SCIENCE OF ARTICULATION

Some recent scientific studies of clarinet tonguing

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The clarinet has been studied scientifically in more detail than any other wind instrument, and much is well understood. Our lab has a website explaining music acoustics, including our own contributions on clarinets and saxophones, especially on the frequency response of instruments, on how pitch, loudness and timbre are related to blowing pressure, lip force and vocal tract properties, and on the use of the vocal tract on altissimo notes, pitch bending, bugling and multiphonics. Most studies, however, have concentrated on steady notes. The start and end of notes (collectively called transients) are important to the quality of the sound and the elegance of the performance. Several students and staff in our lab have worked on transients over the last few years, which explains the number of authors listed for this brief report, which aims to explain some of our recent results in simple language.

Two studies involved experts and students playing modified clarinets. These had sensors to measure blowing pressure and sound in the player's mouth and microphones in the barrel and bell. In one study, a sensor on the reed measured tongue contact. In the other, an endoscope inside the mouth recorded high-speed video of tongue and reed motion.

Two additional studies used an automated clarinet playing system. We hasten to say that this machine is not intended to replace musicians. Rather, it provides us with a tireless, reproducible, experimental subject, which has exactly and independently controlled blowing pressure, lip force and position, tongue force and acceleration. It also has a transparent mouth, in which we can drill holes without asking the university ethics committee. You can hear it play on our website. The site also has the scientific reports of our research, so we omit the technical details and most of the results in this brief account.

Figure 1 shows results for the low E on a B flat clarinet (D3 concert, 147 Hz) tongued normally. The mouth pressure and barrel pressure are shown in kilopascals (kPa); one kPa is 1% of atmospheric pressure (or about 0.15 psi for Americans). The change in pressure in the air near the bell is much smaller and shown in pascals. At the right of the curves, we notice also that the sound wave at the bell has a more interesting shape than that inside the instrument. This is because the bell radiates higher harmonics better than the fundamental, whereas the sound inside is dominated to a great extent by the fundamental.

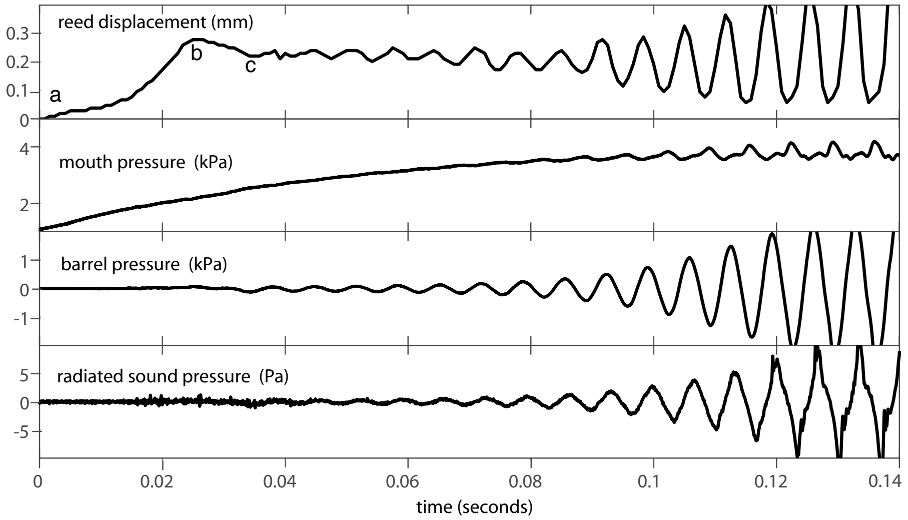
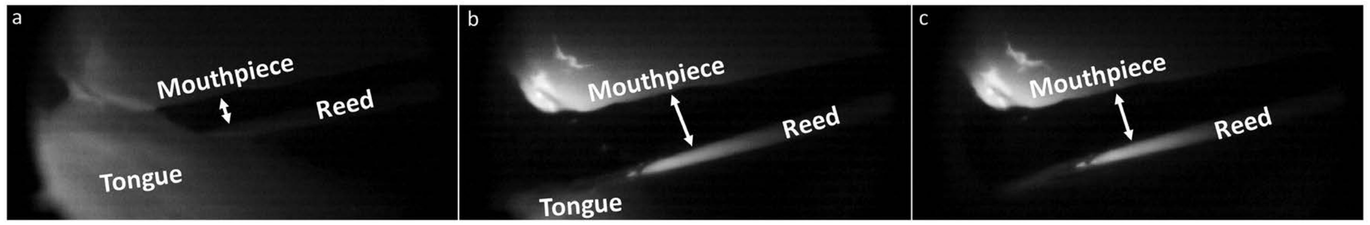


Figure 1: *Three frames from the high-speed endoscope video as a clarinettist tongues low E (below). The images correspond to the times labelled a, b and c on the top graph, which shows the reed's displacement from its initial position. The graphs above show the pressure in the player's mouth, the sound pressure in the barrel, then the sound outside the bell (from Inwood et al., 2016).*



Initially, the reed is pushed towards the mouthpiece by the tongue (frame (a) from the high-speed video) and the graphs begin as the reed begins to move. For about 0.02s, the reed stays in contact with the wet tongue, which pulls the reed beyond its point of mechanical equilibrium. (If you exaggerate your tonguing – a bit like slap tonguing – you can probably feel the tongue pulling the reed.)

At (b), the reed's springiness has pulled it away from the tongue and it begins to return to its mechanical equilibrium position (c): its rest position for this blowing pressure and lip force. Tongue and reed have no further contact during the note except in the case of staccato, when the tongue touches and immobilises the reed to begin the final transient.

The reed is stiff and light. So, if there were no lip, it would return to equilibrium, overshoot and proceed to oscillate at its own resonance frequency of a few thousand vibrations per second. But the lip slows the reed's motion and also has mechanical losses. These effects discourage the reed from vibrating at high frequencies — occasional squeaks excepted. So, because of tongue and lip, the motion (a–c) is much slower than the natural vibration of the reed. At (c), the reed has lost the mechanical energy initially provided by the tongue: from here on it will be driven only by the sound wave in the bore.

As in most examples we recorded, the blowing pressure in Figure 1 gradually increases throughout the attack. Here, it is about 1kPa above atmospheric when the reed starts to move. When the note starts, the blowing pressure is about 2kPa. Consequently, as the reed moves away from the mouthpiece (a–b) and back towards it (b–c), the aperture into the mouthpiece correspondingly increases and decreases, producing a sudden increase then decrease in airflow. These changes in flow produce a small increase then decrease in pressure in the mouthpiece. One of our technical papers explains these changes and gives experimental measurements of them: the physics of the process is somewhat similar to the 'water hammer' that one hears sometimes in old plumbing. For now, just note that the early changes in the pressure are tiny and, on this scale, only just visible on the graph before 0.03 s.

The change in pressure travels down the bore at the speed of sound: 340 metres per second. (Why this speed? Because a travelling variation in pressure is a sound wave.) When this sudden change in pressure reaches the bell, it is reflected and returns, and when it reaches the reed it is reflected again (more about reflections and resonances on our website). In practice, this is complicated because, especially for high notes, the reflected wave returns while the tongue is still moving with the reed. So one of our experiments used a normal mouthpiece and a three-metre long 'clarinet' (a plastic tube) while we worked on understanding and quantifying transients.

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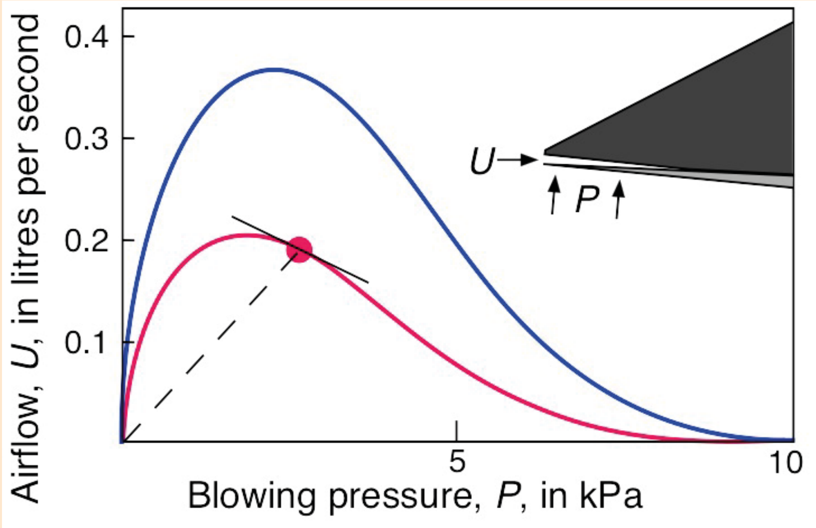
Over a tenth of a second or so, these reflecting waves grow in size, due to amplification by the reed and the player's breath. Let's see why. Imagine a sudden increase in pressure in the bore arriving at the reed. It pushes the reed away from the mouthpiece, which increases slightly the aperture between reed and mouthpiece. This increased aperture allows slightly more air to enter the mouthpiece, which increases the mouthpiece pressure: an arriving increase in pressure produces an even larger increase in pressure. Conversely, a decrease in pressure arriving at the reed pulls it towards the mouthpiece, reducing both the aperture and the flow of air ➡

HOW DOES THE REED CONVERT THE ENERGY OF STEADY AIR FLOW INTO SOUND ENERGY?

In the absence of a resonating bore, let's see how the flow *U* into the mouthpiece depends on blowing pressure *P*. At first, *U* increases rapidly with increasing *P*. But if you blow hard enough, *P* will close the reed against the mouthpiece, stopping the flow. This occurs at lower *P* for large lip force (red curve on the graph) than for small (blue). Consider playing with *P* and *U* values given by the red dot. The ratio of pressure to flow for steady or DC flow (the reciprocal slope of the dashed line, P/U) is the DC resistance for this point and, like an electrical resistance, it takes energy out of the system. But now consider the ratio of small *change* in pressure to the corresponding *change* in flow ($\partial P/\partial U$ for mathematicians). Near the red dot, increased pressure *decreases* the flow, and vice versa, so the resistance for a varying or AC flow is negative (reciprocal slope of the solid black line). So the positive DC resistance of the reed takes energy out of the steady flow and the negative AC resistance puts some of that energy into the oscillating air flow.

Airflow vs blowing pressure



into the mouthpiece, which lowers the pressure further. So the combination of the mouth pressure and the elastic reed provide amplification for pressure waves reflecting at the reed. See the **box** for another way of understanding the reed gain. (This simple argument neglects the time for the reed to accelerate and so it fails for high notes. This is related to one of the limits to the high range of the instrument.)

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Over most of the example shown in Fig 1, the amplification gain of the system is about three decibels per cycle: each oscillation in pressure is roughly 40% bigger than its predecessor, and has twice the energy. A sequence whose amplitude increases by the same factor over equal times is an exponential increase. Exponential increases cannot continue indefinitely. In the case of our amplification system, once the pressure peak in the mouthpiece is equal to the pressure in the mouth, then further opening of the reed does not increase the maximum mouthpiece pressure – we call this saturation. Further, if the reed vibration is so big that the reed actually closes the mouthpiece aperture, the vibration doesn't get any bigger – though the aperture can stay closed for longer. As the note approaches saturation, the proportional rate of increase falls below exponential and, in just several cycles, the note reaches its steady amplitude (Figs 1 and 2).

On a different timescale, Figure 2 shows whole notes. It graphs three different pressure measurements (bell, mouthpiece and mouth) for four different articulations: normal tonguing, with accent, sforzando, and staccato. The note is C5: written C in the middle of the stave. On this time scale, we don't see the individual vibrations, just the envelope of the sound wave.

The sound pressure in the mouthpiece is much larger than that at the bell, but their envelopes are roughly the same shape. Unlike the others, the average pressure in the player's mouth is not zero, because the player is blowing high pressure air to power the instrument. Notice that the black line for the mouth pressure becomes wider when the note starts: that wider shading is the sound measured in the mouth. The vibrating reed produces an oscillating flow into the clarinet and an oscillating flow of equal magnitude into the mouth. However, the sound pressure in the mouth is smaller than that in the mouthpiece. This is because the clarinet resonates at the frequency of the note played — and more importantly, the reverse: a resonance of the bore is driving the reed. The player's vocal tract also has resonances, but usually the frequencies of the vocal tract resonances occur well away from the playing frequency. (Interesting exceptions occur in pitch bending, altissimo, bugling and the first bar of *Rhapsody in Blue*; see our web site for details.)

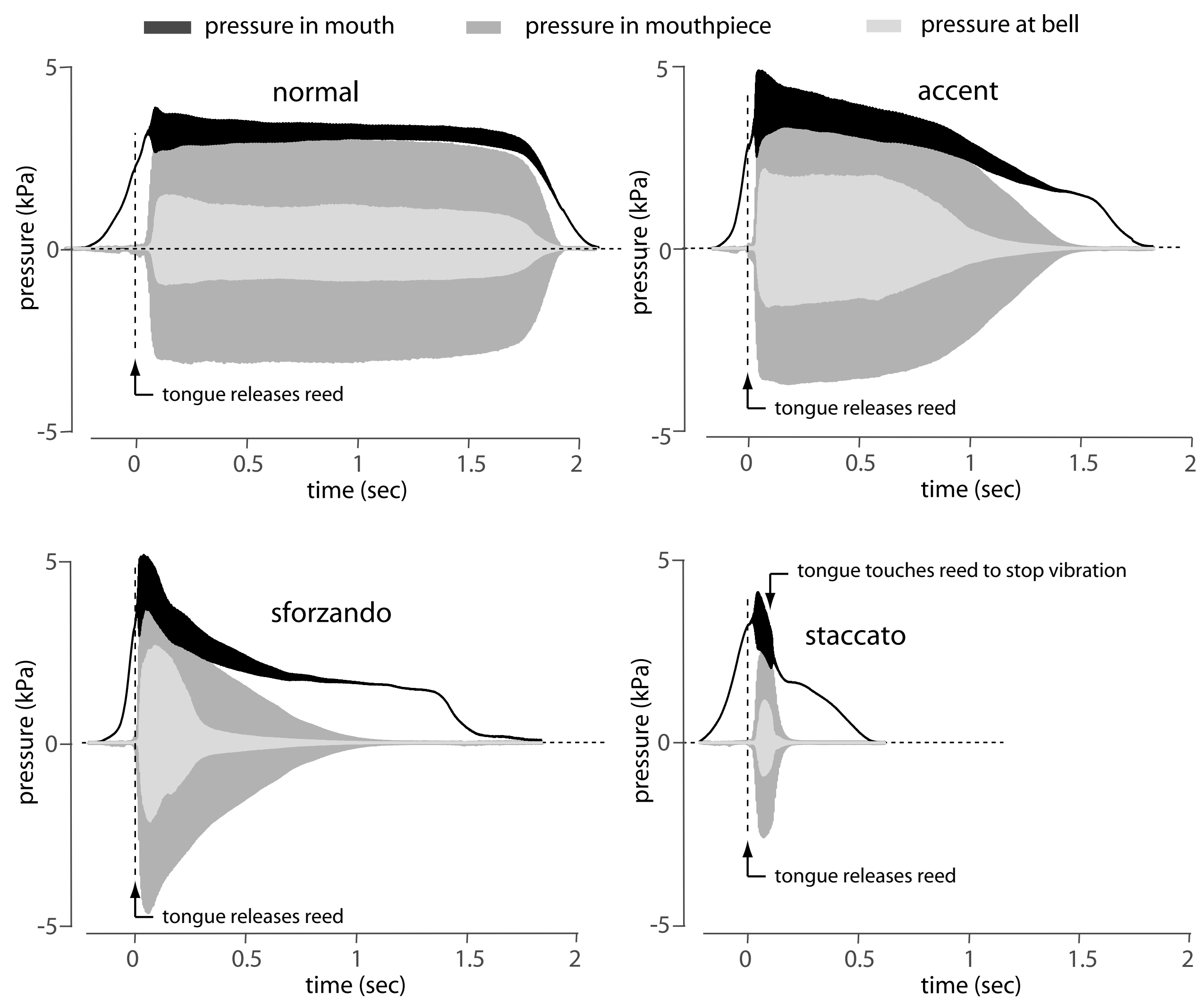

Figure 2. *The pressures measured at the bell (pale), in the mouthpiece (darker) and mouth (black) for four different articulations. The dashed line shows the moment when the tongue ceases to touch the reed, an arrow (in staccato only) where it touches the reed again. (From Li et al., 2016).*

Notice how the blowing pressure is varied during the note, and how the moment when the tongue releases the reed is coordinated with the blowing pressure. For the normal note, the mouth pressure builds at the slowest rate and reaches its maximum value shortly before the note reaches its maximum amplitude. It then stays constant at that value throughout most of the note. In the accented and sforzando notes, the pressure reaches a higher value than for the normal note, but is then reduced, so that the note amplitude is, as required, largest near the start and reduces through it. Observe that, in the normal note, the tongue is released at the lowest blowing pressure. From our brief discussion of the amplification at the reed, we expect that lower blowing pressure causes less air flow into the mouthpiece and lower initial amplification, and therefore a slower rate of increase in the sound amplitude. Probably without thinking, the player has done this because he wants the normal note to start more slowly than the accented, sforzando and staccato notes. (Most players in our study could not describe confidently their coordination of tongue and pressure.)

Two additional studies used an automated clarinet playing system, which provides us with a tireless, reproducible, experimental subject

To understand the end of the notes, let's consider first the staccato final transient. Here, the tongue immobilises the reed, so the sound wave in the bore receives no amplification. The sound cannot stop immediately, however. (If it did, we'd hear a 'click' or 'pop' at the end of the note.) The energy stored in the standing sound wave in the bore is gradually lost, as heat to the walls and as sound energy radiated from the bell and tone holes. The fraction of energy lost in each cycle is nearly constant, so this produces an exponential decay in the amplitude.

For the other notes, the decay is slower. In each of these, the note is stopped by gradually lowering the blowing pressure. As it is lowered, the amplification factor gradually falls; when the pressure reaches a level at which the amplification factor in a cycle becomes less than the fraction lost each cycle, then the note begins to decay. For this player, the accented and sforzando notes have slowly falling blowing pressure. Near the end of the note, the pressure falls slowly below the break-even value: the value where reed amplification just makes up for losses. So for this player's accented and sforzando notes, the decay rates are slower than for the normal note, which is in turn slower than the staccato, where the amplification is 'turned off' suddenly by the tongue.

From thinking about the explanation in the box, you can probably see that the reed gain depends on blowing pressure, lip force and position, lip damping, reed 'hardness', the shape of the mouthpiece and the amplitude of the note. Further, the losses depend on the note played and acoustic properties of the clarinet with a given fingering, so the rate of increase in sound after tonguing is a complicated function of all these factors. Experiments under controlled conditions using the playing system showed that increased tongue force or initial reed acceleration make the note start earlier after tongue release, but do not affect the exponential rate of increase. Large tongue forces or sudden tongue release can however cause the higher harmonics to grow more quickly, which affects the timbre of the transient.

Clarinettists sometimes like to start a note slowly. If the tongue releases the reed when the blowing pressure is below the break-even value, then the note does not start until the break-even value is reached. If the blowing pressure doesn't rise much above this value, the note starts slowly. When we asked players to play minimal attack, they raised the pressure slowly until the note started, then either held it steady or reduced it slightly before slowly increasing it again. For a given lip force, however, tonguing can start notes at lower blowing pressure than the starting pressure in a slow pressure increase.

For human players, the coordination of tongue release and increase in blowing pressure was different at different pitches: for all articulations at the higher pitches, the tongue almost always released the reed before the break-even point; this rarely happened for low notes, particularly with expert players. There is a likely explanation for this. First, low notes have longer vibration cycles (a note an octave lower has a vibration that takes twice as long), so the same amplification per cycle gives a lower rate of exponential increase (in decibels per second) for lower notes. Further, lower notes saturate at higher pressure amplitudes. For notes initiated with the same pressure perturbation, these effects give longer transients for low notes. By starting the transient for low notes above the break-even point, players achieve transient times more comparable with those of high notes.

As Figure 2 suggests, when playing at *mf*, our players used the highest blowing pressures and thus achieved the highest exponential rates of increase for accents and sforzando. In fact, their attacks for these articulations were much like their attacks for normal notes at *ff*. We also noted that expert players could achieve faster rates than students. Finally, not all clarinettists use the same tonguing technique. For some, unlike Figure 1, the tongue motion had a large component of motion parallel to the reed. For others, the sides of the tongue curled upwards on either side of the reed. For further discussion and detail, and for much more about clarinet and saxophone acoustics, we refer you to our website. ■

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The introductions 'Clarinet Acoustics' and 'Saxophone acoustics' are at *http://newt.phys.unsw.edu.au/music/* or search 'music acoustics'

The scientific papers supporting the present article, as well as sound files and video, are at *http://newt.phys.unsw.edu.au/jw/articulations.html*

A multimedia introduction to waves and sound is at *http://www.animations.physics.unsw.edu.au* or search 'physclips'