TPA> values of the classical mouthpieces and the jazz mouthpiece is observed. The <TPA>

value at a reed strength of 2.00 was almost two times greater for the Spirit mouthpiece than for the classical mouthpieces.

Differences between the classical mouthpieces are observed mainly in the <TPA> values with the stiffer reeds. The S80 mouthpiece offers a significantly larger playability range than the Concept mouthpiece if exact tuning is not the issue. For a reed strength of 2.75, the <TPA> value of the S80 mouthpiece is 4.4 N.kPa, while, for the Concept mouthpiece, it is only 3.0 N.kPa. The lowest value in <CTPA>/<TPA> is observed for the Spirit mouthpiece in combination with a reed strength of 2.00, which means it is challenging to maintain good tuning. It should be noted that <TPA> and <CTPA>, and the ratios above, are averaged out over the different notes. This was the most reliable way to categorize mouthpieces.

At first glance, one could conclude that playing a harder reed is always the best choice since both the <TPA> and the dynamic range strongly increase with reed strength. However, although <CTPA> also increases as a function of reed strength, it increases less strongly than <TPA> and dynamic range. For stronger reeds, the growth of <CTPA> at the higher lip forces comes at the expense of losing <CTPA> at the lower lip forces. Especially on the Spirit mouthpiece, the <CTPA> cloud moves mainly upward to higher lip forces: sound can still be produced at low lip force, but only extremely loudly and out of tune. To play softly on the Spirit mouthpiece with a reed of strength 3.50, a lip force as high as 15N is required.

3.4. Mouthpiece comparison: Stability across notes

Figure 6 provides an overview of SPL, lip force, and blowing pressure for the three different mouthpieces, with a reed of strength of 3.50. The results are calculated on the full measured range of lip positions for data points within the TPA. The results are visualized as box plots. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles respectively. The whiskers extend to the most extreme data points not considered outliers (99.3% coverage if the data are normally distributed), and the outliers are plotted individually using the 'o' marker symbol. A red line connects the medians.

For the SPL, shown in the first row of Figure 6, there is a noticeable difference between the classical and jazz mouthpieces. The jazz mouthpiece is louder across all notes than the classical mouthpieces. For example, the SPL measured at D3 is 114 dB(A), while the measured values for the S80 and Concept mouthpieces are 109 dB(A) and 108 dB(A) respectively. Across notes, the measured SPL is relatively stable when the calculation is based on data points where the saxophone produces the note, but not considering the correct pitch tuning of the note. A decreasing trend of SPL is observed for notes of the first register, which was also noticed in a previous study (Ukshini and Dirckx, 2022).

For lip force, a difference is seen mainly between the Spirit and classical mouthpieces. The median value of the lip force never exceeds 4 N on the classical mouthpieces, while at C#4 on the Spirit mouthpiece, a median lip force of 7 N was measured. The blowing pressure is the most stable across notes of the three investigated parameters. For the classical mouthpieces, it is noticeable that, for the lowest notes of the first register, the blowing pressure is about 1 kPa lower than for the notes of the second register. For the jazz mouthpiece, a lower blowing pressure at the lowest notes is less noticeable.

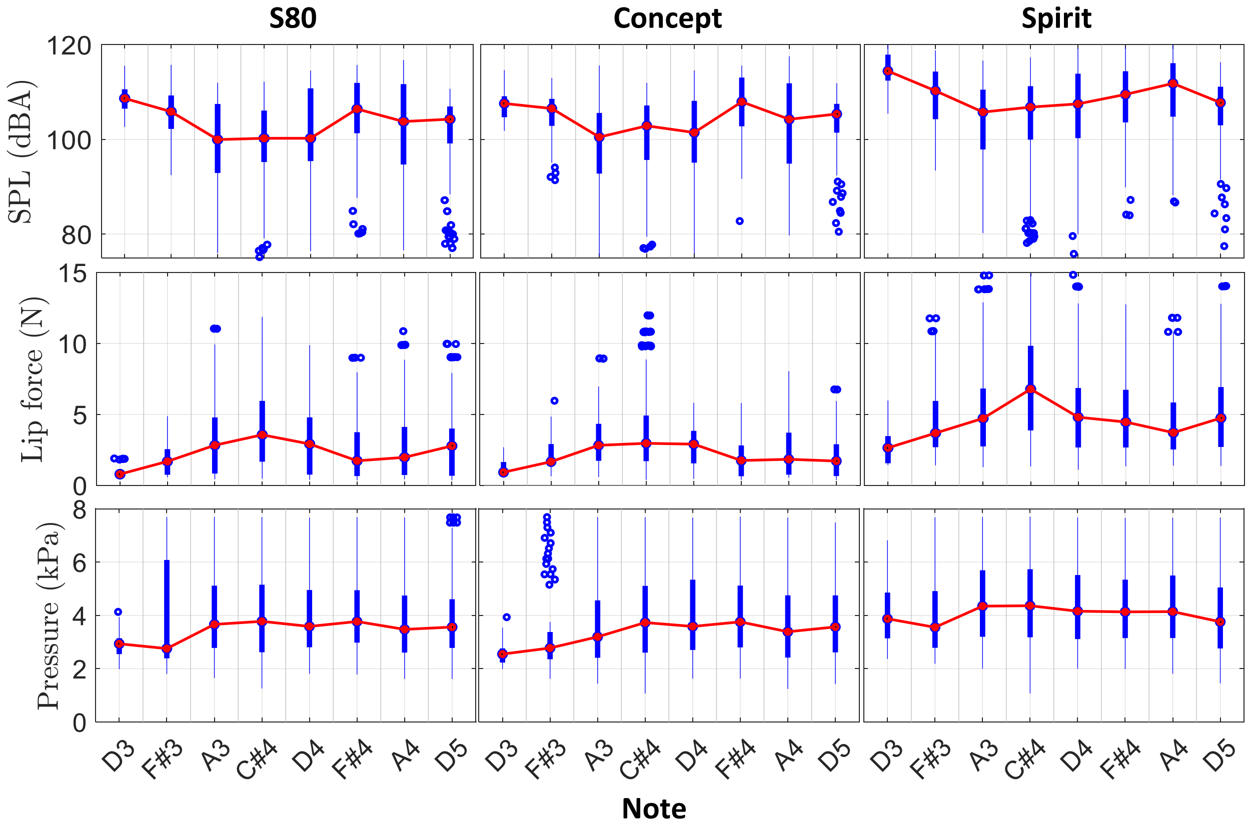


Figure 6: Boxplots of the measured data points which fall in the total playability range (TPA) for different notes measured on a reed with a strength of 3.50. The rows show the results for the SPL, lip force, and blowing pressure respectively. The columns show the results for the different mouthpieces. The median values are connected by means of red trend lines.

Compared with the data calculated for the CTPA, median values are more stable across the different notes. In general, the blowing pressure is lower for the lowest notes. From A3/C#4, the blowing pressure remains relatively stable across the different notes. The median blowing pressure averaged over all notes for the classical mouthpieces is 3.4 kPa. For the Spirit mouthpiece, it is higher (4 kPa), but the body of the boxplot (q1–q3) for the blowing pressure is approximately the same for each mouthpiece across the different notes.

A low blowing pressure at the low notes is accompanied by a lower median lip force. A general trend is seen in the first register for lip force. Lip force increases as a function of note. There is a noticeable difference between the bodies of the boxplots for lip force. The median lip force over all notes is 2.3 N, 2.1 N, and 4.4 N for the S80, Concept, and Spirit mouthpieces respectively. On average, the lip force needed to play the Spirit mouthpiece is two times higher than the classical mouthpiece. Due to the larger tip opening, the effect is to be expected. However, the measurement procedure now allows us to quantify the additional effort needed to play the mouthpiece objectively. The data also show that on the Spirit mouthpiece, lip force varies stronger amongst notes, requiring a more dynamic adaptation of lip force by the musician while playing.

For SPL, a decrease is observed between D3 to A3, which is the opposite of the trend for lip force and blowing pressure. A similar trend is observable for all reed–mouthpiece combinations. The mean of the median SPL over all notes is 104 dB(A), 105 dB(A), and 110 dB(A) for the S80, Concept, and Spirit mouthpieces respectively: if playing in tune is not the main issue, the Spirit mouthpiece offers approximately 6 dB more SPL than the other mouthpieces. The mean of the median flow over all notes (not shown in the boxplots) for the three mouthpieces is 7.5 LPM, 7.5 LPM, and 11.3 LPM respectively. The additional energy needed to produce the louder sound on the Spirit mouthpiece is delivered by the higher airflow, in combination with higher blowing pressure.

Figure 7 shows a similar representation of the results as in Figure 6, but now only data points in the CTPA were used for the boxplots. A significant difference is visible between the results for TPA and CTPA. For all results shown in Figure 7, it can be observed that the trend line (in red) fluctuates much more across notes. Furthermore, it is noticeable that the differences between the mouthpieces become more pronounced. The trend lines for SPL show that the loudness of the Concept mouthpiece is much more stable over the notes than the loudness of the S80 and Spirit mouthpieces. The largest difference between the median values of the different notes is 18 dB with the S80 mouthpiece. For the Concept mouthpiece, this value is 13 dB. Playing D4 in tune is 10 dB louder on an S80 than on a Concept mouthpiece. D4 is the first note of the second register, where all the tone holes of the instrument are again closed. On the Concept mouthpiece, the transition between the first and second registers is much smoother. For the Spirit mouthpiece, the loudness change between C#4 and D4 is also noticeable. The jump in loudness between the two notes is 14 dB.

Comparing the data in the second rows of Figures 6 and 7 indicates that the lip force in the TPA strongly differs from that in the CTPA. Figure 6 shows that the lip force increases for the first register as a function of note pitch. The lip force in the first register is significantly higher for the CTPA than for the TPA. When we consider only whether the note is produced, the median value for the classical mouthpieces does not exceed 4 N. When correct tuning is considered, the median values for the first register are higher. For example, for C#4, the median value is 5 N.

Figure 6 shows that the median values of blowing pressure remain extremely stable across notes, but Figure 7 shows that the value varies much more for the CTPA. This means that more adaptation is needed to stay in tune. For CTPA, the median blowing pressure generally increases from D3 to D4. For the S80 mouthpiece, the median value increases from 2.5 kPa to 5.5 kPa. For the Spirit mouthpiece, the median blowing pressure increases from 2.9 kPa to 5.5

kPa. For the Concept mouthpiece, the increase is much less pronounced (2.2 kPa to 4.2 kPa) and pressure is more stable across the notes.

Figures 6 and 7 show that, in the lower register, median lip force must be increased as a function of note pitch when notes are required to be in tune. For the high register, the variation in median lip force is less pronounced.

The minimum values of the boxplots in Figures 6 and 7 show the pressure threshold at which the reed started to vibrate. Though the tip opening and facing are terribly similar for the S80 and Concept mouthpieces, a clear distinction can be observed: the Concept mouthpiece generally has a lower blowing pressure threshold for each note. Hirschberg et al. (Hirschberg et al., 1991) mention that the vena contracta effect influences the pressure threshold. Sharp edges in the internal design of the mouthpiece cause flow separation, which results in a free jet in the mouthpiece. This contraction effect results in a jet cross-sectional area smaller than the reed channel opening.

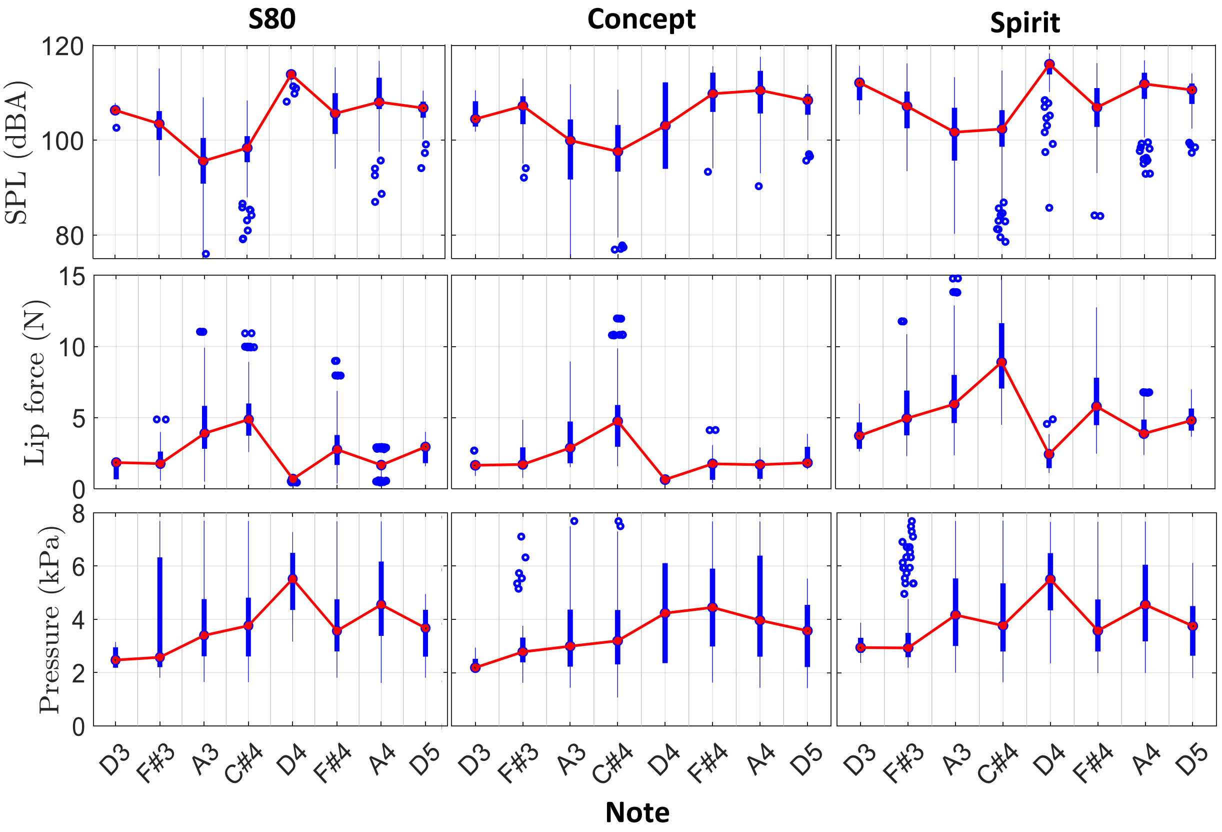


Figure 7: Boxplot representation of SPL, lip force, and blowing pressure for different mouthpieces and a reed strength of 3.50 for the data points which fall in the acceptable tuning range (CTPA). The rows show the results for the SPL, lip force, and blowing pressure respectively. The columns show the results for the different mouthpieces. The median values are connected by means of red trend lines.

Table 2 shows an overview of mean SPL, lip force, and blowing pressure values for the three different mouthpieces and the three different reed strengths. The results were obtained by averaging the median values across the measured notes. The standard deviation over the note range is also shown. For a reed strength of 2.00, no significant differences are observed between the different mouthpieces in terms of SPL. The average values differ by less than 3 dB. In addition, no significant differences in SPL values are present between the two classical mouthpieces for higher reed strengths. For both mouthpieces, the average SPL value is 102.1 dB(A) for a reed strength of 2.75 and 105.0 dB(A) for a reed strength of 3.50. For the higher reed strengths on the Spirit mouthpiece, the SPL is more than 3 dB higher than the classical mouthpieces. Blowing pressure also depends on reed strength: between the lowest and highest reed strength, the difference in median blowing pressure is 1.4 kPa, 1.2 kPa, and 1.3 kPa for the S80, Concept, and Spirit mouthpieces respectively. No noteworthy differences were found between the median blowing pressure measured for the classical mouthpieces.

For all three mouthpieces, SPL, lip force, and blowing pressure show much more variability over the different notes for the CTPA than for the TPA. Using the CTPA, an important difference between the two classical mouthpieces becomes apparent, which cannot be seen from the TPA. On the Concept mouthpiece, median blowing pressure and median loudness vary more smoothly over notes without the sudden jump around D4, which is noticeable for the S80 mouthpiece (and for the Spirit mouthpiece). This demonstrates that the Concept mouthpiece is easier to play across notes with equal blowing pressure in correct tuning, although it has the same tip opening and facing length as the S80 mouthpiece. Specifying a few geometric parameters, such as tip opening and facing length, does not suffice to specify mouthpiece playability range.

Table 2: Mean SPL, lip force, and blowing pressure of the CTPA data with standard deviations averaged over the different measured notes and lip positions for different reed–mouthpiece combinations.

Reed strength		**2.00**	**2.75**	**3.50**
SPL (dBA)	**S80**	100.6 ± 3.3	102.1 ± 4.2	104.8 ± 5.7
	Concept	99.3.0 ± 4.3	102.1 ± 3.7	105.1 ± 4.7
	Spirit	101.8 ± 5.5	106.5 ± 4.4	108.6 ± 5.0
Lip force (N)	**S80**	1.1 ± 0.8	1.8 ± 1.0	2.6 ± 1.4
	Concept	1.5 ± 0.8	1.6 ± 0.7	2.2 ± 1.2
	Spirit	2.5 ± 1.3	4.3 ± 1.8	5.1 ± 2.0
Blowing pressure (kPa)	**S80**	2.3 ± 0.6	2.6 ± 0.6	3.7 ± 0.9
	Concept	2.2 ± 0.5	2.7 ± 0.5	3.4 ± 0.7
	Spirit	2.6 ± 1.1	3.5 ± 1.1	3.9 ± 0.8

The most prominent observation from Table 2 is that average SPL, lip force, and blowing pressure increase as a function of reed strength. The average SPL values for the classical mouthpieces are almost the same; the Spirit mouthpiece is about 3dB louder. For all reed strengths, the lip force needed on the Spirit mouthpiece is far higher than on the classical mouthpieces, but median blowing pressure varies far less between mouthpieces.

3.5. Lip, loudness, & pitch change across notes

Figure 8 shows how lip force (8(a)), pitch deviation (8(b)), and loudness (8(c)) change when musicians move from one note to the next. Calculations were made for reed strength 3.50, and values for each note were averaged over the data points within the CTPA. Results were obtained by taking the differences between subsequent values and dividing those by the numbers of semitones between the two subsequently measured notes to obtain the change per semitone. The horizontal axis is divided linearly into semitones (logarithmic for frequency). The names of the measured notes are indicated, and data points lie midway between two subsequent measured notes. Figure 8(a) shows that the change in lip force decreases slightly between D3 and C#4. An extremely abrupt change occurs for the transition from C#4 to D4. The S80 and Concept mouthpieces behave in almost identical ways: between C#4 and D4, the sudden change in lip force is 4N/semitone for both mouthpieces. Lip force must be adapted with almost 7 N/semitone for the Spirit mouthpiece. Figure 8(b) shows that, with respect to tuning change, the S80 and Spirit mouthpieces behave almost identically, while for this same parameter, the Concept mouthpiece is much more stable: in changes from C#4 to D4, tuning changes with more than 25 cents for both S80 and Spirit mouthpieces, while, for the Concept mouthpiece, this change is less than 5 cents. Figure 8(c) displays similar behavior for loudness: while for the S80 and Spirit mouthpieces, loudness changes with 15 dB and 14 dB respectively, the loudness change for the Concept mouthpiece is less than 6 dB.

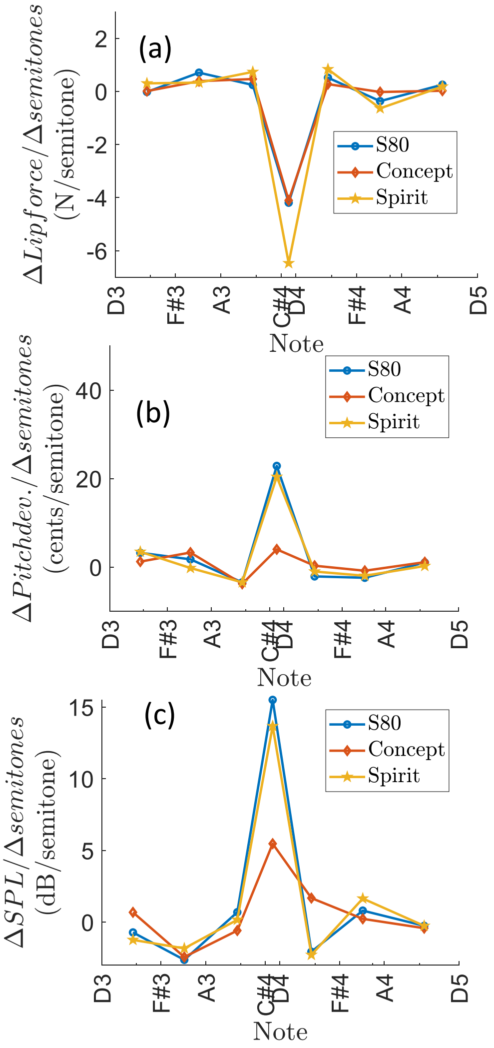


Figure 8: Change of lip force, pitch deviation, and SPL per semitone across the measured notes for the different mouthpieces

A prominent aspect in Figure 8 is the sudden changes at the transition from C#4 to D4. For the classical mouthpieces, the change in lip force between C#4 and D4 is 4 N, whereas, for the Spirit mouthpiece, it amounts to 7 N. Although the significant change in lip force leads to acceptable, correctly tuned notes, the change in pitch between C#4 and D4 remains more than 20 cents for the S80 and Spirit mouthpieces. For the Concept mouthpiece, the change in pitch for the C#4/D4 transition is far smaller than for the other two mouthpieces. In addition, for sound pressure, the Concept mouthpiece is markedly more stable at the C#4/D4 transition than the other two mouthpieces, while the change in lip force is the same for the Concept and S80 mouthpieces.

Section 3.2 showed that C#4 is systematically tuned too low for all mouthpieces. This is a specific aspect of the alto saxophone (and other instruments with tone holes). In the median lip force curve for the CTPA, a peak is observed at this note, which is logical, since higher lip force tends to increase note pitch. For D4, the opposite is observed: the note is tuned too low, and, in the CTPA, a dip in median lip force occurs, since lower lip force is needed to get the note into tune. Because of the lower median lip force at D4, the reed opening becomes larger, so that flow increases and the note is louder. This effect is evident for S80 and Spirit mouthpieces. However, the data show that mouthpiece design can improve the transition from the first register to the second register. For the Concept mouthpiece, D4 is not significantly louder than the surrounding notes. Although median lip force for the two classical mouthpieces is the same for D4 (and also for C#4), the transition from the first register to the second register through D4 is much more homogeneous for the Concept mouthpiece. This shows once again that not only exterior design parameters (tip opening, lay profile, and facing length) determine mouthpiece playability but also the internal design. We speculate that the improved behavior of the Concept is mainly determined by the baffle, which influences the aerodynamics and pressure filed beneath the reed, especially near the tip. In future work, we intend to investigate this pressure distribution.

4. General Discussion

The <CTPA> and <TPA> increase with reed strength (from 0.7 N.kPa to 3.9 N.kPa averaged over the different mouthpieces). The <CTPA> differs little between the mouthpieces for the weakest reed strength. For higher reed strengths, a clear distinction can be observed between the jazz mouthpiece and the classical mouthpiece: the <CTPA> of the Spirit mouthpiece is about two times larger than the classical mouthpiece.

For a reed of strength 2.00, the S80 mouthpiece gives the highest <CTPA>/<TPA> ratio (38.3%). For higher reed strengths, the Concept mouthpiece shows the highest ratio (about 50%).

When we analyzed the results of SPL, lip force, and blowing pressure for the TPA data, the most noticeable differences are found between the jazz mouthpiece and classical mouthpieces. When we analyzed the results for different notes for the CTPA data, differences between the S80 and Concept mouthpieces become clear. For example, the median blowing pressure across notes is more homogeneous for the Concept mouthpiece.

A sudden change of the measured parameters (Figures 7 and 8) at the transition from C#4 to D4 is observed for all mouthpieces and is related to the design of the saxophone. Figure 8 showed that the change of lip force at C#4/D4 was largest in magnitude and negative. This means the lip force for D4 is much lower than C#4, leading to a larger tip opening. For the Spirit and S80 mouthpieces, this resulted in a 14–15 dB increase in loudness. For the Concept mouthpiece, the loudness is much more homogeneous between notes. In addition, the change in pitch at the C#4/D4 transition is far smaller for the Concept mouthpiece. Although the Concept and S80 mouthpieces have similar tip openings and facings, results show that the internal shape of a mouthpiece may have an important effect on changes in loudness and pitch between notes.

It must be emphasized that the current parameters describe only how the mouthpiece reacts to an artificial blowing device. The method has the advantage that well-defined testing conditions can be easily reproduced, but it does not consider the musician's reaction and the complicated acoustics of the mouth and larynx.

The S80 mouthpiece has sharper edges (see Figure 1) at the transition from the chamber to the bore. For the Concept mouthpiece, the baffle is more curved near the throat, resulting in a less sharp edge. The ramp of the mouthpieces differs as well. The ramp is longer for the S80 mouthpiece than the Concept mouthpiece.

Moreover, the slope of the ramp is more in line with the bore of the S80 mouthpiece, whereas, for the Concept mouthpiece, the ramp is steeper. An especially noticeable difference between the two classic mouthpiece designs is baffle shape. The baffle of the Concept mouthpiece is more convex near the throat, while the baffle of the S80 mouthpiece is more concave. These internal shape differences may influence oscillation thresholds. The strongest internal geometrical differences between the jazz and classical mouthpieces are observed at the throat and the baffle. In the Spirit mouthpiece, the transition from the chamber to the bore proceeds without almost any reduction in the cross-section area. The baffles of the classical and jazz mouthpieces differ most near the mouthpiece tip. For the jazz mouthpiece, the baffle remains at an approximately constant height for a few millimeters and then rolls over. In the first part, a thin channel is formed between the baffle and the reed. For the classical mouthpieces, the length of this channel is shorter. These subtle design differences have a substantial influence on playability and hence on the parameters measured in this paper.

5. Conclusion

This paper presented a procedure to compare mouthpiece playability quantitatively in terms of lip force, blowing pressure, sound pressure, pitch deviation, and airflow. Objective parameters such as TPA, CTPA, <CPA>, <CTPA>, and inter-note variability were calculated.

By defining TPAs and CTPAs for different notes and by quantifying the change in tuning between notes, differences in mouthpiece playability can be objectively characterized. Results showed that the method allows us to detect and quantify playability differences between mouthpieces with extremely similar tip openings and facings. While the Concept and S80 mouthpieces have remarkably similar tip openings and facing lengths, internal geometry and lay profiles differences lead to better tuning for the Concept mouthpiece. The Spirit mouthpiece is louder, but it requires more lip force and more adaptation of blowing pressure and lip force over the note range than the classical mouthpieces. The Concept mouthpiece is also more stable in loudness over the note range. The data show that mouthpiece design influences saxophone tuning problems in the transition from the first register to the second register.

The objective characterization parameters can help to categorize mouthpieces correctly and deliver valuable input for parameter-driven improvement and customization of mouthpiece design.

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