How clarinettists articulate: The effect of blowing pressure and tonguing on initial and final transients

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Articulation, including initial and final note transients, is important to tasteful music performance. Clarinettists' tongue-reed contact, the time variation of the blowing pressure $\bar{P}_{\text{mouth}}$, the mouthpiece pressure, the pressure in the instrument bore, and the radiated sound were measured for normal articulation, accents, *sforzando*, *staccato*, and for minimal attack, i.e., notes started very softly. All attacks include a phase when the amplitude of the fundamental increases exponentially, with rates $r \sim 1000\,\text{dB s}^{-1}$ controlled by varying both the rate of increase in $\bar{P}_{\text{mouth}}$ and the timing of tongue release during this increase. Accented and *sforzando* notes have shorter attacks ($r \sim 1300\,\text{dB s}^{-1}$) than normal notes. $\bar{P}_{\text{mouth}}$ reaches a higher peak value for accented and *sforzando* notes, followed by a steady decrease for accented notes or a rapid fall to a lower, nearly steady value for *sforzando* notes. *Staccato* notes are usually terminated by tongue contact, producing an exponential decrease in sound pressure with rates similar to those calculated from the bandwidths of the bore resonances: $\sim 400\,\text{dB s}^{-1}$. In all other cases, notes are stopped by decreasing $\bar{P}_{\text{mouth}}$. Notes played with different dynamics are qualitatively similar, but louder notes have larger $\bar{P}_{\text{mouth}}$ and larger r.
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I. INTRODUCTION

In woodwind playing, performers control the geometry of the instrument using their fingers, but for any given instrument geometry, they use their lips, breath, vocal tract configuration, and tongue to produce a note with (or approaching) the desired pitch, loudness, timbre, and transient behaviour. The initial or attack transient at the start of a note is associated with one of the salient perceptual dimensions of timbre and is important in identifying instruments (Berger, 1963; Thayer, 1974). Musicians refer to the transients that begin and end a note as articulation and consider articulation techniques to be an important part of expressive and tasteful playing. Different articulations are associated with different envelopes in the amplitude of the sound.

On the clarinet and other reed instruments, articulation usually involves control of the breath and also "tonguing," by which is meant the use of the tongue to touch the reed and to release it to start a note (Sadie, 1984; Sullivan, 2006), and also its less common use to stop a note by touching the reed. Discussion of tonguing and articulation techniques can be found in clarinet teaching material (e.g., Anfinson, 1969; Brymer, 1977; Thurston, 1977; Thurston and Frank, 1979; Sadie, 1984; Gingras, 2004; Sullivan, 2006) and, while there is some variation, some general principles may be summarised. In normal single tonguing, the tip of the tongue usually touches the reed and quickly releases it. Clarinet teachers usually advise moving the tongue as one would to pronounce a syllable beginning with t, such as "te." For rapid non-*legato* passages, double tonguing is often recommended: here the tongue mimes pronouncing "te-ke." The tongue alternately touches the reed ("te") and the hard palate ("ke"), the latter interrupting the flow of air. Other syllables such as "tat," "tah," "la," "ya," "da," *etc*. are also used to describe how to achieve different kinds of articulation (Gingras, 2004).

Although tonguing is involved in producing most articulations, the crucial aspect of its coordination with the mouth pressure remains unknown. Do players release the tongue at the same mouth pressure and then increase the pressure at different rates to produce different articulations? Do they release the tongue at different mouth pressures, if so do they release it above or below the oscillation threshold? Do the maximum pressures vary? Is the pressure ever increased or reduced after a note has started? Answers to these questions are important in understanding the acoustics of wind instruments in their transient state.

Furthermore, the answers could be highly useful in pedagogy. Despite the importance of this coordination between mouth pressure and tonguing, it is usually not mentioned explicitly in the pedagogical literature. Clarinet players and teachers, when asked, are usually unable to explain confidently how the mouth pressure varies in each different attack, and how it is coordinated with the tongue; this inability is not surprising given the brevity of the attack.

The clarinet is an obvious instrument on which to study these important questions about articulation, because its acoustical properties in the steady state are relatively well understood (e.g., Wilson and Beavers, 1973; Bak and Dolmer, 1987; Dalmont and Frappé, 2007, Almeida *et al.*, 2010; Almeida *et al.*, 2013). Although it might become possible to answer some of the above questions using a playing machine, it raises the problem of requiring additional psychophysical experiments to determine which envelopes

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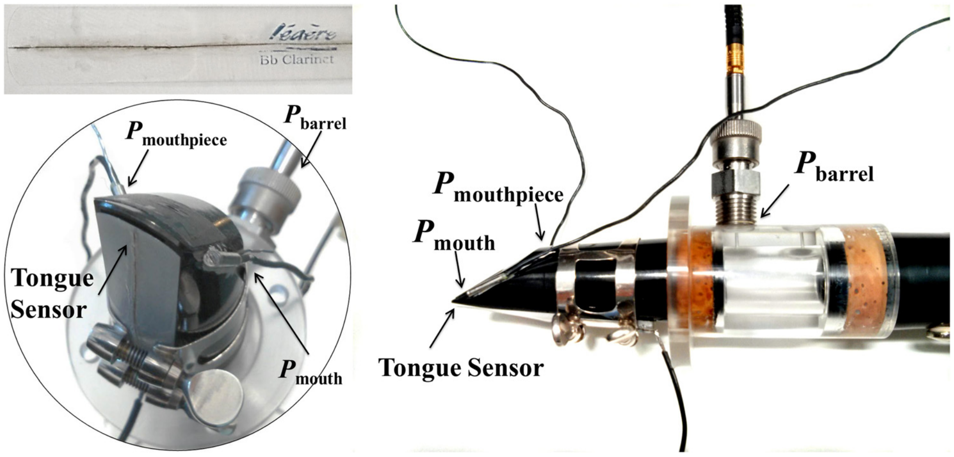

FIG. 1. (Color online) Photograph of the clarinet reed, mouthpiece, and barrel modified to measure tongue contact, mouth pressure, mouthpiece pressure, and barrel pressure during performance. The circular inset at bottom left shows a close-up of the mouthpiece tip, where the tongue sensor (reed with a wire glued on its axis) and the two pressure transducers are visible. A photo at top left shows the modified reed.

of the produced sound correspond to those consistent with musical notation. Performing ecological experiments with experienced players removes this problem—for example, an experienced player will produce a *sforzando* note that is consistent with the accepted meaning of the term.

In this paper, six different kinds of articulation played by six clarinettists were studied by simultaneously measuring the action of the tongue, the time course of the blowing pressure, the mouthpiece pressure, the pressure in the bore of the instrument, and the radiated sound. This allows the coordination between tonguing and the mouth pressure to be studied during the different attack transients, and the quantification of their relationship to the rise time of the sound.[1]

II. MATERIALS AND METHODS

A. Experimental setup

A Yamaha YCL 250 clarinet with a Yamaha CL-4C mouthpiece was used in this study. (This is a B♭ clarinet, and the written pitch is reported, e.g., written C5 sounds B♭4.) A Légère synthetic clarinet reed (hardness 3) was chosen because synthetic reeds can easily be played dry, are disinfected quickly and have stable physical properties during long studies (Almeida *et al.*, 2013).

An Endevco 8507C-2 miniature pressure transducer of 2.42 mm diameter was fitted at one side of the mouthpiece for measuring the blowing pressure inside the player's mouth during playing (Fig. 1). The tongue sensor was an insulated copper wire of 80 μm diameter that was glued to the middle of the lower surface of the reed. One end of the wire, with the insulation removed over 2 mm, was positioned flush with the tip of the reed. The other end connects to a simple circuit involving a 1.5 V battery and a 40 MΩ resistor connected to the player's thumb—see Fig. 2. When the player's tongue touches or releases the reed, it also makes or breaks contact with the end of the wire. The resultant change in the electrical current produces a voltage change across the resistor that is recorded via an optical isolator. (The optical isolator uses a modulated light signal to transfer an electrical signal between two isolated circuits that have no electrical connection. This ensures that, even in the event of insulation failure in the equipment, no electrical connection is possible between the player and the mains-operated apparatus.) Changes in contact between tongue and reed produce a sharp pulse in the recorded signal when differentiated by the high pass filter of the FireWire audio interface. Players said that they could not notice the very small current involved. Players reported that the presence of the wire increases the apparent hardness of the reed from 3 to approximately $3\frac{1}{2}$, but that otherwise it played normally. (3 or $3\frac{1}{2}$ are typical values of reed hardness used by professional "classical" clarinettists.) The mouth pressure signal was modulated to avoid its slowly varying (DC) component being removed by the high pass filter of the audio interface and was demodulated in subsequent data processing.

A second Endevco pressure transducer with the same specification was fitted into the mouthpiece through a hole on the other side of the mouthpiece, 27 mm away from the tip (Fig. 1), to measure the mouthpiece pressure. The normal clarinet barrel was replaced with a (transparent) plexiglass barrel with similar internal dimensions. A $\frac{1}{4}$-in. pressure-field microphone (Brüel & Kjær 4944A) was fitted into the wall of this barrel, 20.5 mm from the mouthpiece junction, to record the acoustic pressure inside the bore via a hole of 1 mm diameter. (The signal at this position is less affected

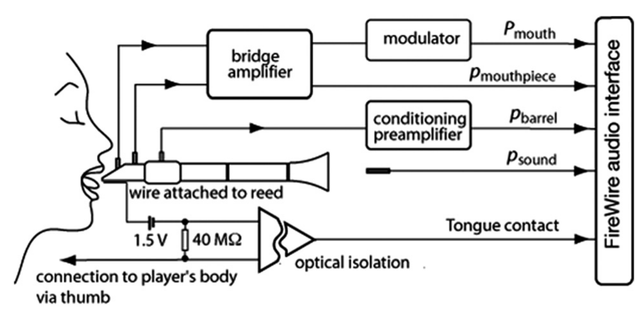

FIG. 2. A schematic diagram (not to scale) shows how tongue contact, mouth pressure, mouthpiece pressure, and barrel pressure are measured during performance.

by noise induced by turbulence than that measured in the mouthpiece.) Both Endevco and Brüel & Kjær microphones have frequency responses that vary by less than 0.5 dB over the range 20–5000 Hz. Another microphone (Rode NT3) was positioned one bell radius from and on the axis of the bell of the clarinet to record the radiated sound. Figure 2 shows the schematic setup.

B. Players and protocols

Six clarinettists having both classical and jazz backgrounds were involved in this study. Three of them were music students with at least seven years' music training and playing experience (players A, B, and C hereafter). The other three were expert players with at least eleven years of music training and extensive professional experience playing in orchestras and as soloists (D, E, and F).

This study was "ecological": its aim was to discover how players control the parameters involved in articulation in a musical context. For that reason, while players were told that the study was to investigate articulation, no detailed instructions were given in words. Instead, the "instructions" were given to them as music, using the normal notation, of which a short section is shown in Fig. 3. Before the formal measurements began, the players were allowed to practise until they became accustomed to the clarinet, mouthpiece, and reed. They were then given a sheet of music paper with the notes written C4, G4, C5, G5, and C6 (but sounding one tone lower on the B♭ clarinet). Six different kinds of articulation were written, all separated by extended rests (*fermate*), to allow players to release completely the mouth pressure between successive notes. The requested articulations included normal (no articulation instructions given with the note), accented (with > above the note), *sforzando* (*sfz*), *staccato* (a dot above the note). Normal, accented, and *sforzando* were notated as half notes (minims) and *staccato* was notated as quarter notes (crochets) and, in all cases, the loudness (or "dynamic," in musicians' terms) was notated *mf* (*mezzo-forte* or medium loud). Following this exercise, subjects were asked to produce notes starting as softly as possible, both using the tongue and without using the tongue (hereafter called minimal attack with tonguing and without tonguing). Every articulation for each note was repeated at least six times. Finally, normal and *staccato* notes were also played with the notations *pp* (very soft) and *ff* (very loud) for comparison. The notation used is shown in Fig. 3 for the case of C4, but not including the repetitions of the note. Tongue contact, mouth pressure, mouthpiece pressure, barrel pressure, and radiated sound were recorded simultaneously. These experimental tasks and data obtained are summarised in Table I. After the measurements had finished, each player was asked to complete a questionnaire about their musical background and experience, and how they understand and play different articulations.

To extract the amplitude of individual harmonics, an algorithm first divides the quasi-periodic signal into individual frames, each of which has a length approximately equal to the period of the fundamental. A set of time markers are then extracted which have approximately the same phase. In a second step, a Fourier transform gives an estimate of the amplitude and phase of each harmonic. This provides a time-resolution of one period, at the expense of a slightly noisier amplitude value, because any random noise in the signal contributes to the amplitude of the harmonics. This procedure can also introduce some errors because the exact period usually corresponds to a non-integral number of samples. Tested on some synthesised signals, the method showed up to twice the amplitude error that could be obtained using a heterodyne detection (HD) method, but gave twice the time resolution. For this paper, the improved time-resolution allowed a better estimate of the exponential rate of increase, particularly for rapidly increasing signals. It also avoided any small errors that the presence of frequency modulation might introduce when using the HD method.

III. RESULTS AND DISCUSSION

A. Responses to the questionnaire

Subjects described the different ways in which they use their tongues and how they play different articulations. Five of the six subjects reported that they had not thought about the questions in detail previously. Nevertheless, interesting generalisations can be made from their answers.

About tonguing techniques, all the subjects reported that for starting a note, the "proper" or "correct" way is to increase the blowing pressure before the tongue releases the reed. When starting a note, subjects all agreed that the tongue is used like a switch, i.e., it prevents reed vibration until the moment when the note is required to start. For the accent articulation, they agree that a higher blowing pressure is allowed to build up before the tongue release. This suggests that players could be aware of the existence of the oscillation threshold above which a note can start spontaneously and that tongue control allows a note to be started at a required moment despite the blowing pressure being higher than the threshold. When finishing a note, most of the subjects mentioned that whether the tongue is employed depends on the music style. Decreasing blowing pressure without the tongue touching the reed provides a "soft" finish, but the rapid finish involved in *staccato* requires the use of the tongue to stop reed vibration.

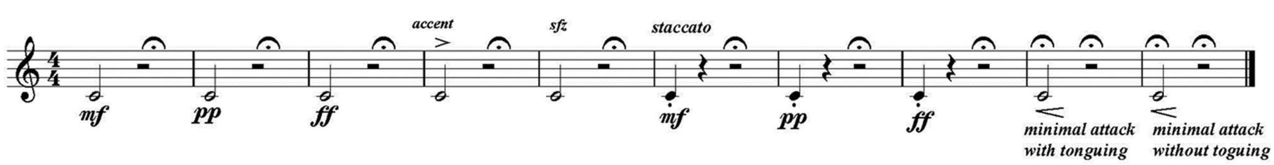

FIG. 3. Sample using the note C4 to illustrate the notation used to elicit the articulations studied here.

TABLE I. Summary of experimental protocols. Lower case p indicates an acoustic pressure, P the total pressure. Every articulation for each note was repeated at least six times.

Subjects	Articulations	Notes	Dynamics	Measured signals
3 experts	normal	C4	*mf*	tongue contact
3 students	accented	G4	*pp* (normal and *staccato* only)	P_{mouth}
	sforzando	C5	*ff* (normal and *staccato* only)	$p_{mouthpiece}$
	staccato	G5		p_{barrel}
	minimal attack with tonguing	C6		p_{rad}
	minimal attack without tonguing			

Two subjects emphasised that only the tip of the tongue should touch the very tip of the reed. However, different views were expressed when discussing the motion of the tongue. Some subjects thought the tongue travels forwards and backwards (horizontally) and others thought it should only move vertically. The cinefluorographic study by Anfinson (1969) showed that the tongue tip can travel in both directions.

The subjects also expressed different opinions about whether there is air flowing into the instrument while the tongue is still touching the reed. Two subjects suggested maintaining air flow whereas one suggested blocking the reed aperture by the tongue. Others mentioned that either can happen depending on the type of articulation.

Three subjects expressed the view that the tongue action is basically the same for all of the articulations, but that the time dependence of blowing pressure varies among different articulations, and that its coordination with the instant of tongue release may also vary for different articulations. [The initial transient occurs over a timescale (∼100 ms) that makes it difficult to sense the order of events, so it is possible that players may be mistaken.]

Players reported that playing an accent usually requires a higher blowing pressure and a "stronger" use of the tongue than normal. *Sforzando* may require "lighter" tonguing at onset, but (after the peak pressure) a faster decay of blowing pressure than an accent. They all agreed that *staccato* involves a brief tongue touch after the sound starts, to stop the note. Minimal attack, either with or without tonguing, is reported to require a slower increase and a lower value of blowing pressure. All the subjects thought that the softest possible start occurs without tonguing. In addition, one subject also emphasised the importance of maintaining a constant force applied on the reed by the lip while starting a note.

B. Mouth and mouthpiece pressure

In the following, the measured pressures are compared and contrasted in three stages. First, the overall features of the mouth and mouthpiece pressures are compared. Then the radiated sound is discussed. Next the attack transient and its components are examined in detail.

Figure 4 shows typical examples of the mouth pressure P_{mouth}, mouthpiece pressure p_{mp}, and radiated sound p_{rad} when subject D played the written C5 note (nominally 466 Hz) with four of the different types of articulations.

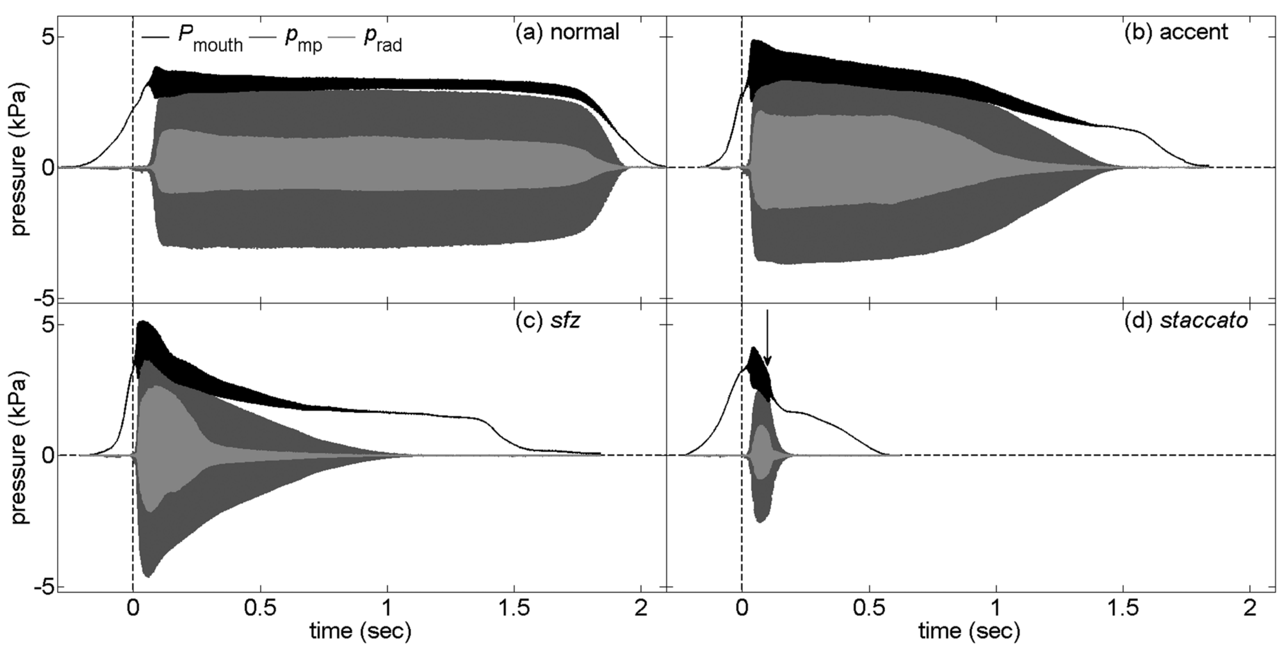

FIG. 4. Measured mouth pressure P_{mouth} (black, including DC and AC components), mouthpiece pressure p_{mp} (dark grey), and radiated sound p_{rad} (light grey, not calibrated) as functions of time for typical examples of four of the different articulations of the written C5 note, as played by subject D (one of the expert players). $t = 0$ is defined as the instant when the tongue ceased contact with the reed. In (d), the vertical arrow shows the moment when the tongue touches the reed to stop the note. These and other sound files from this study are available online (Music Acoustics, 2015) and in supplementary materials.

Subject D is one of the three expert players and the data of this subject are used to present typical features of the tonguing and mouth pressure variation here and in the discussion later. In each of the plots, the zero of the time axis is defined as the instant when the tongue breaks contact with the reed. In Fig. 4(d), i.e., *staccato*, the downwards arrow shows the moment when the tongue touches the reed to stop the note—the only articulation when this occurred. (Details of the onset region for these four articulations are shown on an expanded time axis in Fig. 5.)

P_{mouth}, the pressure measured inside the mouth, contains a slowly varying (DC) component and a high-frequency or AC component due to the vibrating reed and finite acoustic impedance of the mouth. The DC mouth pressure $\bar{P}_{\mathrm{mouth}}$, as one of the important parameters that players can control, was extracted for further study by averaging the measured mouth pressure using a moving Blackman window covering three or four cycles of the note.

For the normal articulation, $\bar{P}_{\mathrm{mouth}}$ increases rapidly before the tongue releases the reed at $t = 0$—see Fig. 4(a). After $t = 0$, $\bar{P}_{\mathrm{mouth}}$ continues increasing and then remains almost constant for most of the duration of the note, before gradually decreasing. Soon after the tongue releases the reed at $t = 0$, the amplitude of the acoustic pressure in the mouthpiece p_{mp} starts to increase until its amplitude is comparable with $\bar{P}_{\mathrm{mouth}}$. Towards the end of the note, p_{mp} decreases while $\bar{P}_{\mathrm{mouth}}$ decreases. For this normally articulated note, p_{mp} decays to zero when $\bar{P}_{\mathrm{mouth}}$ decreases to about 1 kPa.

For the simply accented note, $\bar{P}_{\mathrm{mouth}}$ is increased more rapidly, and attains a higher value at tongue release $t = 0$ and a higher peak value before decreasing—see Fig. 4(b). Unlike in the normal note, both $\bar{P}_{\mathrm{mouth}}$ and p_{mp} then begin a small, steady decrease during the note before a final, more rapid decrease. Here, p_{mp} decays to zero when $\bar{P}_{\mathrm{mouth}}$ decreases to about 1.5 kPa.

The *sforzando* note has an even more rapid increase of $\bar{P}_{\mathrm{mouth}}$, and an even higher value of $\bar{P}_{\mathrm{mouth}}$ at $t = 0$—see Fig. 4(c). After reaching a higher peak value, $\bar{P}_{\mathrm{mouth}}$ decreases rapidly to a nearly steady value and remains near that value while the note fades to zero when $\bar{P}_{\mathrm{mouth}}$ decreases to around 1.8 kPa.

For the *staccato* note, $\bar{P}_{\mathrm{mouth}}$ rises more slowly than for the accent or for *sforzando*, but reaches a comparably high value—see Fig. 4(d). Only for this articulation is the tongue used to stop the reed vibrating after $\bar{P}_{\mathrm{mouth}}$ has decreased.

In all measurements, the acoustic component of the mouth pressure is typically 5–10 times smaller than the pressure in the mouthpiece. On all notes, the acoustic pressure in the mouth is also much less than that in the mouthpiece or barrel. This can be explained using the observation of Elliot and Bowsher (1982) and Benade (1985): From continuity, the flow out of the mouth $-U_{\mathrm{mouth}}$ is equal to that flowing into the bore of the instrument, U_{bore}. Thus, writing Z for the acoustic impedance

$$\frac{p_{\mathrm{mouth}}}{p_{\mathrm{bore}}} = \frac{Z_{\mathrm{mouth}} U_{\mathrm{mouth}}}{Z_{\mathrm{bore}} U_{\mathrm{bore}}} = -\frac{Z_{\mathrm{mouth}}}{Z_{\mathrm{bore}}}. \quad (1)$$

Usually, the magnitudes of the peaks in the mouth impedance spectra are substantially smaller than those of the bore impedance, except for advanced techniques such as pitch bending (Chen *et al.*, 2009). Further, if the player is not tuning the vocal tract resonance, which is usually the case for normal playing, the frequency of the note played is not exactly at a peak of the mouth impedance. Thus, the magnitude ratio of mouth impedance to bore impedance, and therefore the ratio of acoustic pressure magnitudes, is expected to be substantially less than 1.

C. Radiated sound

The envelope of the radiated sound in Fig. 4 is not simply proportional to that of mouthpiece pressure because the two signals have different spectral envelopes. The standing wave in the bore is dominated by the fundamental. However, the radiated sound has proportionally more power at high frequencies because these are more efficiently radiated by the bell. The difference in harmonic content and brightness can be clearly heard in the online sound files.

For the musician, the radiated sound, p_{rad}, is very important. Players (and, for students, their teachers) listen to the sound and adjust their technique so as to approach what is thought to be an ideal envelope of the sound produced in a particular musical situation. For that reason, and because of the time spent practising, the envelope recorded can be considered to approach the ideal that the player wished to achieve: the radiated sound shows how the players interpreted the instructions (none), (accent), *sforzando*, and *staccato*.

In all the four cases in Fig. 4, the maximum in p_{rad} is achieved in the first $\sim$150 ms after the tongue release. For the normal and accent case, it then reduces slightly before maintaining a near steady value. For the accented note, however, p_{rad} rises about twice as rapidly as for the normal note. A difference in the attack rise time is a salient feature (Krumhansl, 1989; Caclin *et al.*, 2005). p_{rad} also rises quickly in the *sforzando* note, but it rises to a higher level, then falls rapidly before a further slow decay. The key feature of the *staccato* note is its brevity: p_{rad} rises to a level slightly below that of the normal note and then decays. The sound examples shown in Fig. 4 and others are available on line (Music Acoustics, 2015) and also included as supplementary material.

D. Attack transients

The attack transients are of particular interest. Figure 5 shows examples of the mouth pressure $\bar{P}_{\mathrm{mouth}}$, barrel pressure p_{barrel}, and p_1, i.e., the amplitude (RMS) of the fundamental frequency extracted from p_{barrel}, when subject D played the written C5 note with normal, accent, *sforzando*, and *staccato*. Again, $t = 0$ is defined as the instant when the tongue ceases contact with the reed. The vertical arrow in Fig. 5(d) indicates the instant when the tongue touches the reed to stop the note. p_{barrel} and p_1 are shown on a logarithmic scale (dB with respect to 20 μPa) to illustrate their approximately exponential growth, while $\bar{P}_{\mathrm{mouth}}$ is shown on a linear scale.

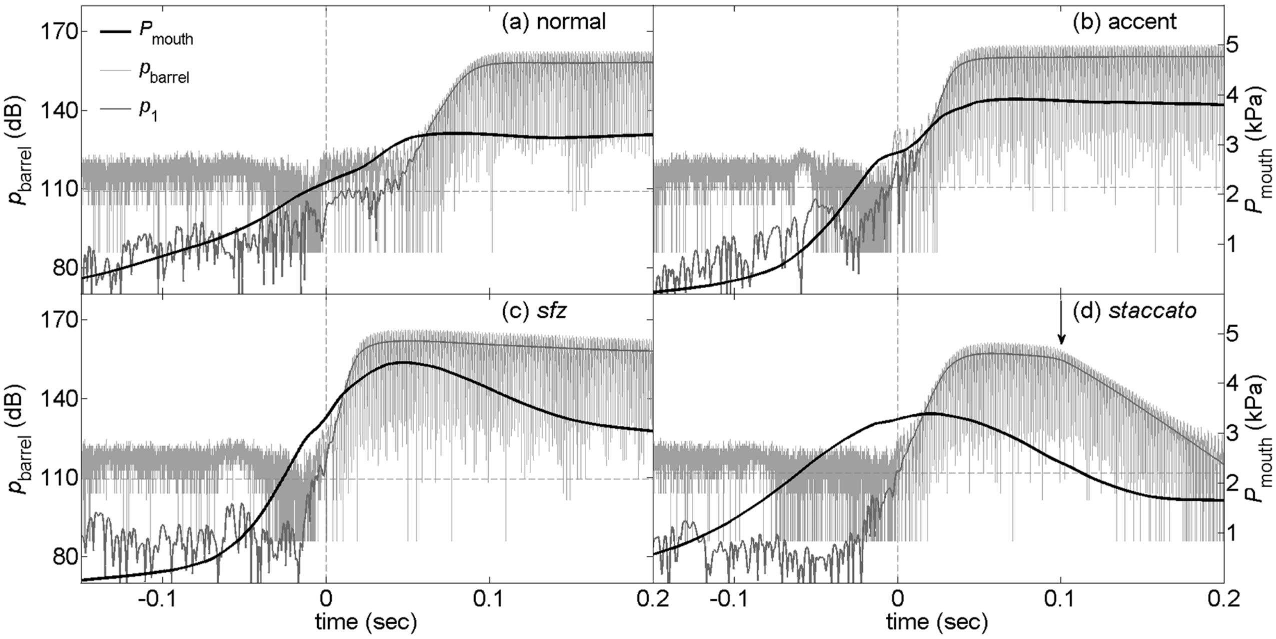

FIG. 5. The slowly varying (DC) component of the mouth pressure $\bar{P}_{mouth}$ (black), and the amplitude (RMS) of the fundamental p_1 (dark grey) extracted from the barrel pressure p_{barrel} (light grey) for different articulations for the written C5 notes played by subject D. In each example the horizontal dashed line indicates the noise level in the barrel in dB calculated over the 0.1 s before tongue release.

Rather than studying the amplitude of the overall radiated sound, the amplitude of the fundamental frequency in the barrel (p_1) is plotted because it can be determined in the presence of considerably larger background noise. (The power in the noise is distributed over many frequencies and so contributes little power at the frequency of p_1.) Further, p_1 is extracted from p_{barrel} rather than p_{mp} because the barrel signal is much less affected by the noise due to turbulent flow past the reed than is the pressure in the mouthpiece, and this allows p_1 to be distinguished at a much lower level. The barrel microphone is located 93 mm from the reed tip and, for example, the wavelength for the written G4 note is about 1 m. So, with an antinode of pressure in the standing wave occurring in the mouthpiece, there is only a small variation in p_1 between mouthpiece and barrel (several % for this note).

Before the tongue releases the reed, no periodic sound is observed and the noise level in the barrel calculated over the immediately preceding 100 ms (about 109 dB with respect to 20 μPa) is used as a reference level for the beginning of the note; it is indicated by the dashed line in each figure. The brief and slight increase in the noise in p_{barrel} that occurs about 50 ms before the tongue release at $t = 0$ is due to the tongue touching the reed. Then the noise decreases as the tongue starts to release from the reed. After the tongue release and until a few tens of ms before the maximum value occurs, the growth of p_1 during the initial transient appears approximately linear on this semi-log graph, indicating an exponential growth in p_1 during most of the attack transient in each case. However, this growth starts about 40 ms after the tongue release in the example of Fig. 5(a), suggesting that, for this player and this note, the normal articulation has the tongue release the reed at a $\bar{P}_{mouth}$ value below the oscillation threshold. In the other three examples, the approximately exponential increase in p_1 starts immediately after tongue release, indicating a tongue release at or above the threshold. (Differences among players are discussed below.) As shown in Fig. 5, the attack time and the exponential rate of increase of p_1 vary substantially for different articulations. The variation in $\bar{P}_{mouth}$ with time—another example of how players can control the attack—also shows different features.

E. Rise time and rate of increase in the fundamental

For further analysis, several additional parameters describing the behaviour of $\bar{P}_{mouth}$ and p_{barrel} are now defined and illustrated in Fig. 6. Using the subscript s for "starting," p_s is defined as the value of the fundamental (p_1) when it first exceeds the average noise level (i.e., p_s equals the average noise level) and P_s is defined as the value of $\bar{P}_{mouth}$ at this instant. An empirical measure to characterise the end of the exponential phase of the attack is taken when p_1 has a value 6 dB below the peak value of p_{barrel}. (6 dB is chosen because the exponential phase does not terminate abruptly.) The rise time Δt is accordingly defined as the time taken for p_1 to increase from p_s to the end of the exponential phase. P_{av} is the average value of $\bar{P}_{mouth}$ during this rise time Δt. R (in Pa s^{-1}) denotes the average linear rate of increase in $\bar{P}_{mouth}$ and r (in dB s^{-1}) denotes the average exponential rate of increase in p_1 during the rise time.

Figure 7 shows Δt, the rise time and r, the exponential rate of increase of the fundamental p_1. (There is a strong negative correlation between these, but they are not exactly in inverse proportion, because the starting and maximum pressures vary.) The averages and standard deviations are shown for normal, accented, *sforzando* and *staccato* notes played by experts (grey) and students (white). Figures 7(a) and 7(c) show the results for the written C4 note, Figs. 7(b)

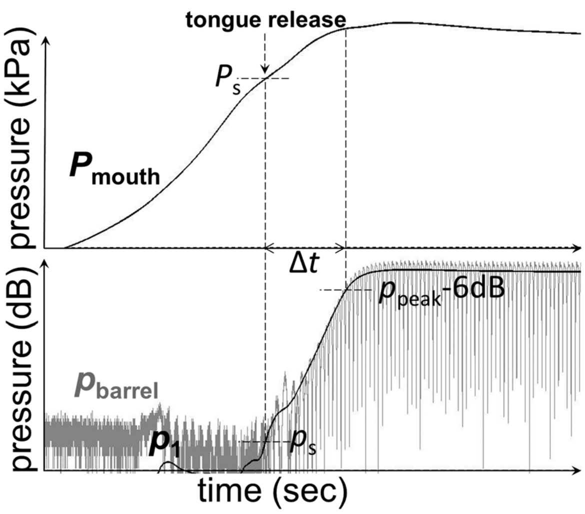

FIG. 6. Plot showing how the parameters are defined. The graph at top shows the variation of $\bar{P}_{mouth}$ with time. That at bottom shows on a dB scale the time variation of p_{barrel} (grey) and p_1, the amplitude (RMS value) of the fundamental extracted from p_{barrel}. The "starting value" p_s is defined as the value of the fundamental (p_1) when it first exceeds the average noise level and the "starting" mouth pressure. P_s is defined as the value of $\bar{P}_{mouth}$ at this instant.

and 7(d) for the written G5 note. These two notes are chosen for discussion because C4 is near the middle of the lower or chalumeau register and G5, 12 notes higher, is near the middle of the clarino register. The only difference in fingering for the two is the addition of the register key for G5: this weakens and de-tunes the first impedance peak (Dickens *et al.*, 2007) causing the instrument to play at the second peak. Typical standard deviations of Δt and r for both groups are about 20%. About half of this variation is due to variations among players: for an individual player the standard deviation is typically 10%, as shown below.

For experts playing C4 and G5, and for students playing C4, the accented and *sforzando* notes usually have the shortest rise time and the largest averaged r among the four articulations studied here, while *staccato* notes have intermediate values (as shown in the typical example in Fig. 5). A two-sample t-test comparing both Δt and r of normal notes with those of the other three articulations showed that the accented, *sforzando* and *staccato* notes are significantly different from normal notes at the 5% significance level. The exception was for the written G5 *staccato* notes played by the students. A two-sample t-test also shows that the normal, *sforzando*, and *staccato* notes played by the students have longer rise times and smaller p_1 rates of increase than those played by experts (significant at the 5% level), except for the rise time for the written C4 *staccato* notes. The rise times and p_1 rates of increase of accented notes played by the two groups are similar.

Figure 8 shows the averaged rise time Δt and the rate r of exponential increase in the fundamental p_1 with standard deviation for normal, accented, *sforzando* and *staccato* notes played by each of the three experts. Figures 8(a) and 8(c) show the results of the written C4 note, Figs. 8(b) and 8(d) for the written G5 note. The repetitions of each note with each articulation played by each expert were reproducible, with typical variations in the averaged rise time and p_1 rate about 10%.

The foregoing qualitative similarities among the different players indicate the influence of a common musical culture: each player understands what accent, *sforzando*, etc., mean, and has learned how to produce gestures with qualitatively appropriate features. Thus, when compared with normal notes, accented and *sforzando* notes have a shorter rise time and larger p_1 rate, whereas *staccato* notes have intermediate values. Quantitatively, however, the rise time and p_1 rate values of notes with a given articulation vary somewhat

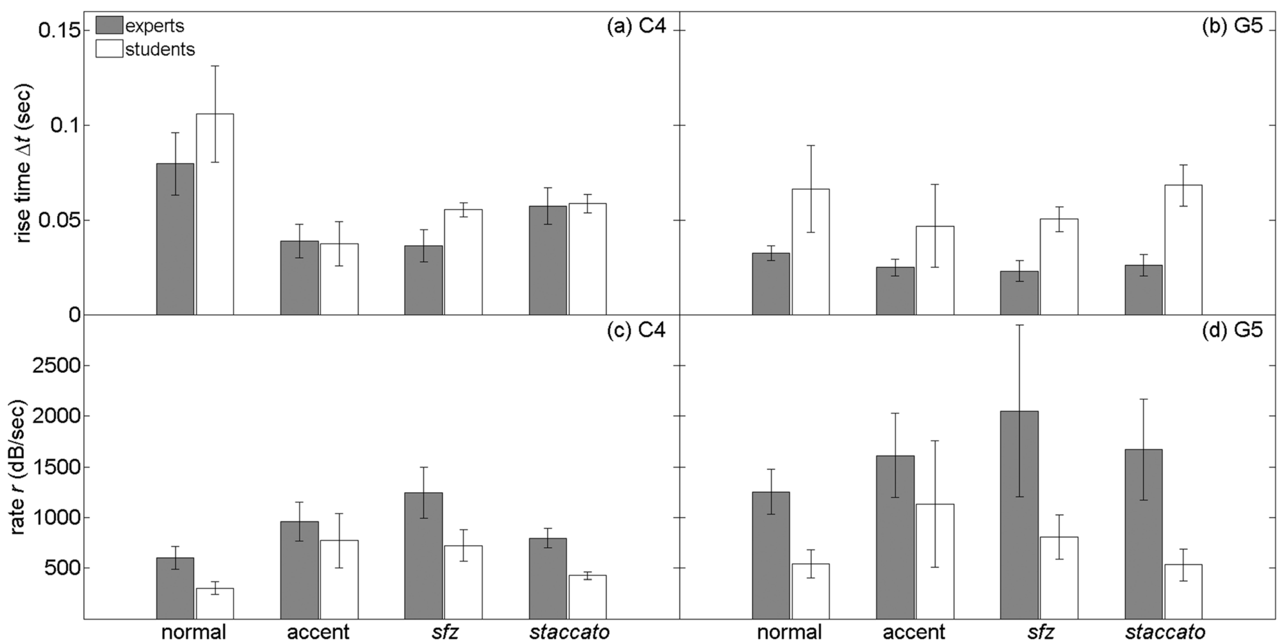

FIG. 7. The average rise time Δt and the rate r of exponential increase of the fundamental p_1. The averages and standard deviations are displayed for normal, accented, *sforzando* and *staccato* notes played by experts (grey) and students (white). (a) and (c) show the values for the written C4 note, (b) and (d) for the written G5 note. Vertical lines indicate the standard deviations.

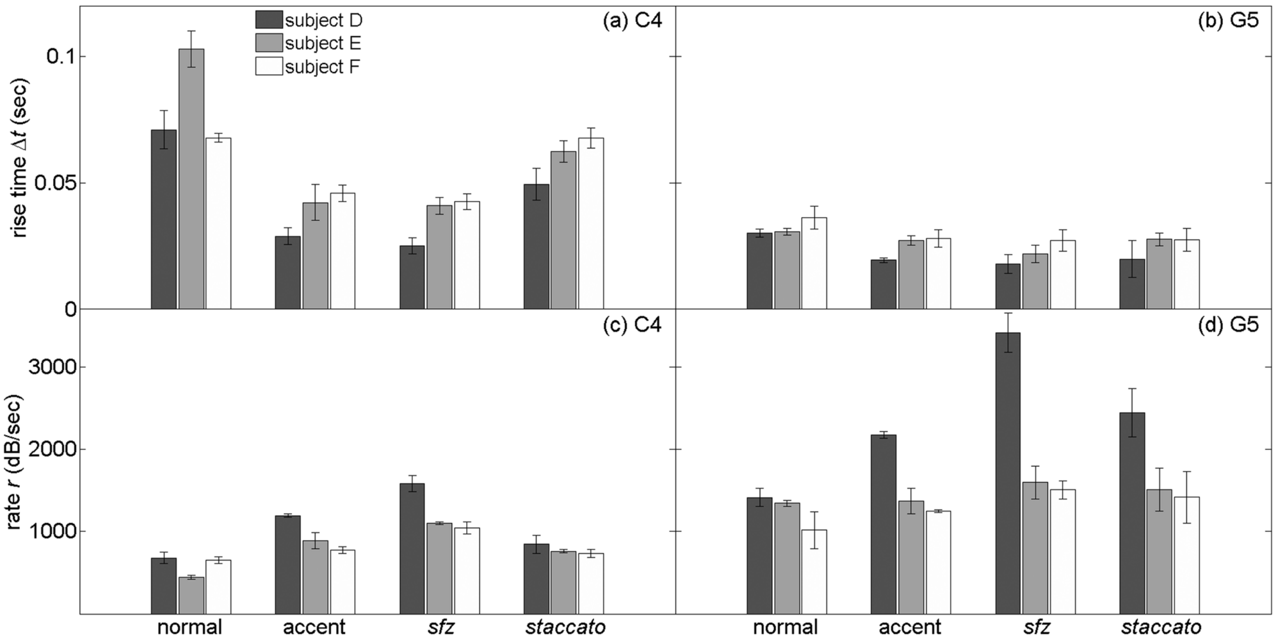

FIG. 8. The averaged rise time Δt and the rate r of exponential increase in the fundamental p_1 for normal, accented, *sforzando*, and *staccato* notes played by each of the three experts. (a) and (c) show the values for the written C4 note, (b) and (d) for the written G5 note. Bars with different shading represent the three expert subjects. Vertical lines show standard deviations.

among players. Expert subject D (dark grey bars in Fig. 8) generally played the notes with a shorter rise time and a larger p_1 rate than the other two expert subjects (E and F), whose data are more similar. This occurs for other notes investigated here as well. Results for the three students also suggest that each player shows consistent values that might be said to contribute to that player's personal style.

F. Tonguing and mouth pressure variations during the attack

The effects of tonguing and $\bar{P}_{\text{mouth}}$ upon p_1 can now be considered. Figures 5 and 6 show that the increase in p_1 can occur immediately upon tongue release [Figs. 5(b), 5(c), 5(d), and 6], or be delayed [Fig. 5(a)]; these conditions correspond to the tongue being released when $\bar{P}_{\text{mouth}}$ is, respectively, above or below the oscillation threshold. The timing of the tongue release with respect to the attaining of the oscillation threshold thus affects the attack transients and could be different for different articulations and for different notes; it could also vary among players. Figure 9 shows the proportion of cases in which tongue release precedes note onset for the four articulations discussed above, for the student and expert players. Two general observations can be drawn from Fig. 9. First, for all the articulations, tongue release precedes the note onset more frequently for higher notes. For the written G5 and C6 notes, 95% of all measurements of these notes showed that both experts and students tend to release the tongue below the oscillation threshold, whereas the proportion is much lower for C4, G4, and C5 notes. Subject C (one of the students) always plays *sforzando* notes without using the tongue, thus the proportion for *sforzando* notes of the student group is higher than that of expert group. Second, for C4, G4, and C5 notes, tonguing above the threshold occurs more frequently for accent and *sforzando* notes than that for normal and *staccato* notes, i.e., higher

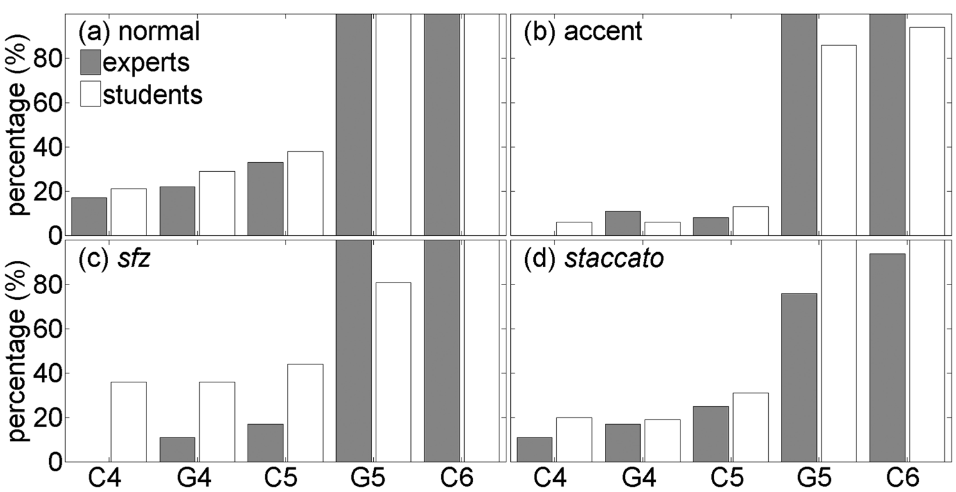

FIG. 9. The percentage of measurements in which the tongue release precedes the note onset, i.e., the tongue is released below the oscillation threshold.

chances of tongue release above the threshold for articulations with higher rate r. Why do players coordinate the tongue and breath in this way?

Tongue release above the threshold involves a higher value of $\bar{P}_{\mathrm{mouth}}$, and this in turn produces a higher rise rate r and a shorter rise time Δt for the note. The shorter rise time is required for playing accent, *sforzando* and *staccato* notes so, for lower notes, these articulations are tongued above the threshold. For higher notes, however, shorter rise times are achieved without tonguing above threshold—see Fig. 9. Players (particularly experts) always tongue below threshold for all of the high note articulations, except *staccato* (where the proportion is high but not 100%, perhaps because of the speed required for *staccato*). It is worth noting that tonguing below threshold introduces a delay between tonguing and note onset that may be tens of ms [e.g., Fig. 5(a)]. In this case, note onset may be largely controlled by an analogue variable ($\bar{P}_{\mathrm{mouth}}$), rather than a binary one (tongue contact).

The values of $\bar{P}_{\mathrm{mouth}}$ during the rise time are expected to be important for controlling the attack transients. Figure 10 shows the mouth pressure at onset, P_{s}, the rate R of increase in mouth pressure, and the average mouth pressure P_{av} during the rise time. These are shown with standard deviation for normal, accented, *sforzando*, and *staccato* notes played by each of the three experts, with the same shading as in Fig. 8. The rate R is similar for both of the written C4 and G5 notes, but the P_{av} values required for playing G5 with rapid attacks are lower (cf. Fig. 8). Hence G5 is usually initiated below threshold (Fig. 9), whereas the lower note is tongued above threshold. For a given note, accented and *sforzando* notes usually have higher P_{av} and rate R than normal and *staccato* notes. Expert subject D (dark grey shading in Figs. 8 and 10) showed a much larger increase rate in $\bar{P}_{\mathrm{mouth}}$ and also showed a somewhat higher P_{av} than the other two expert subjects. The three students also show individual consistency, but there are differences between notes and between players.

G. Minimal attack

The accent, *staccato*, and *sforzando* articulations discussed above each have a specific musical notation, and normal articulation is elicited by the absence of a specific instruction. Another articulation, idiomatic to the clarinet, is to begin a note at very low sound level and with the least noticeable attack. This articulation is variously called minimal attack, softest start, lightest tonguing or, colloquially, "sneak in." All players were asked to produce minimal attack both with and without tonguing.

$\bar{P}_{\mathrm{mouth}}$ and p_{mp} profiles for minimal attacks with and without initial tonguing present features that differ from those of other articulations. For comparison, Fig. 11 shows typical examples of $\bar{P}_{\mathrm{mouth}}$, p_{mp}, and p_{rad} when subject D played the written C5 note with these two articulations. Compared with normal notes, $\bar{P}_{\mathrm{mouth}}$ for minimal attack notes, either with or without tonguing, is increased more slowly and has a lower value when the sound starts. Then $\bar{P}_{\mathrm{mouth}}$ continues to increase until it is decreased to end the note. For minimal attack with tonguing, the values of $\bar{P}_{\mathrm{mouth}}$ when the tongue is released are also lower than those for normal notes. As might be expected, the rate of increase R for initial tonguing was smaller than that for normal playing; for experienced players, $R = 1.55 \pm 0.74$ (C4) and 1.22 ± 0.99 (G5) kPa s^{-1}; the rate was even lower for students, with $R = 1.03 \pm 0.69$ (C4) and 0.72 ± 0.68 (G5) kPa s^{-1}.

For both types of minimal attack, $\bar{P}_{\mathrm{mouth}}$ shows a local maximum or overshoot that approximately coincides with

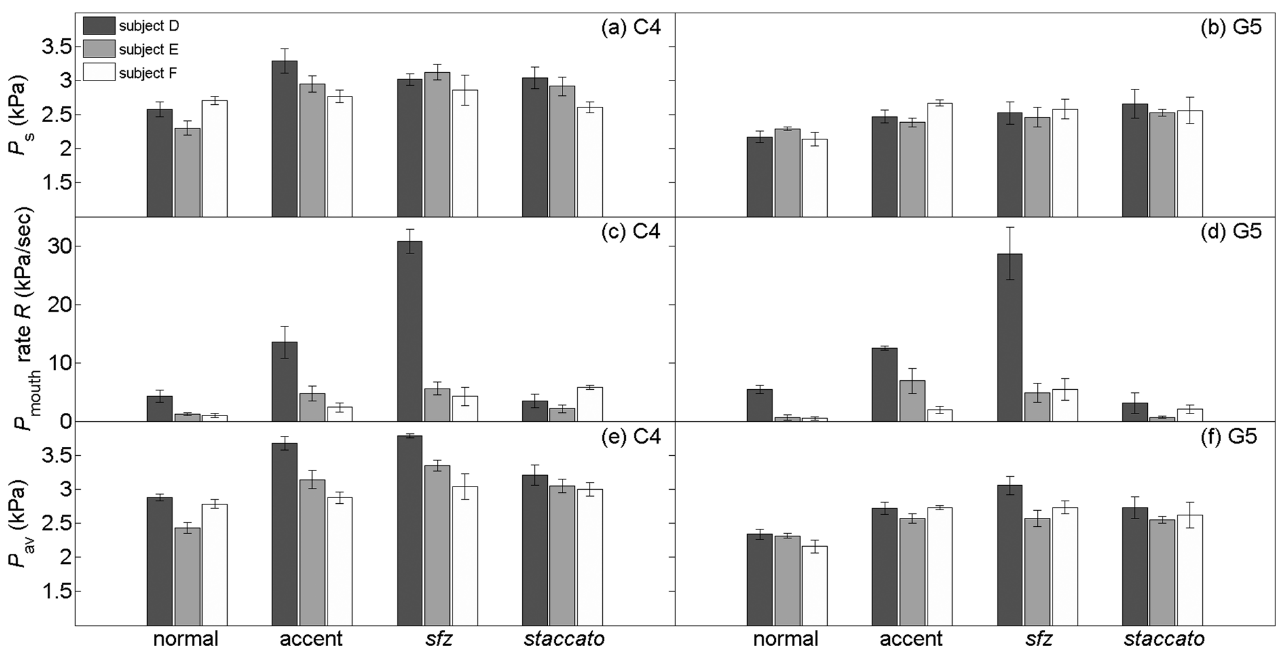

FIG. 10. The starting mouth pressure P_{s}, the rate R of increase in $\bar{P}_{\mathrm{mouth}}$, and the average mouth pressure P_{av} during the attack. Means and standard deviations for normal, accented, *sforzando*, and *staccato* notes played by each of the three experts are shown. Written note C4 at left, G5 at right. Different shading indicates the three expert subjects.

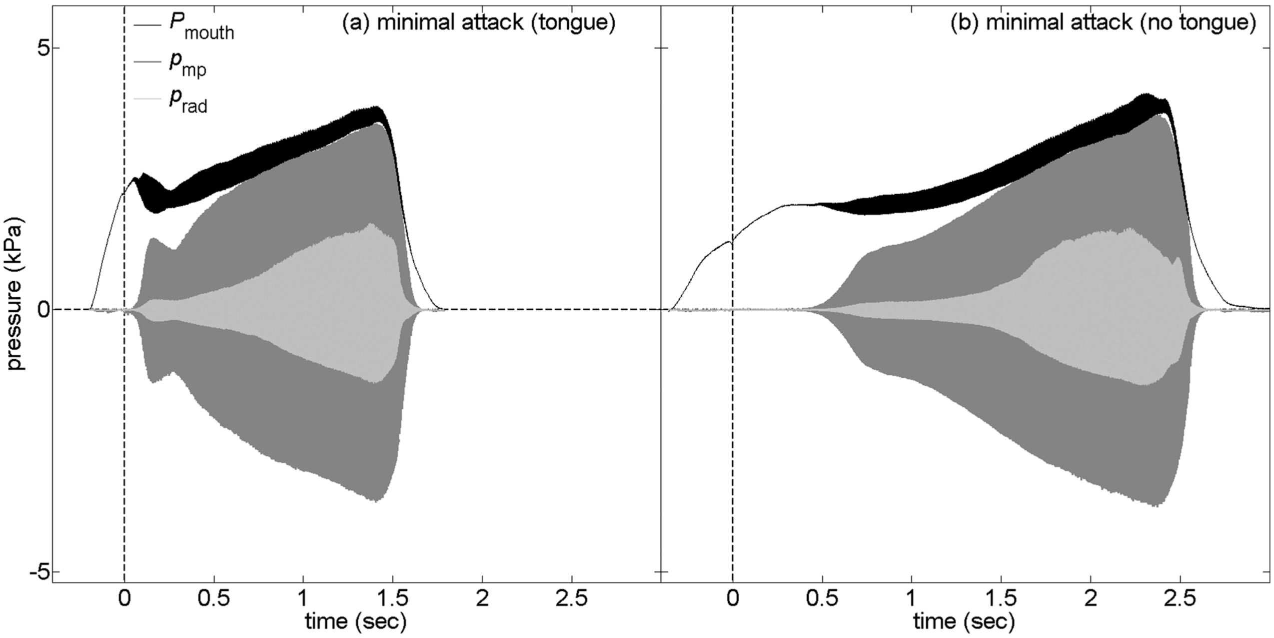

FIG. 11. Measured mouth pressure P_{mouth} (black), mouthpiece pressure p_{mp} (dark grey), and radiated sound p_{rad} (light grey) as functions of time for typical examples of minimal attack (a) with tonguing and (b) without tonguing of the written C5 note, as played by subject D (one of the expert players). $t = 0$ is defined as the instant when the tongue breaks contact with the reed.

the start of the note. It appears that the player briefly increases the pressure above a threshold level, then reduces it to avoid a too rapid increase in the sound. Compared with minimal attack notes with tonguing, those without tonguing have smaller values of the local maximum in $\bar{P}_{mouth}$. Further, the time to reach this pressure is several times longer and has much greater variability, indicating that, without tonguing, notes can be started at even lower $\bar{P}_{mouth}$ and $\bar{P}_{mouth}$ rate R, but with a greater uncertainty in time. This is consistent with observations by Bergeot *et al.* (2014) using a clarinet-playing system: a lower average rate for $\bar{P}_{mouth}$ corresponds to a lower dynamic threshold. (Note that, for the minimal attack performed "without tongue," the tongue is released while the mouth pressure is already a little elevated but still well below threshold.)

For both types of minimal attack, the fundamental p_1 also shows approximately exponential growth during attack transients, but the exponential increase rate, r, is rather lower, usually less than 500 dB s^{-1}. r also has a larger standard deviation. This slower rate is the consequence of smaller values of P_s and P_{av}, ranging from approximately 1.5 to 2.5 kPa. In the interview, all the subjects said that the softest possible start occurs without tonguing. Consequently, it is not surprising that the minimal attack without tonguing has even smaller values for P_s, P_{av}, and the rate r of exponential increase in the fundamental p_1. The values of these parameters vary between players and for different notes, but all players produce the two articulations using qualitatively similar gestures.

The lower values of $\bar{P}_{mouth}$ and r were one reason for including the minimal attack articulations, because they allow investigation of the dependence $r(\bar{P}_{mouth})$ in the lower range. The inclusion of *pp* and *ff* notes (discussed below) also contributes data at either end of the $r(\bar{P}_{mouth})$ range.

H. Control of the attack transient by mouth pressure and tonguing

For a given threshold pressure, a player can, in principle, control the attack in two main ways. The rate R of the rise in mouth pressure is one control parameter. P_s, the mouth pressure when the level of the fundamental (p_1) first exceeds the average noise level, is another: if the tongue is released early as the mouth pressure rises, P_s can be small. The results in Table II show a correlation between R, the linear rate of increase of $\bar{P}_{mouth}$ and r, the exponential rate of increase of p_1: a higher r can thus be obtained by increasing R. However, the correlation between r and P_s is even stronger.

So r depends on both P_s and R. The average mouth pressure P_{av} during the rise time of the attack can also be viewed as a control parameter which depends directly on both P_s and $\bar{P}_{mouth}$ rate R: starting at a larger P_s or increasing R gives a larger P_{av}. Table II shows the linear regression analysis of r and P_{av}, r and P_s, and r and $\bar{P}_{mouth}$ rate R for the two notes discussed. P_{av} and r have the strongest correlation suggesting that P_{av} can be regarded as a single, effective control parameter for obtaining a desired r. For instance, playing accented and *sforzando* notes generally requires a larger P_{av}, though different players may use different combinations of P_s and R to achieve a larger P_{av} value. p-values for all cases are less than 10^{-7}.

In Fig. 12, the exponential rise rate r in the fundamental p_1 is plotted against P_{av} for the written C4 and G5 notes. Different symbols correspond to different articulations; grey and white symbols correspond to experts and students, respectively. The strong correlation is evident between P_{av} and r: this is not surprising: a pressure well above the threshold gives a more rapid increase rate r, while the relatively low P_{av} (produced mainly in the minimal attacks) gives a small r.

TABLE II. The correlations between the rate r of exponential increase in the fundamental frequency and three parameters describing the mouth pressure $\bar{P}_{\text{mouth}}$: P_{av} is the average mouth pressure, P_{s} is the mouth pressure when the note starts, and R is the rate of increase of $\bar{P}_{\text{mouth}}$. The number of samples for each regression varied from 75 to 78.

		Correlation between r and P_{av}		Correlation between r and P_{s}		Correlation between r and R, the rate of increase of $\bar{P}_{\text{mouth}}$	
Players	Notes	Slope (dB s^{-1} kPa^{-1})	Coefficient of determination	Slope (dB s^{-1} kPa^{-1})	Coefficient of determination	Slope (dB kPa^{-1})	Coefficient of determination
Experts	C4	600	0.92	680	0.80	20	0.58
	G5	1840	0.85	2020	0.70	50	0.55
Students	C4	610	0.84	740	0.75	20	0.43
	G5	910	0.78	1070	0.78	70	0.40

For the written C4 [Fig. 12(a)] and for G4 and C5 (data not shown), the correlation between P_{av} and r is similar for the experts and students. Both experts and students usually use a higher P_{s} and P_{av} values while playing accented and *sforzando* notes, and these higher pressures lead to a more rapid increase rate and a shorter rise time. At the other end of the range, the professionals use lower values of P_{av} when playing minimal attacks. For playing the same articulation, the differences in r and P_{av} between experts and students are modest, although experts use a larger range of P_{av}. However, for the higher notes G5 [Fig. 12(b)] and for C6 (data not shown), the experts achieve more rapid rise rates r with P_{av} values lower than those used by students.

The strong dependence of r on P_{av} shows that players can control r and thus the rise time Δt by controlling P_{av}, the average pressure between tongue release and near saturation. P_{av}, in turn, depends on the rate R of increase in $\bar{P}_{\text{mouth}}$ and the pressure P_{s} at note onset, which is usually the moment of tongue release (see Fig. 9). Wind instrument players are able to vary mouth pressure using muscles of the torso and airways (Vauthrin *et al.*, 2015). Varying P_{s}, on the other hand, is often achieved by timing the release of the tongue, whose mass is smaller and whose muscles are presumably more agile than those of the torso. So it is interesting to see how P_{s} and R contribute to r.

Figure 13 shows the average values of r plotted against the average values of P_{s} and of R for normal, accented, *sforzando* and *staccato* notes played by each subject for the note C4. To show how individuals vary these parameters to achieve the different articulations, a line joins the normal to each other articulation, for each player. Compared with normal notes, almost all the subjects increase both P_{s} and R (though with different combinations) while playing accented, *sforzando*, and *staccato* notes. Qualitatively similar results were observed for other notes. So, overall, players use both P_{s} and $\bar{P}_{\text{mouth}}$ rate R to determine the exponential rate r (and thus the rise time Δt). However, while there is considerable scatter in R, the dependence of r on P_{s} is more consistent.

I. Finishing transients of *staccato*

Among the six types of articulations studied here, *staccato* is the only one for which players consistently used the tongue to stop notes. For other articulations, the tongue occasionally touched the reed at the end of a note, but for most of these cases, $\bar{P}_{\text{mouth}}$ was already well below the oscillation threshold when the tongue touched and, although there is significant hysteresis, the level of the periodic sound had already decreased to very low values (less than 20 dB above the noise level). In contrast, for the *staccato* articulation, the three expert subjects and one of the student subjects (A) all stop the notes using the tongue when playing C4, G4, C5, and G5 notes. However, for the C6 note, tongue touch occurs during the decay produced by decreasing $\bar{P}_{\text{mouth}}$. Student subject C did not use the tongue to stop any notes and subject B only terminated the note with the tongue when playing G4. (In the interview, all six subjects stated that they used

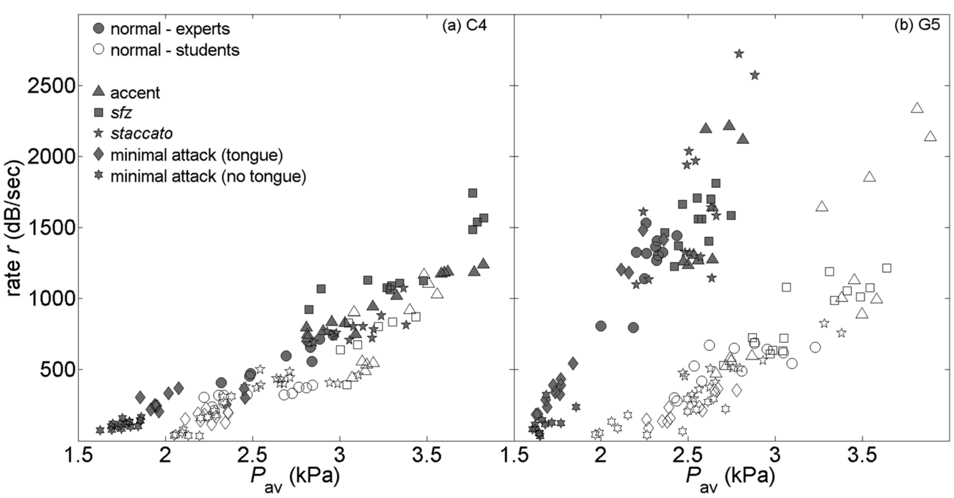

FIG. 12. The rate r of increase in fundamental p_1 versus P_{av} for normal, accented, *sforzando*, *staccato*, and minimal attack notes with and without tonguing played by experts (grey) and students (white), (a) C4 and (b) G5 notes. Different symbols indicate different articulations.

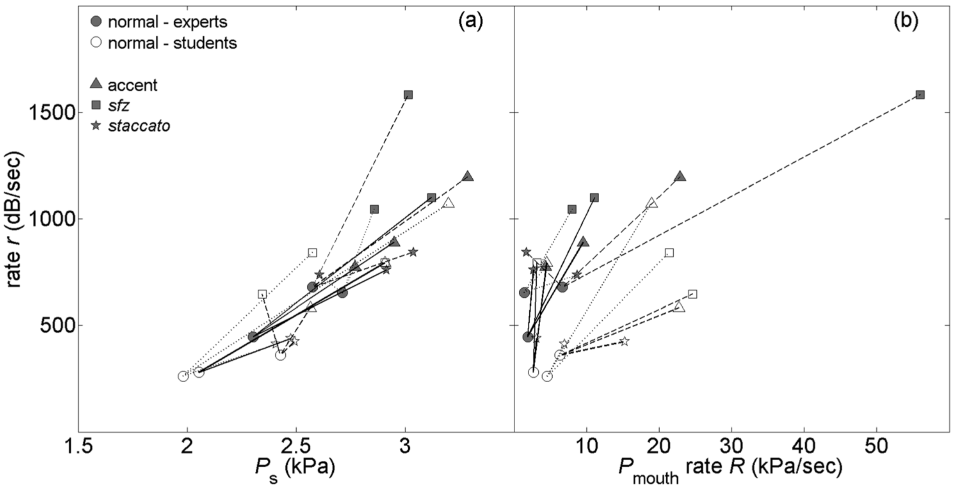

FIG. 13. The average rate r of increase in fundamental p_1 versus (a) average P_s and (b) $\bar{P}_{mouth}$ rate R for normal, accented, *sforzando*, and *staccato* notes played by each subject for C4 note. A line is shown for each subject connecting each accented, *sforzando*, and *staccato* note to the normal note of that subject. Different symbols and lines indicate different articulations and subjects; grey and white symbols stand for experts and students.

the tongue to stop the notes. This confusion by two of the students is understandable: the *staccato* note stops quickly and the relative timing may be hard to perceive.) Why is the tongue not used to stop the high notes? A likely explanation is that these have higher values of threshold pressure, which means that they can be stopped by a small reduction in the mouth pressure, so the tongue is not needed to achieve a rapid final transient. The players may use the same gesture as for low notes, but the note has already stopped by the time the tongue touches the reed.

Figure 14 shows two examples of *staccato* notes played by two subjects: stopped with and without using the tongue. For the note stopped using the tongue, the fundamental amplitude p_1 shows a nearly exponential decrease in amplitude (a constant rate of dB s^{-1}) in the finish transient immediately after tongue touch. The total duration of the tongue-stopped note is much shorter in this case (a) than in the case (b) where the note is stopped by allowing the mouth pressure to fall below the value where the note can be maintained.

When or very soon after the tongue touches the reed, the process of auto-oscillation is assumed to stop. From this moment, the energy in the standing waves in the bore is lost due to viscothermal losses in the walls and, to a lesser extent, radiation from the bell and tone holes (e.g., Benade and Gans, 1968). For a resonance, the quality factor Q, by definition, is 2π times the ratio of the energy stored in the oscillating resonator (E_S) to the energy dissipated per cycle (E_L) by damping processes. Defining E as the time average of energy stored:

$$Q = 2\pi \frac{E_S}{E_L} = 2\pi f \frac{E}{dE/dt} = \frac{2\pi f}{2\frac{d(\ln p)}{dt}}, \tag{2}$$

where f is the oscillating frequency and p is the pressure in the resonator, i.e., p_{barrel}. So the exponential rate of decrease r can be expressed as

$$r = \frac{d(20\,\log_{10}p)}{dt} = 20\log_{10}e\,\frac{d(\ln p)}{dt} = \frac{20\pi f\,\log_{10}e}{Q}. \tag{3}$$

Q is also equal to the frequency-to-bandwidth ratio of the resonator. Thus, the rate r can be calculated using the Q values derived from the acoustic impedance spectra measurements of the clarinet (Dickens *et al.*, 2007), for the resonance at the fundamental frequency, which is the dominant component for all these notes. The decay rates thus calculated are shown in Table III, together with the values measured in the finishing transients of the *staccato* notes stopped using the tongue.

The two sets of data in Table III are in approximate, but not excellent, agreement. One possible explanation for the

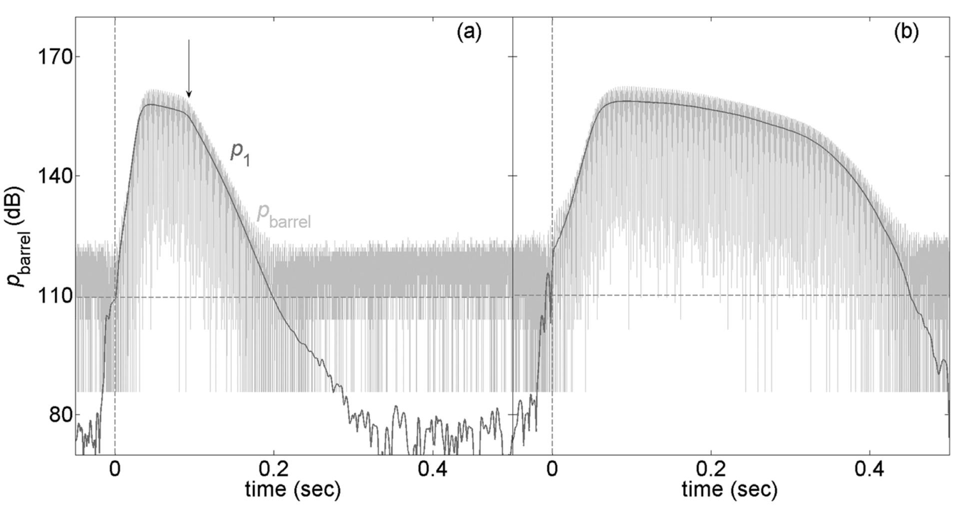

FIG. 14. p_{barrel} (light grey) and p_1 (dark grey) of two G4 *staccato* notes played by subject D and C, respectively: stopped (a) with and (b) without using the tongue. The vertical arrow in (a) shows the moment when the tongue touches the reed. Note the nearly exponential decrease over 4 orders of magnitude (a linear decrease on this semi-log plot). In (b), the note is stopped by allowing the mouth pressure (not shown here) to fall below the value where the note can be maintained.

TABLE III. Values of the exponential rate of decrease r calculated from the measured acoustic impedance of the clarinet and those obtained from the finishing transients of the *staccato* notes stopped using the tongue.

Rate r (dB s^{-1})	C4	G4	C5	G5
Calculated from bandwidth	250 ± 40	320 ± 30	450 ± 50	540 ± 50
Measured here	340 ± 80	400 ± 30	380 ± 30	520 ± 50

difference is the boundary condition in the mouthpiece: a reed touched by the tongue might still leave a gap, which would give a boundary condition that could vary among players and notes, and which would differ from the sealed mouthpiece used for the impedance measurement. Similar values of r are found in a study on note extinction by stopping a note in different ways (Guillemain *et al.*, 2014).

The exponential decrease in the sound level when the reed stops vibrating explains why stopping the note with the tongue does not produce the unpleasant sensation of a "click" in the sound, as is produced when a periodic sound is stopped by reducing its amplitude abruptly to zero.

J. Different dynamics

As well as the *mezzoforte* notes discussed above (medium loud, notated *mf*), the subjects were also asked to play normal and *staccato* notes with different sound levels or, as a musician would say, different dynamics. These instructions were given using the usual musical notation: *pp* (very soft) and *ff* (very loud). As expected, they show qualitative similarities but quantitative differences in the rise time Δt, the p_1 rate r, the onset pressure P_s, and the averaged value of $\bar{P}_{mouth}$ during rise time compared with those played with *mf*: notes played with *pp* have smallest r and smallest P_{av} values, *ff* notes the largest. The correlation between P_{av} and p_1 rate r for the normal and *staccato* notes played with *pp* and *ff* also follows the correlation for those played with *mf* and those of other articulations shown in Fig. 12, but with data points distributed in the different regions, e.g., P_{av} values for the C4 normal notes played with *pp* and *ff* played by experts range from 1.9 to 2.4 kPa and from 2.6 to 3.6 kPa, respectively.

For normal notes played at *ff*, it is interesting to compare the attacks with those of accented notes at *mf*. A series of two-sample t-tests at the 5% significance level compared Δt, r, and P_{av} values of these two types of notes. For Δt, only 48% of all the 30 cases (five notes for each of the six subjects) show a rejection of the null hypothesis (significant difference), and for r and P_{av}, the rejection rate of the null hypothesis is 56% and 65% (when comparing these values for accented and normal note played with *mf*, the rejection rate is higher than 83%). This suggests that, for these players, an accented note at *mf* has a faster attack than a normal note, and this is achieved with a greater mouth pressure: the accented *mf* note is achieved using values comparable with those used in a normal note at *ff* and for a comparably brief period.

IV. CONCLUSIONS

All the initial transients of the fundamental frequency in the bore pressure show approximately exponential increases with rate r. A large range of values of r (from 50 to 2700 dB s^{-1}) can be produced by varying the mouth pressure P_s at note onset and R, the subsequent rate at which the mouth pressure is increased. The rate r is most strongly correlated with P_{av}, the average mouth pressure during the rise for the attack transients of all the notes of all the articulations studied, including those of minimal attack notes with low P_{av} and r values. P_{av} is in turn dependent on P_s and R. To achieve a larger r in the attack transients used for accented and *sforzando* notes ($r \sim 1300$ dB s^{-1}, compared with $r \sim 800$ dB s^{-1} for normal and *staccato*), players increase both P_s and R: they control both the timing of the tongue release and the rate of increase in $\bar{P}_{mouth}$ ($P_{av} \sim 3.0$ kPa, compared with $P_{av} \sim 2.6$ kPa for normal and *staccato*). Experts usually produce shorter rise times and larger rates r of increase in the fundamental p_1 than do students. For higher notes, the experts achieve large rise rates r with P_{av} values lower than those used by students.

Minimal attack notes show a much lower exponential increase rate ($P_{av} \sim 2.1$ kPa and $r \sim 250$ dB s^{-1}) and greater variability in the attack transients, with $\bar{P}_{mouth}$ reduced after its maximum, which avoids a rapid increase in the sound level. Minimal attack notes without tonguing can be started at even lower $\bar{P}_{mouth}$ than those with tonguing, but with greater uncertainty in onset time. For all articulations in the higher notes, the tongue almost always releases the reed before the note onset; this is rare in low notes, particularly for expert players.

When playing *staccato*, players usually touch the tongue to the reed at the end of the note. For all but the high notes, this tongue touch initiates the end of the note via a rapid exponential decay. The quality factors calculated using these decay rates are similar to those calculated from the bandwidth of the corresponding impedance peaks. For low *staccato* notes, experts use the tongue to stop the note more frequently than do students. For high *staccato* notes, and for all notes with other articulations, the note is stopped by reducing the mouth pressure before the tongue touch.

Normal and *staccato* notes played with *ff* are qualitatively similar to those played with *mf*, but with larger p_1 rate and averaged $\bar{P}_{mouth}$ values, and vice versa for those with *pp*.

It appears that notes with different types of articulations produced by different players are qualitatively similar, but have often been achieved through different combinations of mouth pressure and tonguing.

ACKNOWLEDGMENTS

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[1]A report of a pilot study on this topic, using only one subject, was presented at ISMA 2014 (Li *et al.*, 2014).

Almeida, A., Lemare, J., Sheahan, M., Judge, J., Auvray, R., Dang, K. S., John, S., Geoffroy, J., Katupitiya, J., Santus, P., Skougarevsky, A., Smith, J., and Wolfe, J. (**2010**). "Clarinet parameter cartography: Automatic mapping of the sound produced as a function of blowing pressure and reed force," in *Proceedings of International Symposium on Music Acoustics*, Sydney, Australia.

Almeida, A., George, D., Smith, J., and Wolfe, J. (**2013**). "The clarinet: How blowing pressure, lip force, lip position and reed 'hardness' affect pitch, sound level, and spectrum," J. Acoust. Soc. Am. **134**, 2247–2255.

Anfinson, R. E. (**1969**). "A cinefluorographic investigation of selected clarinet playing techniques," J. Res. Music Educ. **17**(2), 227–239.

Bak, N., and Dolmer, P. (**1987**). "The relation between blowing pressure and blowing frequency in clarinet playing," Acta. Acust. Acust. **63**, 238–241.

Benade, A. H. (**1985**). "Air column, reed, and player's windway interaction in musical instruments," in *Vocal Fold Physiology, Biomechanics, Acoustics, and Phonatory Control*, edited by I. R. Titze and R. C. Scherer (Denver Center for the Performing Arts, Denver, CO), Chap. 35, pp. 425–452.

Benade, A. H., and Gans, D. (**1968**). "Sound production in wind instruments," Ann. N.Y. Acad. Sci. **155**, 247–263.

Bergeot, B., Almeida, A., Gazengel, B., Vergez, C., and Ferrand, D. (**2014**). "Response of an artificially blown clarinet to different blowing pressure profiles," J. Acoust. Soc. Am. **135**, 479–490.

Berger, K. W. (**1963**). "Some factors in the recognition of timbre," J. Acoust. Soc. Am. **36**, 1888–1891.

Brymer, J. (**1977**). *Clarinet* (Macmillan, New York).

Caclin, A., McAdams, S., Smith, B. K., and Winsberg, S. (**2005**). "Acoustic correlates of timbre space dimensions: A confirmatory study using synthetic tones," J. Acoust. Soc. Am. **118**, 471–482.

Chen, J. M., Smith, J., and Wolfe, J. (**2009**). "Pitch bending and glissandi on the clarinet: Roles of the vocal tract and partial tone hole closure," J. Acoust. Soc. Am. **126**, 1511–1520.

Dalmont, J.-P., and Frappé, C. (**2007**). "Oscillation and extinction thresholds of the clarinet: Comparison of analytical results and experiments," J. Acoust. Soc. Am. **122**, 1173–1179.

Dickens, P., France, R., Smith, J., and Wolfe, J. (**2007**). "Clarinet acoustics: Introducing a compendium of impedance and sound spectra," Acoust. Aust. **35**, 17–24.

Elliott, S. J., and Bowsher, J. M. (**1982**). "Regeneration in brass wind instruments," J. Sound Vib. **83**, 181–217.

Gingras, M. (**2004**). *Clarinet Secrets: 52 Performance Strategies for the Advanced Clarinetist* (Scarecrow, Lanham, MD), p. 18.

Guillemain, P., Vergez, C., and Almeida, A. (**2014**). "Several ways to stop a note in a clarinet—A comparative view of note extinctions," in *Proceedings of the International Symposium on Music Acoustics*, Le Mans, France.

Krumhansl, C. L. (**1989**). "Why is musical timbre so hard to understand," Struct. Percept. Electroacoust. Sound Music **9**, 43–53.

Li, W., Almeida, A., Smith, J., and Wolfe, J. (**2014**). "Tongue control and its coordination with blowing pressure in clarinet playing," in *Proceedings of the International Symposium on Music Acoustics*, Le Mans, France.

Music Acoustics (**2015**). "Clarinet articulations," http://newt.phys.unsw.edu.au/jw/clarinet-articulations.html (Last viewed June 19, 2015).

Sadie, S. (**1984**). *The New Grove Dictionary of Musical Instruments* (Macmillan, London), pp. 129.

Sullivan, J. M. (**2006**). "The effects of syllabic articulation instruction on woodwind articulation accuracy," Contrib. Music Educ. **33**(1), 59–70.

Thayer, R. C. (**1974**). "The effect of the attack transient on aural recognition of instrumental timbres," Psychol. Music. **2**(1), 39–52.

Thurston, F. J. (**1977**). *Clarinet Technique* (Oxford University Press, London), p. 4.

Thurston, F. J., and Frank, A. (**1979**). *The Clarinet* (Hawkes, London), pp. 31.

Vauthrin, C., Fabre, B., and Cossette, I. (**2015**). "How does a flute player adapt his breathing and playing to musical tasks?," Acta. Acust. Acust. **101**, 224–237.

Wilson, A., and Beavers, G. S. (**1973**). "Operating modes of the clarinet," J. Acoust. Soc. Am. **56**, 653–658.