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Assessment of Bassoon Tuning Quality from Measurements under Playing Conditions

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Summary
In reed woodwinds, the pitch of a sound is the result of an interaction between the air column, the reed, and the player. The air column is well described by its resonance frequencies and their damping. The reed is a pressure-controlled valve, which drives a coupled oscillation that settles with a fundamental frequency near a resonance frequency of the air column. The musician provides the blowing pressure and can alter the dynamical properties of the reed with his embouchure. An experimental study is presented that investigates from the player's perspective the tuning quality of the whole system under playing conditions for the case of the bassoon. A strong influence on tuning is reported for the bocal or crook, which is the interchangeable part of the resonator's top end. Here we focus on the lip force a musician has to exert for the instrument to play in tune. For normal playing regimes, the relation between lip force and pitch is roughly linear: higher lip force at constant blowing pressure increases the pitch. However, as each fingering requires a different lip force, playing a succession of notes may require considerable lip force changes that are tedious: the instrument appears to be badly tuned. Covering the full tonal and dynamical range on three modern German bassoons, this study investigates the tuning properties in two ways. Firstly, a professional musician has been asked to play notes without embouchure corrections on three bassoons. Secondly, the lip force and blowing pressure to play notes in tune were measured on these bassoons with an artificial mouth. A linear fit explains a half of the observed relation of the tuning discrepancy in uncorrected playing to the measured lip force when playing in tune. This link between objective and subjective tuning measurements justifies the method of measuring lip forces during playing with an artificial mouth to assess tuning quality. The results point to a common tuning trend of bassoons of the modern German type independent of the bocal and reed.

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1. Introduction

The human ear is very sensitive to frequency. The just noticeable difference in pitch of a pure sine is smaller than a half percent for a wide range of frequencies [1]. This pitch deviation corresponds roughly to a tenth of a semitone. For musicians this implies strong requirements on the frequency tuning of their sounds. In reed wind instruments, the sounding frequency is a result of an interaction of a resonating air column and a reed mouthpiece driven by the blowing pressure, which is set by the musician. While the acoustical properties of the air column, namely the resonance frequencies and their damping, are given from its geometrical shape as manufactured, the reed mouthpiece is less well defined. Usually it is hand-made and the material properties depend upon moisture content and aging as well as the complex geometry. During playing, the reed acts as a pressure-controlled valve whose characteristic properties can be altered by the musician to influence pitch and dynamic level. A way to do so is by narrowing the slit opening by applying force with the lips to the reed, which shortens the reed blade's free length and thus increases the resonance frequency of the reed [2]. Musicians call the action of their lips on the reed the *embouchure*.

Embouchure adjustments are required to vary the dynamic level of a note without pitch-change and to change between notes while playing at the same dynamic level. The degree and regularity of these necessary adjustments provide an information on the overall tuning quality of the instrument as it is perceived by the musician. In single-reed instruments musicians can also use their vocal tract to modify the sound [3, 4, 5]. We consider this influence to be minor for the case of the bassoon, and exclude variations of the vocal tract from this study. An assessment of tuning quality is important for woodwind instrument manufacturers.

They face the challenge to make instruments that are comfortable to interact with for a broad community of mu-

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sicians with individual preferences concerning the reed. The geometry of the bore and the tone-holes has to be optimized, such that more notes than there are tone-holes can be played in tune by use of fingering combinations.

On the one hand, the relation between the geometry of an air-column and its acoustic properties is well studied. One-dimensional air column models of wind instrument bores (e.g. [6, 7]) prove accurate enough to explain the acoustic properties (e.g. [8]). For experimental investigations, highly accurate acoustic impedance measurement devices have been developed [9, 10, 11]. On the other hand, despite the achievements in accuracy and practicability of impedance measurements, the relation between the linear acoustic properties of a resonator and its tuning quality under playing conditions is hard to describe. Theoretical predictions of playing frequency are based on strong simplifications and reduced models of the reed.

In general, attaching a reed to the instrument changes the acoustic properties of the resonator. The resonance frequencies are shifted compared to what can be measured at the bore input. This effect can be captured by a reed equivalent volume [12, 13, 7] to account for the prolongation of the bore and the flow induced by the reed motion. While playing bassoon the reed is beating, and this non-linear system is on a limit cycle whose frequency can be shifted by alterations of lip position, lip force, and blowing pressure. Dalmont *et al.* [13] provide an overview on several modeling approaches to calculate the sounding frequency and point out the role of the harmonicity of the resonator on tuning and timbre.

Recent studies with theoretical physical models quantify the effect of variations in blowing parameters on the sounding frequencies [14, 15, 16, 17]. Despite these advances in explaining the musician-musical instrument interaction in terms of relative pitch, it seems that physical models, regardless of their complexity, are not yet accurate enough to draw conclusions on an optimal resonator design [14] and the need for empirical corrections remains [18, 19].

Here we investigate experimentally tuning aspects under realistic playing conditions, with two different approaches. First, the subjective impression of tuning imperfection is determined in playing experiments in which a musician was asked not to correct tuning problems of the instrument with his embouchure. Second, the embouchure actions needed to correct the tuning have been measured by means of an artificial mouth which allows us to measure the lip force precisely [20].

2. Intonation study with musician

For a musician, an instrument is well tuned if no embouchure corrections are needed for the individual notes. Thus, an indirect measure of tuning is the deviation D_{mus} in sounding pitch when the player omits embouchure corrections. Each musician may have a different, note- or register-dependent reference for what is considered a correction. It can be assumed however, that the impression of a well-tuned instrument will have a smooth variation of this reference over the tonal range. With this definition of tuning quality we note that it is a subjective property that can only be assessed under playing conditions. For the modern German bassoon we quantified this by a playing experiment, instructing a bassoonist to play without changing lip force. To avoid any disturbance for the musician, we decided not to measure lip force or blowing pressure in this part of the study. Being aware that we measure a subjective quantity we consider that the musician does not significantly change its embouchure.

Considering the musician, reed, and instrument as one unit, tuning estimates of all notes are retrieved from pitch analysis of recorded bassoon sounds. Specific notes which appear considerably flat or sharp constitute a unique characteristic, which has been determined on three bassoons with different combinations of bocals and reeds. A principal bassoonist of a professional orchestra agreed to volunteer in this study. One measurement series consisted of playing chromatically all notes from B♭1 (f_0 = 58 Hz) to D5 (f_0 = 591 Hz) at the *mezzoforte* level in ascending order. A set of 18 measurement series was carried out for all combinations of three different bocals and two different reeds on three different bassoons of the modern German type. The bassoons were from the German manufacturers Adler, Heckel, and Hüller, the bocals were the models CC1, CD0, and C1 from Heckel, and the reeds were a hand-made cane reed from the bassoonist and a machine-made cane reed (ProReeds Model 116, Kreedo, Frankfurt a. M., Germany). The reeds were classified by the musician as a "hard" and a "soft" reed, respectively. One combination of these components was in use by the musician on a regular basis. The data were recorded in a laboratory environment.

The air temperature was not controlled during this experiment, but all measurements of this series were recorded on the same day under the same and comfortable conditions for the musician. The bassoon was fixed in a stand in the middle of the room to be played in a seated position. A 1/2" free-field microphone (Brüel&Kjaer Type 4190) was positioned 1.5 m from the instrument in a typical listener direction. The sound was recorded by a Brüel&Kjaer Pulse measurement system at a sampling rate f_s = 32.768 kHz and subsequently analyzed by the autocorrelation pitch detection algorithm implemented in the speech analysis software Praat [21]. For each of the sustained notes with a duration of approximately three seconds an instant pitch information $f_0(t)$ in time-steps Δt = 15 ms was extracted and converted to a pitch deviation D in Cent as

$$D(t) = 1200 \log_2 \frac{f_0(t)}{f_{0,\mathrm{nom}}}, \qquad (1)$$

where $f_{0,\mathrm{nom}}$ is a nominal frequency according to the equally tempered scale. The temporal tuning stability of the notes can be evaluated by the histogram count of $D(t)$. Independently of the fundamental frequency, the interquartile range in $D(t)$ during playing of a sustained note was not more than 10 Cent, including attack and decay. The detuning of the three bassoons studied here follows a common trend (Figure 1). It appears that the reed's "hardness" is related to the pitch offset but does not affect the generic shape of the tuning curve. Comparing two measurement series on the same bocal and bassoon in Figure 1, for the "soft" reed the tuning is shifted to higher pitches. This effect is more pronounced than the influence of the bocal length. Suprisingly, no general pitch shift is observed for Bocal 2 (CD0), although it is 5 mm shorter than the other two bocals.

The accuracy of the subjective tuning impression has been tested by repeating one measurement with an identical setup about three months after the initial run (Figure 2). In the lowest register, the repeatability of the musician was surprisingly good, with a maximum deviation of 10 Cent between first and second measurement. The deviation is higher in the upper registers, but apart from some outliers (for C4: 40 Cent) the general trend is still the same. The reed used for the second run was the "hard" reed of the initial run, which was not in use in the meantime.

3. Artificial mouth experiment with adjustable lip

In a musical performance, the tuning offsets as measured in the previous section are not permissible. Musicians have to correct flat or sharp notes by tightening or loosening the embouchure. The lip force applied to the reed is a measure that quantifies this correction, and thus provides an information on the tuning. Measurements of lip force on the reed under real playing conditions are difficult to carry out without disturbing the musician or changing the reed's properties. Successful attempts are reported for the saxophone [22], but similar studies for double-reed instruments are missing. To measure lip force on the bassoon mouthpiece under realistic playing conditions we use a self-built artificial mouth that facilitates precise lip adjustment (Figure 3). The main component of the device is a synthetic bassoon double-reed (270M, Conn-Selmer Inc., Elkhart, Indiana, U.S.A.) which is rigidly mounted at its rear end in the mouth pressure cavity. An artificial lip can be moved towards the reed. The lip assembly consists of a rigid rib, imitating the teeth, which is sheathed by a piece of cellular rubber. On top of this, a glycerin filled air balloon is overlayed, because a combination of foam and glycerin has similar dynamic properties as human lips [23]. The lip is fixed in a steel tube which is mounted onto a precision load cell (Type KAP-S/10N/0,1 A.S.T. GmbH, Dresden, Germany) that can be positioned by two micrometer screws parallel and normal to the longitudinal axis of the reed. The reed pressure p_r is the differential pressure between inside the reed channel and the surrounding. It is measured with a miniature pressure sensor inside the double-reed near the bocal tip. Details of the setup are given in [20].

The possibility of actuating the micrometer screws from outside of the artificial mouth facilitates lip position and lip force adjustment during playing. The whole artificial mouth setup is robust enough to change the fingering on an instrument or to swap between instruments without affecting the embouchure settings. It was found that bassoons can be excited over the full tonal and dynamical range with only one lip pressed to one side of the double-reed [2], similar to the single-reed lip configuration. This

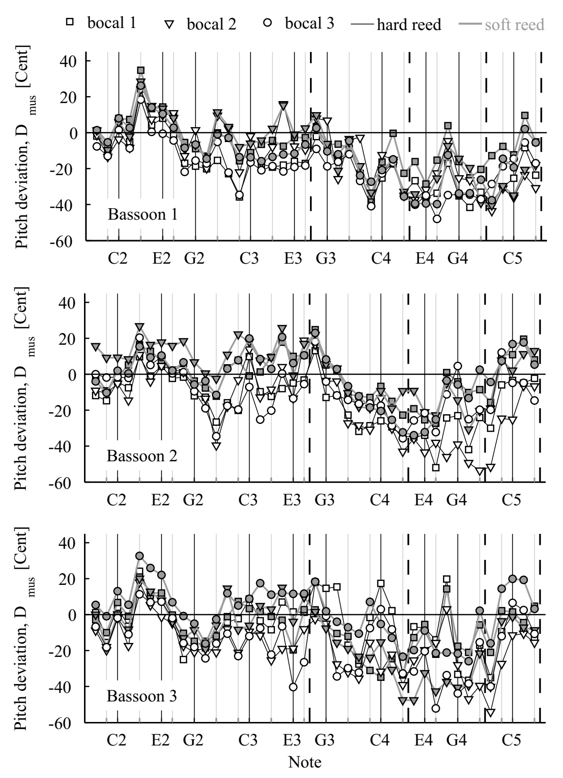

Figure 1. Pitch deviation D_{mus} from blowing experiments with a musician omitting conscious embouchure corrections. The musician played all combinations of three bocals and two reeds on three bassoons. Dashed vertical lines mark the register borders, thin vertical lines mark the notes of the C-major scale.

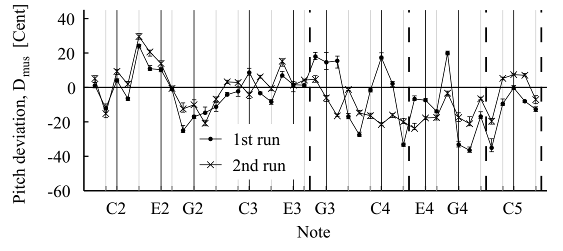

Figure 2. Repeatability of the blowing experiment with a musician omitting conscious embouchure corrections to determine the pitch deviation D_{mus} (Bassoon 3, Bocal 1, "hard" reed). Between the experiments (1st run and 2nd run) lies a time span of three months, in which the reed was not used. Errorbars indicate the interquartile range of the instantaneous tuning deviation $D_{mus}(t)$ during playing of sustained notes for approximately three seconds. Dashed vertical lines mark the register borders, in vertical lines mark the notes of the C-major scale.

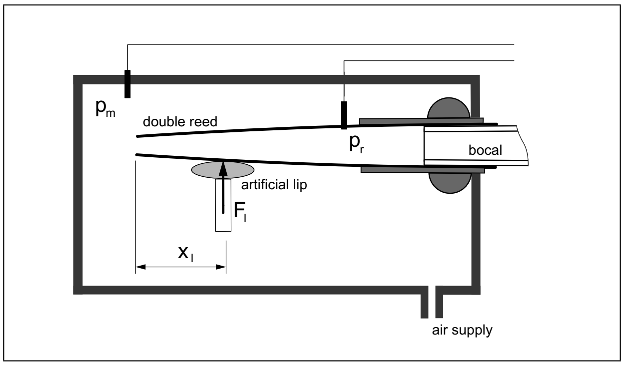

Figure 3. Schematic representation of the artificial mouth.

is an important simplification for experiments: At a fixed lip position x_l with respect to the reed tip, the artificial mouth's working point is fully described by two parameters, namely blowing pressure p_m and lip force F_l (Figure 3). If the parameter combination is properly selected, the instrument plays in a stable oscillation regime. The resulting pitch at this working point (F_l, p_m) can be altered by changing lip force or blowing pressure. The variation of pitch with blowing pressure is of major interest, because playing louder requires blowing harder: The mouth pressure provides the potential for the generated acoustic energy and scales linearly with the root-mean-square of the reed pressure [20]. For stable oscillation regimes, the blowing pressure must be within certain limits. Below the lower threshold, no sound is generated.

Above the upper threshold, the regime abruptly changes to another fundamental frequency (overblowing), to a multiphonic sound, or stops because the reed closes permanently [24]. The pressure thresholds have been studied experimentally for the clarinet [25, 26]. We observe for some bassoon fingerings in the middle of the tonal range that this extinction pressure is well above the usual mouth pressure range of a musician [27]. For these notes, other pressure thresholds below extinction exist at which a smooth turnover into another oscillation regime at nearly the same pitch occurs (see Eb3 and C3 in Figure 4). This turnover is indicated by a change of the ratio $|p_c/p_o|$, where p_o and p_c are the mean pressures measured inside the reed during the open and closed episode, respectively [28]. In a moderate mouth pressure range within these limits, the pitch changes linearly with the mouth pressure while the ratio $|p_c/p_o|$ remains constant. Because regime changes are difficult to control, we consider only the linear range in the vicinity of the nominal frequency to be of musical relevance and exclude other regimes.

The extent to which a moderate blowing pressure variation affects the pitch varies from note to note. This can be quantified by the linear coefficients of fits to the experimental data of tuning change with respect to blowing pressure for approximately constant lip force (Figure 5).

In a musical performance, the tuning has to be controlled independently of the dynamic level. Hence the mouth pressure-induced pitch change has to be compensated by a simultaneous lip force adjustment. Thus, to be able to play in tune, musicians have to train their embouchure with respect to the following two aspects:

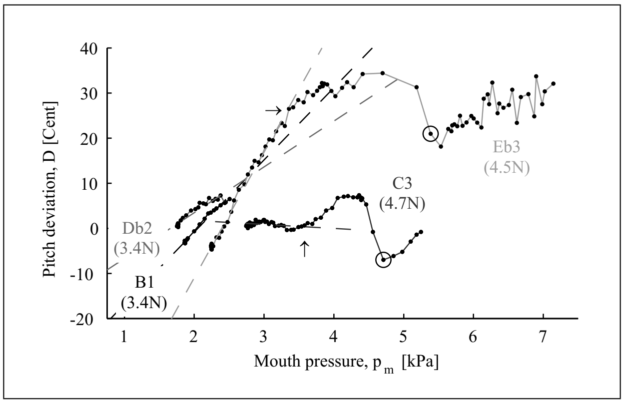

Figure 4. Pitch change due to a mouth pressure change at approximately constant lip force for four bassoon notes. Arrows mark the end of the linear pitch bending range, where $|p_c/p_o|$ becomes smaller than 1.5 if p_m is increased. Black circles mark the regime switch, at which $|p_c/p_o| < 1$. The lip forces did not deviate by more than 5% during the measurements.

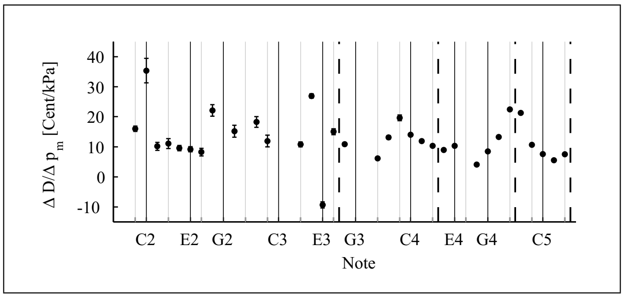

Figure 5. Linear fit coefficients indicating the sensitivity of pitch to moderate mouth pressure changes in the *piano* range at constant lip force. Mouth pressure variations were within $p_{m,pp} < p_m < 1.6\,p_{m,pp}$, where $p_{m,pp}$ is the mouth pressure in the softest possible articulation *pianissimo* at each note. Data were obtained by artifical blowing on Bocal 1 and Bassoon 3 with synthetic reed. Errorbars mark 95% confidence intervals. Missing values indicate notes for which the dependence is clearly non-linear (R^2 of the fit smaller than 0.75). Dashed vertical lines mark the register borders, thin vertical lines mark the notes of the C-major scale.

i) The absolute lip force needed to play a note in tune at a desired dynamic level.

ii) The lip force gradient when adjusting the dynamic level while playing this note.

The subjective impression of tuning quality from playing an instrument will be influenced by these two aspects. As training plays an important role, the judgment of a musician on an unknown instrument may be biased by the experience and habit with the regularly used instrument. In the following, we investigate the characteristics of artificial mouth parameters to play in tune, and relate the results of aspect i) to the subjective measurements studied in the previous section. In the experiments single working points (F_l, p_m) have been measured at which the pitch deviation D is within ± 5 Cent. These constitute the $F_l(p_m)$ -

characteristics for the musically relevant parameter ranges. In all experiments presented here the lip was at a medium position, i.e. the center of the contact area between artificial lip and reed was at $x_l = 7$ mm (Figure 3). The experimental procedure was as follows:

A moderate lip force of $F_l \approx 4$ N was applied by moving the lip towards the reed. The pressure regulating valve connecting a large over-pressure reservoir to the artificial mouth was slowly opened, until the reed started to oscillate near the expected fundamental frequency for the used fingering. Next, the lip force F_l has been increased, which led to a pitch increase, followed by a mouth pressure decrease to compensate the pitch. In this way, both parameters have been leveled iteratively to obtain the smallest blowing pressure $p_{m,pp}$, at which an oscillation at the desired frequency f_0 is possible. Starting from this *pianissimo*-regime the mouth pressure was gradually increased followed by a reduction of lip force. Stepwise, values of lip force as a function of mouth pressure have been recorded at which the instrument sounds in tune.

During the experiment, f_0 was monitored by means of a conventional digital pitch tuner for musicians. Measurements of the $F_l(p_m)$-characteristics for playing in tune have been carried out over the complete tonal range on several bassoons. Some exemplary results are shown in Figure 6, illustrating, that the artificial mouth is able to sound even very low notes on the bassoon at *pianissimo* level with a high degree of repeatability. The measurements shown in Figure 6 were repeated six days after the initial run; meanwhile the artificial mouth had been in use for other experiments. The mean air temperature in the mouth cavity did not change by more than 1.5°C during an experiment.

Between the measurements series, the mean temperature was in the interval 19.25 ±1.25°C. This corresponds to a temperature induced pitch change of not more than 3.5 Cent. Similar to the $D(p_m)$-characteristics for constant F_l (Figure 4), the $F_l(p_m)$-characteristics for constant D (Figure 6a) are roughly linear. As a complement to the input parameters lip force and blowing pressure, we show the resulting output parameters root-mean-square reed pressure and resulting pitch in Figure 6b to prove that the assumption $D \approx 0$ for the relevant playing range was satisfied.

Depending on the fingering, the slope and the range of the $F_l(p_m)$-characteristic lines differ significantly. The comparison of these curves provides insights into the necessary embouchure corrections required to play a succession of notes in tune. The instrument will appear poorly tuned if it requires large changes in lip force for the transition to other notes (e.g. from E♭3 to C3) played at the same dynamic level. The dynamic level of notes with a steep $F_l(p_m)$-characteristics (e.g B1, D♭2) cannot be altered without significant adjustments of F_l.

Another indication for a poorly tuned note is that it is not playable at extreme sound levels of the *pianissimo* or *fortissimo* range without changes of the embouchure other than a sole lip force variation at the same lip position (e.g. B1, D♭2 cannot be played at high mouth pressures). Furthermore, tuning instabilities can be observed in the $F_l(p_m)$-characteristics. The note C3 has a region where the slope is close to zero for the lip force with respect to the mouth pressure ($\partial F_l/\partial p_m \approx 0$, $p_m = 3.2$ to 4 kPa). This indicates, in agreement with the measurement shown in Figure 5, an unstable region which is difficult to control for the musician.

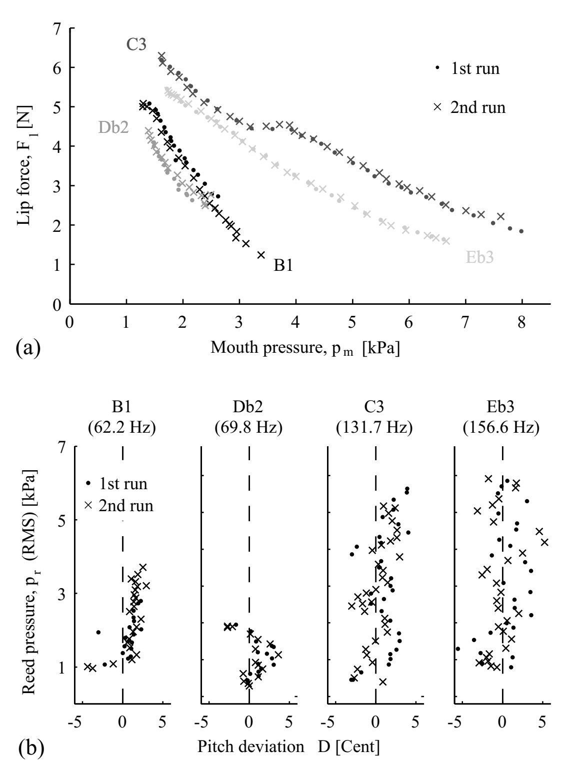

Figure 6. Repeatability of the blowing experiment with artificial mouth. Input parameters are lip force F_l and blowing pressure p_m (a). Output parameters (b) are the resulting root-mean-squared reed pressure p_r (RMS) and the pitch deviation D as control. The reed pressure p_r is measured in a synthetic bassoon reed (Figure 3).

Besides these qualitative relations between tuning perception and the measured lip force also quantitative data can be obtained. In order to characterize the tuning offset of a note by a single measure, we examined the lip force during playing in *mezzoforte*, which will be denoted $F_{l,mf}$.

As no physical reference exists for *mezzoforte* we rely here on the available experimental data. Data for the blowing pressures $p_{m,mf}$ associated with the dynamic level on a modern German bassoon have been measured with musicians by Fuks and Sundberg [27]. We use a quadratic fit to their data versus notes to obtain $p_{m,mf}$ for the full playing range and interpolate the measured $F_l(p_m)$ characteristics at these points.

Given the precise repeatability of the artificial mouth, other sources of variation in $F_{l,mf}$ can be studied. In this part of the investigation, we used two different bocals (Heckel CC1 and CD0) and the tuning reference was A4:

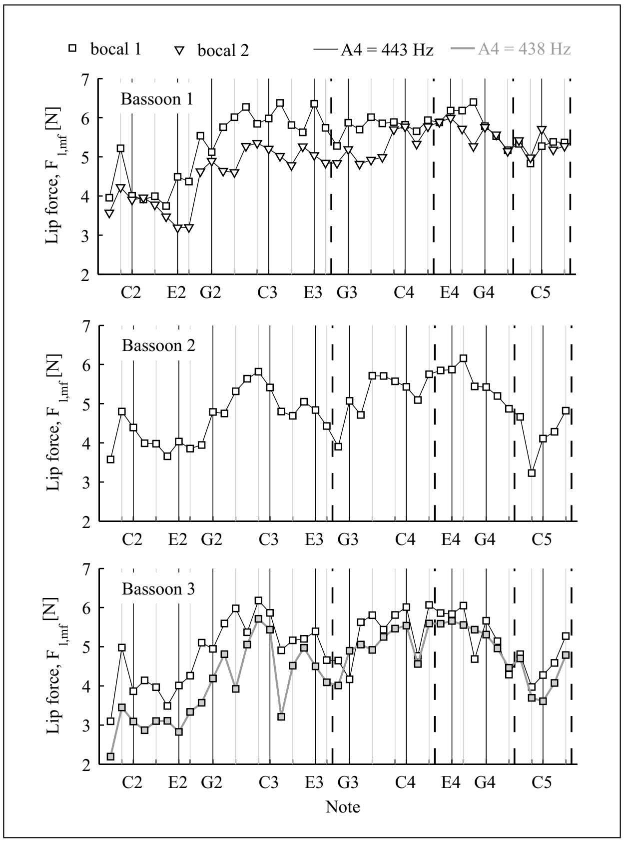

Figure 7. Lip force $F_{l,mf}$ from blowing experiments with an artificial mouth to play each note on the bassoon in *mezzoforte*. Values for the corresponding mouth pressures $p_{m,mf}$ are taken from [27]. For comparison, two bocals of different length have been used on Bassoon 1, and the measurement on Bassoon 3 has been carried out for two different tuning references for A4 (443 and 438 Hz). Dashed vertical lines mark the register borders, thin vertical lines mark the notes of the C-mr scale.

443 Hz. Bocal 1 has the standard length (“length 1”) recommended by Heckel[1]. Bocal 2 (“length 0”) is about 5.0 mm shorter from the far end. For most notes the second, shorter bocal required smaller lip forces to play in tune (Figure 7, upper plot). This is in partial agreement with the subjective intonation study, where some notes played with this bocal on Bassoon 1 and 2, in particular, tended to be sharp (Figure 1).

To study this aspect more in detail, Bassoon 3 has been played with the same bocal for two different tuning references, the standard pitch (A4: 443 Hz) and a low pitch (A4: 438 Hz), which is about 20 Cent lower. Playing the instrument at the low pitch required a significant reduction of lip force in particular for the lowest notes (Figure 7).

4. Discussion

The investigations of the tuning discrepancy of bassoon notes yields consistent results within each of the two different measurement strategies: Blowing experiments with musician and artificial mouth.

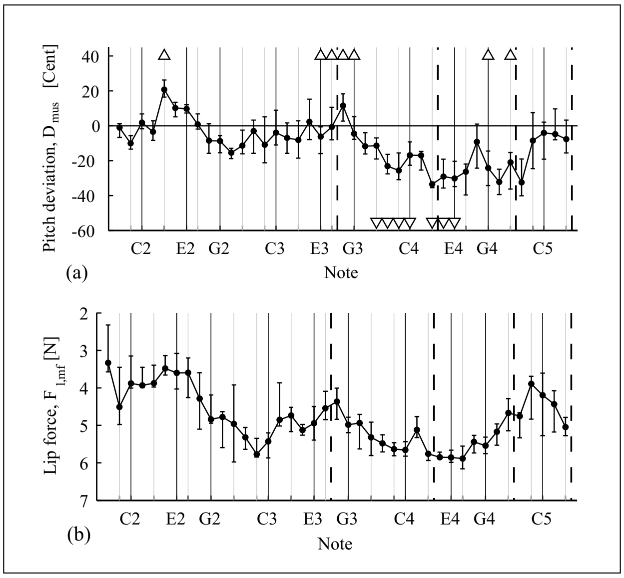

Figure 8. Comparison of (a) intonation characteristics and (b) lip force characteristics. (a) Tuning discrepancy D_{mus} when omitting embouchure corrections. The mean is computed from the data presented in Figure 1. Tuning tendencies of some critical notes as reported by musicians [29] is indicated by △ (sharp) and ▽ (flat). (b) Lip force $F_{l,mf}$ needed to play in tune. The mean is computed from the data presented in Figure 7. In both graphs (a) and (b) medians are marked by dots and the errorbars mark the interquartile range from the individual measurements ((a) $n = 18$, (b) $n = 5$). Dashed vertical lines mark the register borders, thin vertical lines mark the notes of the C-major scale.

In the subjective tuning data, the observed pitch deviations due to the variation of bassoon, bocal, and reed is small (Figure 1), nevertheless larger than the variability between different repetitions of the musician (Figure 2).

The average tuning deviation D_{mus} is significantly different from zero for some notes. These notes (D2, Eb2, E2: sharp, and Gb3, Ab3-Bb4: flat) thus constitute a common tuning characteristic of the bassoons studied here. The reed “hardness” apparently shifts this characteristic, such that “softer” reeds play sharper. To have a representative description, we average over all 18 subjective intonation curves to obtain the average tuning characteristic shown in Figure 8. Qualitatively the tuning characteristic resembles the lip force characteristic in Figure 8b, which is obtained from averaging over five series of lip force measurements on three bassoons with the same synthetic bassoon reed.

For musicians, it is known that some notes on the bassoon usually have specific tuning imperfections which need special attendance when practicing intonation [29]. Comparing the tuning tendencies (triangles in Figure 8a) of these notes with our data, a general qualitative agreement is found in the low and mid register. The agreement with a mean-corrected curve D_{mus} is even stronger (not shown), which might be an indication that the musician in [29] considered relative tendencies for a group of notes

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[1] Heckel recommends length 1-type bocals for a tuning reference A4: 442 Hz, which is to a negligible amount of −2.7 Cents flat compared to the tuning reference used here (A4: 443 Hz)

to be meaningful. The comparison of the present results with [29] however supports the hypothesis that the curves shown here are not merely a subjective result valid only for the one musician who took part in the present study.

The negative correlation between lip force $F_{l,mf}$ and the tuning discrepancy D_{mus} is well represented in the comparison of the present measurements with musician and artificial mouth. A flat tuning has to be compensated by a high lip force; a sharp tuning requires a reduction of force exerted to the reed. This is reflected in a simple linear regression model of the type

$$F_{l,mf} = \alpha_0 + \alpha_1\, D_{mus}, \qquad (2)$$

whose coefficients are $\alpha_1 = -0.039 \pm 0.013$ N/Cent and $\alpha_0 = 4.5 \pm 0.2$ N (95% confidence intervals, $R^2 = 0.49$) for the presented data (Figure 9). Considering the fundamental differences in both measurement approaches, the remaining, non-random variations induced by the individual reeds, bocals, and bassoons makes clear that no high correlation can be expected here.

Accurate lip force adjustment and measurement is crucial to obtain quantitative data for intonation studies that are relevant for the musical performance.

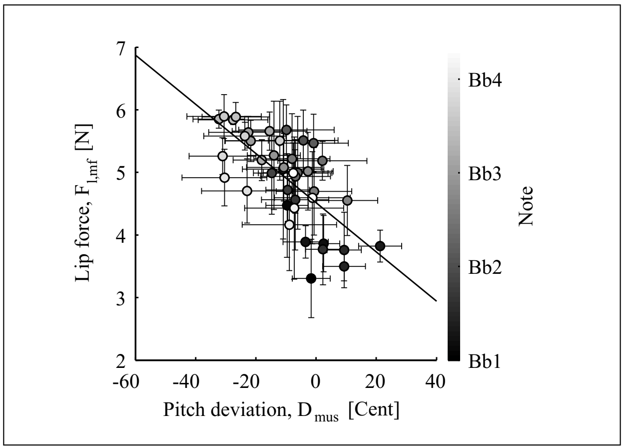

Figure 9. Relation between the lip force $F_{l,mf}$ needed to play in tune and the tuning discrepancy D_{mus} when omitting any embouchure corrections. Data points correspond to medians over five ($F_{l,mf}$) or 18 independent measurements (D_{mus}), respectively. Error bars mark interquartile ranges. The coefficients of the linear fit are $\alpha_1 = -0.039 \pm 0.013$ N/Cent and $\alpha_0 = 4.5 \pm 0.2$ N (95% confidence intervals, $R^2 = 0.49$).

5. Conclusions

Tuning quality of reed wind instruments is difficult to assess because the interaction of player and reed needs to be monitored under playing conditions. In addition to the reed slit height that can be adjusted by applying the lip force, the fundamental frequency depends strongly on the mouth pressure. The comparison of the pressure-force curve for individual fingerings allows to quantify the embouchure actions needed to play a succession of notes in tune and the necessary lip force adjustment due to variations in loudness. The curves further reveal the dynamic limits of particular notes and thus shed light on the overall intonation quality of the instrument. The characteristics can be measured with artificial mouths, but the musical relevance of the data obtained with such technical devices must be proven. The comparisons between musician and artificial mouth experiment presented in this study show a qualitative agreement and can be summarized as follows:

Measuring the lip force needed to play in tune is a useful method to investigate tuning aspects of reed wind instruments.

In artificial mouths the possibility of very accurate lip adjustment and lip force measurement is important to study aspects of tuning quality because very small changes lead to considerable tuning changes. The results show that synthetic bassoon reeds are suited to obtain meaningful information concerning the tuning properties of the acoustic resonator which are usually played with cane reeds. We conclude that bassoons of the modern German type have a common intonation curve and bocal and reed play a subordinate role.

Compared to input impedance measurements the experimental procedure used in this study obviously is much more laborious and longsome. The effort may be comparable to minimal-invasive technologies to directly measure the musician's control parameters during musical performance [22, 30]. The repeatability of the artificial mouth experiment, however, encourages subsequent investigations on the influence of the resonator on tuning and other playing characteristics. The impact of dedicated changes of the resonator's air column modes on the fundamental frequency can be studied during playing. The observation of many bassoonists that not the overall tuning but some dedicated notes are strongly affected by choice of a bocal should be studied further.

The possibility of playing the bassoon over the complete tonal range in a highly repeatable way is a promising feature of the artificial mouth. Stable and musically relevant oscillation regimes can be studied, even at very low blowing pressures and on the lowest notes of the bassoon. As a small set of adjustment parameters is sufficient, experimental data can be obtained which may be useful for parameter estimation in the existing simplified physical dynamical models [31, 17]. A better quantification of the musician-musical instrument interaction is needed to apply research in reed-resonator interaction to the practical problem of woodwind resonator design.

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