Acta Acustica united with Acustica
Vol. 101 (2015) 211 – 223

Scientific Papers

DOI 10.3813/AAA.918820

The Interactions Between Wind Instruments and their Players

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Summary
To play a wind instrument well, the player controls several elements in the player-instrument system, beginning with the source of pressurised air in the lungs. The bore of the instrument is a resonant duct whose geometry is controlled by the player's fingers via keys, valves or a slide. At the mouthpiece the player controls several parameters of a nonlinear element (which is an air jet, reed or the player's lips) that produces sustained oscillations. Upstream from this valve is a second resonant duct–the player's vocal tract–whose geometry is also controlled. This paper gives an overview of the interactions of these elements and how they are controlled by the player.

PACS no. 43.75.Ef, 43.75.Fg, 43.75.Pq, 43.75.Qr

1. Introduction

When complimented on his organ playing, J. S. Bach is reported (e.g. [1]) to have replied: 'There is nothing remarkable about it. All one has to do is hit the right notes at the right time, and the instrument plays itself.' Bach, who also played viola and violin, was making the important contrast between an organ, where the control parameter for a particular note is binary (on-off), and most other instruments, where several different analogue control parameters must be carefully adjusted over time to produce even an acceptable note, let alone a beautiful one. Another way of stressing the importance of the player's control of the instrument is to ask why a good player on a poor quality instrument makes a nicer sound than a poor player on a good instrument. Or one might ask why it is that we can sometimes recognise a player from hearing just a few notes. This paper, which concentrates chiefly on experimental results, is an overview of the various control parameters adjusted by the player of a wind instrument (see Figure 1).

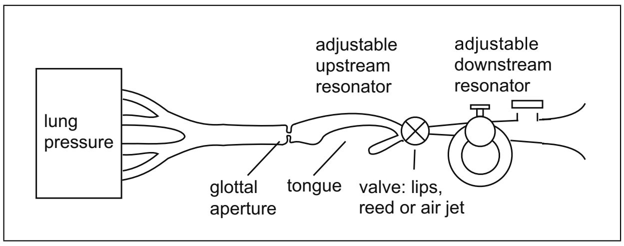

Figure 1. A simplified schematic (not to scale) showing most of the elements controlled by the player, beginning with the pressure of the air in the lungs. The adjustable glottal aperture admits air into an upstream duct of adjustable geometry, including the possible constriction or occlusion by the tongue. Sustained oscillation depends on adjustments to the valve–the air jet, reed or lips–whose parameters are carefully controlled. The geometry of the instrument bore is adjusted by valves, keys or a slide (the last not shown), and the bell, if present, may be modifed by the hand or mutes.

Orchestral wind instruments are generally divided into two major categories: "woodwind" and "brass", with the woodwind category comprising flutes, oboes, clarinets, saxophones and bassoons while the brass category comprises trumpets, trombones, horns and tubas. This omits many ancient and folk instruments, such as recorders, shawms, and the bagpipes in the woodwind category, and the cornetto, serpent and didjeridu, whose excitation mechanism is rather like that of a trumpet or tuba. There is also the anomaly that modern flutes are usually made from copper-nickel alloy, silver, or gold, while saxophones are made from brass. These anomalies, however, need not concern us here, and the material from which the instrument is made has only a small effect upon its performance (e.g. [2]).

From the viewpoint of the player, instruments in the brass category are all played rather similarly, with the player's vibrating lips constituting a valve that controls injection of air at high pressure from the lungs through the vocal tract and mouth into the instrument mouthpiece. Oscillation of the lips is strongly influenced by acoustic resonances in the bore of the instrument itself, but the player has a dominant role by controlling blowing pressure, lip tension, and the configuration of the mouth and vocal tract. It is these individual contributions by the player that we will be concerned with here.

Received 10 March 2014,
accepted 28 October 2014.

Figure 2. A photomontage showing the mouthpieces of some wind instruments. The top row shows a clarinet (single reed), oboe (double reed) and bassoon (double reed). The centre row shows a flute (air jet) and the bottom row shows a trombone (lip-valve) and a trumpet (lip-valve).

Woodwind instruments fall into three categories. First there are flutes, in which the sound is generated by a short jet of air emerging from the player's lips and striking the sharp edge of the embouchure hole of the instrument. Such a jet is aerodynamically unstable and is deflected by oscillating pressure in the instrument bore, thus producing a periodic up-and-down wave-like deflection. As this deflected wave reaches the sharp edge of the embouchure hole, it will either enter the embouchure hole or pass outside it, which maintains the acoustic oscillations that constitute the sound. Clarinets and saxophones, in contrast, have a single reed, which opens and closes against an aperture in the instrument mouthpiece under the differential influence of air pressure in the mouth and the mouthpiece. In the case of the oboe and bassoon, the double reed valve consists of two symmetrically opposing and laterally curved pieces of cane which open and close against each other – see Figure 2.

The physics underlying the operation of all these instrument types has been well studied and is summarised in a book by Fletcher and Rossing [3]. Here we will not be concerned with this general understanding but just with the ways in which the player can influence the sound of the instrument – a matter that distinguishes a great player from a beginner. A more complete knowledge of these topics will increase understanding of why a good player makes a good sound, which in turn should make it easier to teach how to play well.

As noted above, the three different types of valve divide wind instruments into three broad classes – air-jet instruments such as the flute, reed instruments such as the clarinet, and lip-driven instruments such as the trumpet. The player's techniques vary considerably from one class to another, but there are also general features in common. These common features may be briefly reviewed as outputs and inputs.

1.1. Outputs and inputs

The output of a musical instrument is sound, of which the basic parameters most relevant to performance are the pitch, timing, loudness and timbre. In many music styles, the pitch is categorised or approximately quantised, e.g. in semitones. Similarly, the onset timing of notes is usually quantised in notation, in beats and subdivisions of them. However, fine control and subtle variations from the written pitch and timing are important in musical performance [4]. Loudness is varied within notes, within phrases of notes and on longer timescales. Finally, timbre includes both the spectral envelope and its time variation, both of which are important to tone quality. Transients, especially the initial transient, contribute to what musicians call articulation and are also perceptually important in recognising instruments [5, 6]. The coordinated, subtle control of pitch, loudness, transients and timbre are all important in expressive and tasteful performance.

The player provides several inputs. One is pressurised air from the lungs. This passes to the mouth via the trachea, larynx and vocal tract. At or near the lips is a regenerative valve: the air-jet, reed or player's lips, collectively called 'valve' hereafter. This converts some of the DC power of the air flow from the lungs into AC power, and several parameters that affect this conversion are under direct control by the player. The valve interacts with waves in the acoustic ducts downstream (the instrument bore) and upstream (the player's tract). Usually, a playing regime is produced with frequency near one of the extrema of impedance of the bore, though this may be varied by adjusting the impedance spectrum of the tract. In some cases, the playing frequency may be determined by the tract with little influence from the bore. The impedance spectra depend largely on the geometries of the ducts, which are usually also varied by the player. Coordinated control of all of these time-varying elements is important; we now discuss them in turn.

2. Air pressure, flow and constrictions

If one assumes that the pressure from the lungs varies only slowly, and if the acoustic impedance of the upstream resonator as 'seen' by the valve is negligible, then the pressure in the mouth can be approximated as constant, which simplifies analysis (and some experiments) considerably. Consequently, much of the research on the operation of the valve and its interaction with the bore assumes a constant pressure in the mouth. In particular, experiments using a playing machine, whose 'mouth' has a large compliance, can provide a nearly constant upstream pressure, which is appropriate if transients and vocal tract effects are not to be studied. In the case of a steady sound, the pressure and volume flow into the instrument will both be held constant. Physicists usually regard the mouth pressure as the important variable but many teachers discuss instead the 'speed' of the air supply.

Woodwind instruments require only modest blowing pressures, ranging from about 0.2 to 2 kPa (2 cm to 20 cm water pressure) for the flute and from 4 to 12 kPa for the oboe, with the higher pressures applying to louder playing and higher notes [7]. In woodwind instruments, the pressure and the air flow have a roughly inverse relationship, so on the oboe, whose small reed aperture admits only a small flow, players can play a sustained note or phrase for a minute or more on a single breath, while flutists are typically limited to about 20 s or less. Players use volumes up to about 4 litres [8] which gives a flow rate of about 1 to $2 \cdot 10^{-4}\,\mathrm{m^3/s}$ and so a power of about 0.1 to a few watts, depending upon loudness. Since the radiated sound power is typically less than 10 mW, this gives a conversion efficiency of order 1%. A trumpet player uses much of the available physiological range of pressure, with measurements as high as 25 kPa or 2.5 m of water pressure [9]. Again the conversion efficiency is of order 1%, with louder playing having higher efficiency than soft playing.

The DC air flow for flutes, which is relatively large, can be studied by differentiating geometrical measurements of the torso [10, 11]. These and related studies suggest that, during professional performance, some inspiratory muscles are used in antagonism to the expiratory muscles, perhaps giving fine control over mouth pressure. This technique is correlated with what players sometimes call 'breath support'. Such measurements, however, do not give the time resolution necessary to study the transients of notes in detail. The involvement of different muscle groups has been quantified in the case of the flute [10]. Mouth pressure affects pitch and loudness, so the coordinated use of pressure and other control parameters is needed to play a range of loudness at constant pitch, or *vice versa* [11]. We return to this topic below.

The flow from the lungs passes through the laryngeal aperture called the glottis. From nasal endoscopy studies, Mukai [12] reported that experienced players of wind instruments use a much smaller glottal aperture in performance than do beginners. Using X-rays, Rydell et al. [13] made a similar observation for two trumpeters and two saxophonists. A small glottal aperture could allow fine control of mouth pressure (and, for music teachers, air speed), perhaps especially in vibrato. It has the further effect of providing a higher reflection coefficient for acoustic waves in the vocal tract.

2.1. Tonguing

The tongue can also be used to constrict the airway, and can close it completely by sealing against the top of the mouth. To initiate notes, teachers suggest articulating syllables like 'ta', 'te', 'too', or less frequently 'da' or 'la', for 'softer' tonguing. A rapid increase in pressure and flow leads to rapidly increasing sound pressure in the instrument and inharmonic overtones during the first few cycles of the fundamental. To initiate rapidly repeated notes, players often alternate tongue contact with the back and front of the palate, imitating 'ta' and 'ka', a technique that musicians call double tonguing. The procedure to end a note may be simply 'to stop blowing' (i.e. to reduce the pressure in the mouth), or the tongue may be used to terminate air flow in staccato playing (see e.g. [14]). Data from x-ray fluorographic images of clarinetists tonguing under different conditions are given by Afinson [15].

On reed instruments, a small force applied by the tongue can be used simply to provide sufficient mechanical damping to prevent vibration of the reed. In this 'soft tonguing' technique, flow past the reed may start substantially before the note, which begins soon after the moment when the tongue loses contact with the reed. Tonguing the reed can be studied using a reed to which strain sensors are attached: these yield both the slowly varying displacement due to the tongue and the more rapid vibration during a note [16].

In principle, a note can be initiated by simply increasing the blowing pressure slowly in the mouth, and this is done in some playing machine studies [17, 18]. This is rare in performance, however. To achieve a tasteful initial transient, players can release the tongue from the reed in coordination with an appropriate increase in pressure [19].

2.2. Vibrato and other time variations

In some wind instruments (flute, oboe, saxophone, bassoon), vibrato is an important element of style and has a large impact upon the listener's assessment of the sound. Clarinets and brass players, however, report using it only infrequently in an orchestral context. Vibrato consists of an oscillatory variation in the pitch, loudness and/or timbre of the sound with a frequency of about 6 Hz. In musical performance, however, the vibrato can give a gentle, emotional feeling [20].

In an orchestra, each string part is often played by several individuals, and the vibrato rate will vary somewhat from one to another, so that the sound could be described formally as 'narrow-band noise'. This term might seem derogatory, but with good players the resulting chorus effect produces a 'rich' steady sound of well-defined pitch. Wind instruments in an orchestra, on the other hand, generally play individual parts, so that the effects of individual vibrato become noticeable.

Wind instrument players generally report using one or more of the following techniques to produce vibrato. The first is oscillation in lung pressure produced by periodic contraction of muscles of the torso [21], the second is variation in the aperture of the glottis, which is the space between the two vocal folds in the larynx. These two may be related: a varying lung pressure applied to a small glottis could in principle cause the varying glottal area reported for the vibrato for some instruments, especially flute [13, 22, 23]. Conversely, a varying small glottis would be expected to produce variations in pressure. It might therefore be difficult for a player to know, between the sensation of varying pressure in the torso and movement in the larynx, which was the cause, and which the effect.

Vibrato can also be produced by an oscillation in lip shape or position produced by changes in lip or jaw muscle tension. A final possibility is oscillation of the tongue or jaw muscles to change vocal tract resonances. Tradition determines some of the player's actions, so that clarinets, for example, are rarely played with vibrato in orchestral or chamber music, while other woodwinds use it to varying degrees, including a range of different styles for the saxophone [24] and relatively limited use of vibrato on brass instruments. (There are also traditions reported by players, such as the use of lip vibrato or pressure vibrato in flute playing, that may depend upon country of origin, though this distinction is becoming obsolete.)

Because the playing frequency of wind instruments is usually closely linked to a resonance of the air column in the bore, there is generally only a small pitch oscillation, typically less than about $\pm 2\%$ or about ± 0.3 semitones, during a vibrato. This should be compared with the vibrato of a female opera singer, which is often as large as $\pm 10\%$ or about ± 1.7 semitones [20]. There is, however, generally significant oscillation in timbre and intensity in the wind-instrument vibrato which may be more noticeable than any pitch changes. Details of this vibrato vary significantly from one player to another.

In professional flute playing, vibrato is normally produced by oscillation in the pressure in the mouth, and it is found that these oscillations have an effect mainly upon the amplitude of high harmonics and thus on the timbre of the sound. There is very little effect on sounding frequency and so little or no pitch vibrato [20]. Other parameters that can be varied include the shape of the aperture between the lips and the mouth cavity volume. For a jet of given cross sectional area, it is possible to vary the ratio of aperture height to width. If the jet is relatively wide and not thick, then higher harmonics of the sound will be emphasised, while the opposite is true if the jet cross-section tends more towards a circular shape. These adjustments, together with the position of the lips on the lip-plate of the instrument and the exact relative position of the lip aperture contribute largely to the tone quality characteristic of a particular player.

Another source of time variation is movement of the instrument. Changing the distance between a source and the floor or a wall changes the comb filtering and thus the spectral envelope for listeners in different positions. Thus gestures and body movements can also have an acoustic effect. Such movements also have the non-acoustic effect of drawing attention to the performer, and may be useful in emphasising a solo part [25].

3. Excitation mechanisms

Wind instrument players can control several parameters of the valve: the strongly non-linear element that converts the DC power from the lungs into sound power in the instrument, often with relatively high efficiency, and then into the radiation field, with relatively low efficiency, as mentioned above, due to the acoustic impedance mismatch to the open air. The excess power is dissipated mainly by viscothermal losses in the bore and also by vortex shedding at sharp edges such as those of tone holes [26].

3.1. The air jet (flutes)

In the case of a flute, autonomous oscillation occurs when the lip configuration and blowing pressure are adjusted so that there is about half a wavelength of the sinuous deflection wave between the lip opening and the sharp edge of the embouchure hole [27, 28, 29], a requirement that also applies to organ flue pipes and to recorders [30]. Slight adjustments of the blowing pressure and lip configuration can affect both pitch and tone quality. In flute playing, there is an open space between the player's lips and the instrument entrance, which limits the range of tract effects. However, the shape of the mouth probably changes slightly with changes in the lip configuration, and resonances of the tract can affect the jet.

The identity of a professional flute player can sometimes be recognised by the tone quality of the sound, even with little vibrato, and a subtle clue is probably due to the shape of the lips, and particularly the shape of the aperture between them, which in turn shapes the cross- section of the jet. The jet moves backwards and forwards across the sharp edge of the embouchure and the flow of the jet into the mouthpiece is what excites the air column resonances. This flow is clearly dependent upon the shape of the jet cross-section so this influences the harmonic balance in both the steady sound and the vibrato. There are also vortices shed from the jet that influence the tone, and the shape and strength of these vortices depend upon the jet profile, especially the offset [31].

With the flute, as with essentially all musical instruments, the initial transient is important for each note and indeed often encodes the nature of the instrument [5, 6]. There is always a different excitation rate for each harmonic of the sound and this typically extends over the duration of several cycles of the fundamental. An example calculated for the case of an organ pipe with an abrupt jet excitation is shown in Figure 3. Measurements for a flute are given by Castellango [32]. The higher modes are generally excited fairly rapidly at their natural frequencies while the fundamental takes longer to build up, giving a 'crisp' attack. After a few periods of the fundamental, the overtones become locked into exact harmonic relationships [33, 34]. The player can, of course, control this by arranging a slower opening of the aperture above the tongue.

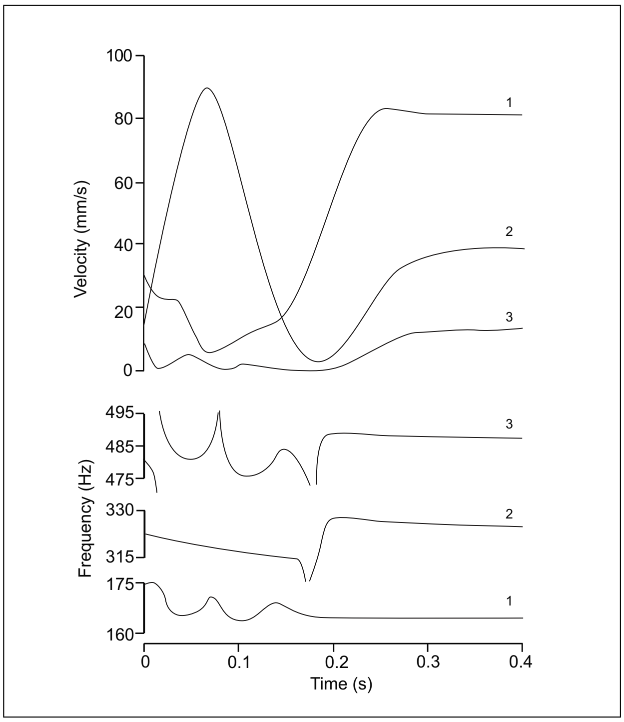

Figure 3. A theoretical calculation for the evolution in time of the velocity amplitude and frequency of the first three modes in a simple pipe abruptly excited by an air jet (after [33]).

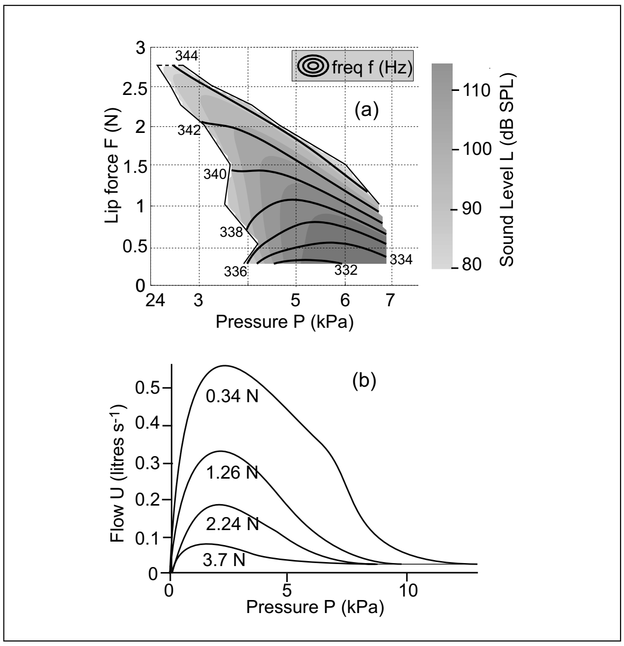

Figure 4. Two of the control parameters available to clarinettists are the pressure in the mouth and the force with which the lip presses the reed. Both are varied using a playing machine in the upper plot [17]. Dark lines show contours of equal frequency (values shown in Hz) and the grey scale shows the sound level measured near the bell. Illustrative sound samples from this plot are available online [38]. These results can be interpreted in terms of the lower plot, showing the flow U past the reed as a function of the pressure difference across the reed (after Dalmont and Frappé [37]). The different curves are for different forces applied by the 'lip' to the reed.

3.2. Reeds

Clarinets and saxophones have a single reed that deflects, to first order, like a cantilever beam. Oboes, bassoons and their relatives have a double reed, comprising two curved pieces that close by flattening the curvature at the entrance. Both types are 'blown closed valves': an increased pressure in the mouth tends to close the reed aperture, while a pressure excess in the mouthpiece downstream of the reed tends to open it. Aspects of both have been studied using both players and playing machines [35, 36, 37]. We concentrate on the relatively simple single reed of the clarinet to describe the effect of its control parameters.

Figure 4a plots the frequency and sound level produced by a clarinet playing machine as functions of the pressure excess P in the artificial 'mouth' and the vertical force F applied, via a soft 'lip', to the reed, other parameters being held constant. (The spectral content is not shown, but the lines of equal spectral centroid are similar to those of equal sound level.) The shaded area shows the region in which the instrument actually played. To the left of this, it was silent where the mouth pressure was insufficient to initiate self-sustained oscillation by the reed. To the right, the combination of lip force and mouth pressure was sufficient to seal the reed against the lay of the mouthpiece.

The playing range can be interpreted using the results in Figure 4b for a clarinet reed, after Dalmont and Frappé [37]. (Analogous results for double reeds are somewhat similar [39].) Here, the flow U past the reed is plotted as a function of pressure difference across the reed, for a range of lip forces. The clarinet bore was damped to prevent standing waves. For low values of the pressure difference p, U increases with increasing p. Assuming that all the kinetic energy of the air jet passing the reed is subsequently lost in turbulence, one would expect the flow to be proportional to $\sqrt{p}$ at low p. However, sufficiently large pressures close the reed and reduce U to zero, the value depending on the lip force. This can be modelled approximately with a factor $(1 - ap)$ where a is a numerical factor and the observed curves have some resemblence to $\sqrt{p}(1 - ap)$. This second effect produces a region of negative AC or slope resistance $\partial p/\partial U$. Neglecting losses in the bore and from radiation, it should be possible in theory to initiate self-sustained oscillation in this region, and thus it should correspond approximately to the shaded region in Figure 4a (with allowances for different experimental conditions as well as losses).

Figure 4a illustrates how control parameters may be used in combination to achieve a musical objective [17]. The contours of constant frequency should be followed to play a crescendo or diminuendo at constant pitch. However, because lines of equal frequency and equal sound level are in places nearly parallel, playing some notes very loudly may require playing flat (bottom right hand of the playing area), unless additional control parameters are adjusted. Areas near the boundaries of the playing region can exhibit hysteresis [37]. That on the left shows an interesting effect of player control: steadily increasing p at constant F initiates sounds at a certain value p_{osc}. Gradually decreasing p from the playing region reaches playing states with $p < p_{\mathrm{osc}}$ and a lower sound level. Playing can also be initiated in this region by supplying a low value of p and providing an initial displacement of the reed with the tongue [40]. On the right hand side hysteresis occurs because, even when the applied p is large enough to close the reed on the mouthpiece, standing waves in the bore can periodically open it.

Outside of actual performance, players can also control the mechanical properties of the reed itself, and we return to this later.

3.3. Brass

In brass instruments, the valve is the player's lips, whose motion is usually described in terms of superpositions of two different modes of oscillation. In 'swinging-door' mode, an aperture is produced as they part while moving outwards from the player into the mouthpiece. This motion is a blown-open valve, because pressure excess in the mouth tends to open it. In 'sliding-door' mode, the lips part by separating in a plane roughly parallel to that of the rim of the mouthpiece. One of the forces contributing to this motion is the pressure between the lips. Because of the Bernoulli pressure difference, this pressure can be considerably lower than the upstream pressure. Depending on where the flow separates from the lips, the pressure between the lips can lie somewhere between the upstream and downstream pressures. In both cases, the upper lip usually moves more than the lower. At low pitches, the swinging door motion dominates, with a superposed vertical motion that is delayed in phase. The outwards motion of the lip leads the pressure in the mouthpiece by a small phase angle, while the aperture between the lips is often behind the mouthpiece pressure in phase [41].

At high pitches, the vertical motion dominates – see [42, 43, 44]. Players vary and coordinate several parameters, including mouth pressure, the force of the mouthpiece against the lips, the motion of the tongue and the tension of muscles in and around the lips. Studies show coarticulation of these parameters, and considerable variation among different players [45].

An important control in brass is the variation in the area of the lip opening with time. This can be quantified by high speed video and related to properties of the output sound [46]. The tensions of different muscles in the lips themselves are presumably important in setting the natural frequencies of the different modes of oscillation, but it is not easy to determine these. Very experienced players have considerable control and are sometimes capable of varying the playing frequency smoothly over a large frequency range (*portamento*), and thus playing at frequencies far from the resonances of the bore, and also in ranges where the bore impedance is inertive or compliant.

At moderate to loud levels, these instruments develop a brassy sound attributed to non-linear propagation and even shock waves in the bore [47]. Players have a degree of control over the level at which this nonlinearity arises by varying the embouchure, and thus probably varying the $U(t)$ function [48], although the exact mechanism is unknown.

4. The bore: the downstream resonator

In normal playing, standing waves in the bore are excited. Usually, the fundamental of the note played, and often one or more of its harmonics, fall near extrema in the acoustic impedance of the bore. The oscillating pressure produced by these standing waves in the mouthpiece interacts with the valve to produce self-sustained oscillations. The measured impedance spectra of some ducts are shown in Figures 5 and 6.

The flute is open to the air at the embouchure and is excited by an oscillating air jet; consequently it operates at frequencies close to minima of the impedance spectrum. For reed and brass instruments, the flow through the valve is relatively small and the pressures across the valve large, so they usually operate close to impedance maxima. Exactly which extremum is selected depends on the natural frequency of the valve and the magnitudes of the extrema.

4.1. Controlling the downstream resonance frequencies

Players control the geometry of the downstream resonator using their fingers. On the trombone, the right hand controls a slide that adds continuously variable length to the bore. On trumpets, horns and other brass, three or four valves add lengths in discrete steps. In woodwinds, up to a few dozen holes in the side of the bore are closed or opened, either directly by fingers or by finger-operated keys. The valves, tone holes and keys are usually, but not always, operated in a binary (on-off) way.

Brass instruments have bells that improve radiation at high frequencies, which not only contributes to the characteristically bright timbre of the family, but also, by emitting power in a range where the ear is sensitive, makes them louder. The effective geometry of the bell is sometimes modified by mutes or by the hand. Especially in natural horns, hand stopping is used to shift bore resonances to 'fill in' the missing notes lying between resonances.

Typically, a given note on the instrument is produced by one of several commonly used bore geometries, each selected by a fingering (i.e. a combination of finger positions). The relevant acoustical properties of a particular bore geometry are quantified by its acoustic impedance (in the frequency domain) or impulse response (time domain). Some representative impedance spectra are shown in the Figures 5 and 6.

4.2. Harmonicity of the bore resonances

Brass and reeds operate near maxima in the input impedance spectrum, Z_{bore}, whereas flutes operate near minima. For brass instruments, Z_{bore} has typically a dozen or so peaks that, with the exception of the first, lie in nearly

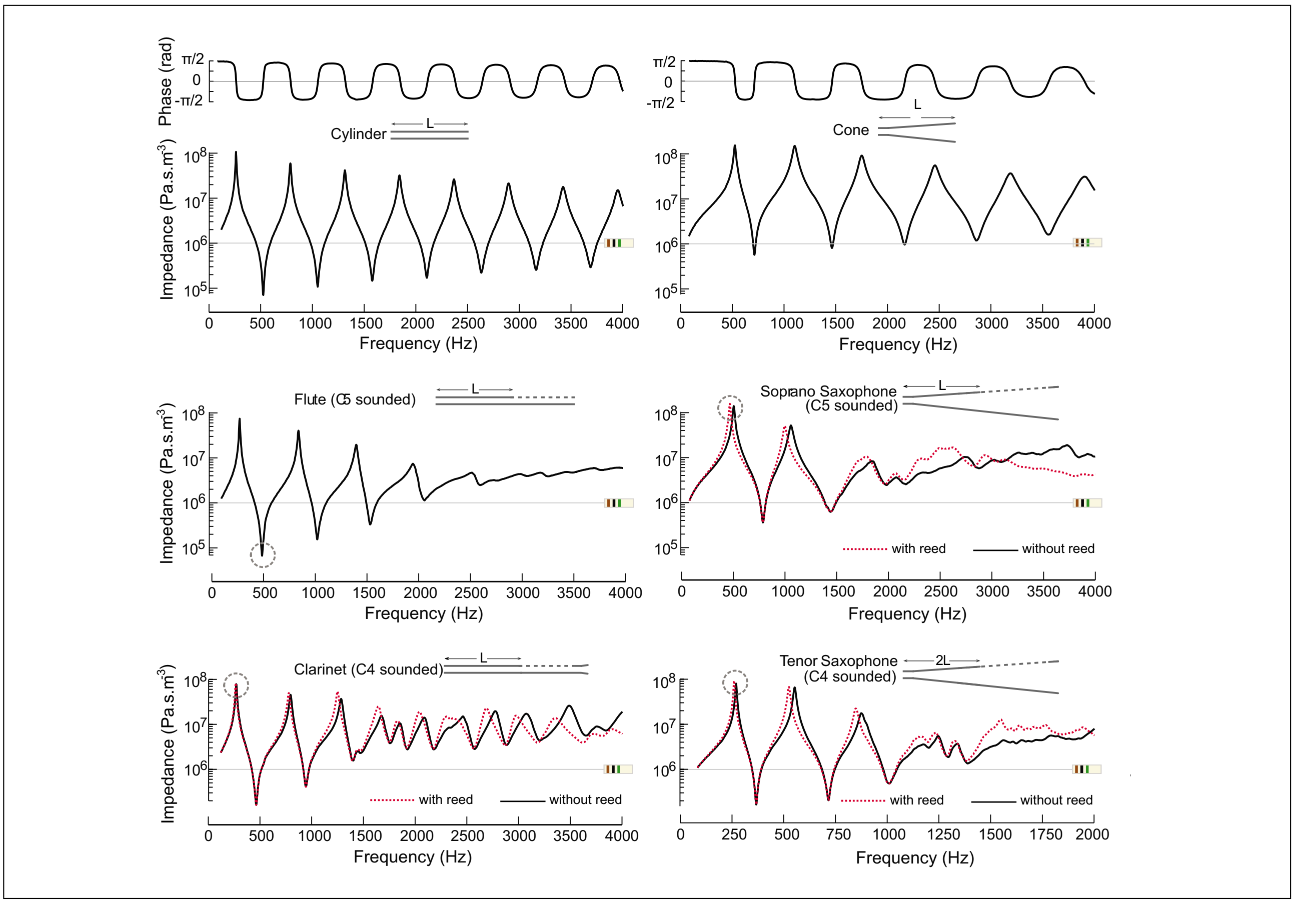

Figure 5. Measured impedance spectra of some ducts with simple geometries and the bores of some woodwinds. To save space, phase plots are only presented for the cylindrical (top left) and conical (top right) bores. To facilitate comparison, a pale horizontal line on each figure shows the value 1 MPa s/m^3. At the top of the figure are shown the measured spectra of a cylinder (left) and a truncated cone (right) with the truncation replaced by a cylinder of equal volume and appropriate radius. Both have an effective length L, of 325 mm, which is a half wavelength for the note C5. For the flute and soprano saxophone with fingering for C5, the same effective length is achieved by opening a lattice of tone holes, as indicated in the schematic. For the clarinet, the same effective length plays C4. The plot for the tenor saxophone is for the same fingering as the soprano, but is plotted on an expanded (doubled) frequency axis to show that it is roughly a 1:2 scale model, the differences being in part due to a narrower cone angle for the tenor instrument. For the three reed instruments, the dotted (red) line shows the calculated bore impedance in parallel with the compliance of a typical reed. The dashed circle shows the playing frequency of each instrument. Note that, for typical fingerings, there are usually only a small number of harmonically related extrema (after [49]).

harmonic ratios, approximately 2 : 3 : 4 : 5 … The first peak lies below the first member of the harmonic series, the latter being indicated by a vertical arrow in each plot of Figure 6.

Thus the Bb trumpet with no valves depressed (Figure 6) readily plays near the second peak (Bb3), the third (F4), the fourth (Bb4), the fifth (D5) and, for a good player, a few more [50]. A note can be sounded near the first maximum (G2) but its higher harmonics do not fall near impedance peaks, so the note is dark and weak. The Bb horn, with twice the length of the trumpet, plays an octave below. The trombone also plays an octave below the trumpet. With the slide in position shown (shortest length), trombonists are sometimes asked to play a pedal note at Bb1, whose frequency is indicated by the vertical arrow. The fundamental of this note does not coincide with an impedance peak, but the next several harmonics do. Because the lip oscillation is strongly nonlinear, the interaction of these harmonics with the impedance peaks stabilises the vibration frequency.

For woodwinds, Z_{bore} of the fingering used for the lowest note also has a dozen or so peaks, all in nearly harmonic ratios 1:2:3… for the approximately conical instruments (oboe, bassoon, saxophone) or 1:3:5… for the approximately cylindrical clarinet. For the (approximately cylindrical) flute, it is the impedance minima for these lowest notes that fall near the ratios 1:2:3…. It is important to note that, for most woodwind fingerings, there are fewer harmonic extrema and, because most notes use an extremum other than the first, only one, two or a few bore resonances may fall near harmonics of a typical played note. The extrema become less prominent as frequency increases. Examples are given in Figure 5.

Consequently, notes in the lower part of the range of wind instruments usually involve standing waves near two or more resonances of the instrument, and mode lock-

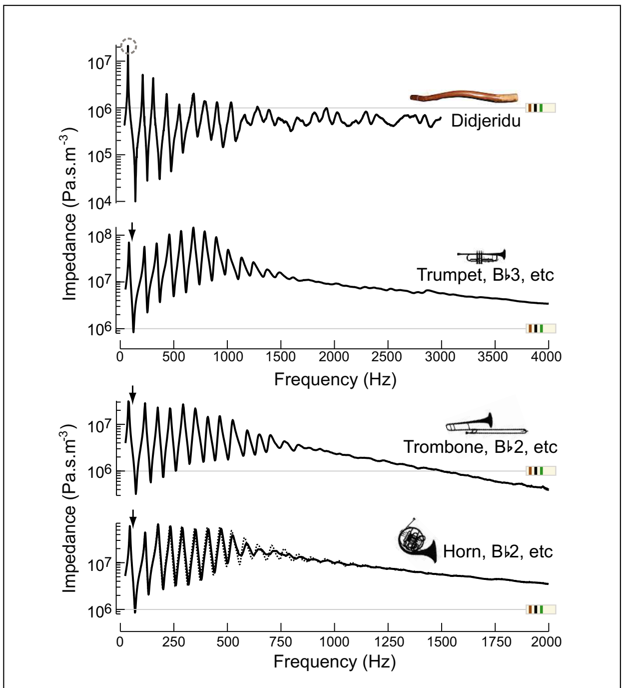

Figure 6. The measured impedance magnitude spectra of four lip-valve instruments: a didjeridu, a Bb trumpet with no valves depressed, a trombone with the slide in its shortest position and Bb horn with no valves depressed: the last two are on expanded frequency scales to demonstrate that the trombone and the Bb side of the horn are approximately 2:1 scale models of the trumpet. For the horn, the dashed line is for when the player's hand is in the bell and the continuous line is for no hand. Again, the pale horizontal line on each graph shows the 1 MPa s/m^3 value. The absence of a bell on the didjeridu allows relatively strong reflections and thus extrema in impedance at high frequency. The lowest playing frequency of the didjeridu occurs at the impedance maximum indicated by the dashed circle. The second and the next several impedance peaks for the brass instruments are approximately integral multiples of the frequency indicated by the arrows (from [49]).

ing produces an exactly harmonic vibration from approximately harmonic resonances.

The fact that the mechanism driving the acoustic oscillations in the bore of the instrument is nonlinear has several important effects on the tone quality. If the valve or air jet driving the instrument behaved in an exactly linear manner, then it would excite all the resonances of the air column in the instrument bore in linear superposition. Because these are never in exact harmonic relationship, the sound would be only approximately harmonic. But when the steady sound of an instrument is studied, it is found that all the dominant modes are in exactly harmonic relationship, though there may be a small background of broadband noise. This is due to the fact that nonlinearity causes combination of air-column modes and, if the inharmonicity is not too great, then the final result is a periodic, and thus harmonic, oscillation at a frequency that maximises the weighted contributions of all the modes (e.g. [50]). If the inharmonicity of the resonances is too great, as may be achieved by non-standard fingerings, then the vibration may separate into two or more components, giving a chord-like sound referred to as a "multiphonic". Details of these mode-lockings and multiphonics may be found in a paper by one of the present authors [34] and the influence of harmonicity on timbre is discussed by Dalmont *et al.* [51]. Players can select the balance of notes in multiphonics using resonances of the vocal tract, as explained later.

4.3. Articulation and transitions

Often, notes in a phrase are separated by a brief silence (described by musicians as separated, articulated, staccato etc.), so their transients are independent. Otherwise, the transition between notes is continuous (joined-up, legato, etc.). In the latter case, one set of standing waves fades while another is increasing, leading to interesting transients between notes. The movement of the key or keys can take from about two to tens of milliseconds, depending on whether it is produced by a finger (fast) or a return spring (rather slower). Even when the key moves more quickly, the establishment of the new standing waves takes tens of milliseconds in the flute [52] and around 80 milliseconds for low notes on the bassoon.

It is interesting to note that, when players move more than one finger in the transition between two notes, the movements are sometimes systematically non-synchronous. Representing the positions of two keys with binary variables, consider the transition from 00 to 11, which could pass briefly through the states 01 or 10. If one of the two possible intermediates produces a pitch near that of the initial and final states, and the other did not, then one might expect players to bias the transition towards the former favourable intermediate state. A study on flutists showed that this did indeed occur for some flutists, but that experts tended towards synchrony [52].

The rapid coordination of nearly simultaneous finger movements, and their coordination with changes in mouth pressure and other control parameters is presumably one of the main reasons why practising scales and arpegii is an important component of a musician's life.

Players control the instrument geometry in other ways, too, to effect the subtle changes beyond the categorical changes usually produced by keys on winds and valves on brass. Partial closing of a key is one such effect [53]. Another possibility is for the player to change the operation of the valve itself.

4.4. Modifying the operation of the valve

The flutist can rotate the instrument slightly around its long axis, which changes the jet length. It also changes the extent by which the lower lip occludes the embouchure hole and thus the solid angle available for radiation, thereby modifying the acoustical end effect. Greater occlusion slightly lowers the frequency of the impedance minimum and thus the pitch of the note, and conversely [54].

A greater lip force applied to the reed of a woodwind reduces the internal air volume of a double reed or the mouthpiece of a single reed. This reduces the compliance of that volume of air, which increases the frequency of the impedance peak. Lip forces, which are both transverse and lateral in double reeds, can also change the compliance, and thus the resonance frequency, of the reed itself, which can significantly change the pitch. On the clarinet, stiffer reeds, whose compliance is small, usually play sharper than soft reeds. (A stiff reed is called a hard reed by clarinetists.)

For brass players, greater intrusion of the lips into the mouthpiece decreases the mouthpiece volume, which in turn slightly increases the frequencies of its Helmholtz resonance [55]. However, doing so probably has a larger effect on pitch via the associated changes in the mechanical properties of the lip valve, which can also be modified using several embouchure parameters under the player's control. Increasing the mouthpiece frequency, however, increases the frequency of the corresponding formant in the output sound [56].

4.5. Selecting and adjusting the instrument

A component of the player-instrument interaction of non-negligible importance in performance is choosing and adjusting the instrument. A good player will usually possess an instrument with desirable acoustical and other properties and ensure that is adjusted to be free of leaks, with smoothly working keys and linkages, valves or slide. Next is the control of the mechanical components of the excitation mechanism.

In the case of the flute, not much "setting up" is needed or can be done, once the embouchure hole shape has been finalised by the expert maker. For a reed instrument, however, things are very different since a given reed will last for only a limited time and the player must have several on hand for when they are required, and often different reeds for different music. Clarinetists and saxophonists use a knife to adjust mainly the thickness distribution along the reed, which determines its stiffness, mass and resonant vibration frequency and the ways in which these will vary as the player varies the contact point and lip pressure upon the reed. For these instruments, the internal and to a lesser extent the external shape of the mouthpiece are often the subject of careful comparison and selection.

Things are much more complex for a double-reed instrument because the reed has several shape parameters that can be varied by scraping the reed and (for bassoon) by changing the tension on the two wire loops that bind the reeds together. Relatively small changes in the mechanical properties of reeds can change their rate of closing and thus their spectral envelope. In both cases, but particularly for double reeds, the adjustment that is required depends not just upon the instrument, but also upon the lip shape and playing technique of the performer. Professionals therefore either assemble their own reeds or have preferred reed makers from whom they buy them, but they still perform careful adjustments upon each individual reed. This subtle art is regarded as very important by most players [57].

For brass players, the analogue to the reed would be their lips. These have to be 'prepared' by training and practice. To some extent, players are likely to find an instrument that suits their anatomy, particularly in relation to the size and shape of the mouthpiece, but it is also likely that training of muscles affects the effective elastic properties of the lip tissues, possibly the vibrating mass and the shape that is best for playing: players adapt their lips to the instrument.

For single reeds and for brass, there is a mouthpiece, whose shape is important. The lay of the clarinet or saxophone mouthpiece is the curved edges against which the reed closes. As well as determining the force and pressure are necessary to close it, the detailed shape of these edges determines how rapidly the reed closes the aperture, and thus the shape of the flow-pressure curve, whose nonlinearity contributes to the spectrum of the sound. This is a critical choice. The internal shape of the mouthpiece also affects intonation (its volume is approximately a compliance in parallel with the rest of the bore) and the flow geometry in the mouthpiece.

'Seen' from the lips, a brass mouthpiece may be approximated as a compliance (the air in the cup of the mouthpiece) in parallel with an inertance (the air in the constriction that separates the cup from the bore). The mouthpiece alone, when sealed across the rim that touches the lips, has a Helmholtz resonance with the 'pop frequency', the frequency that can be heard by slapping the rim [42, 55]. Players can choose shallower or deeper cups to raise or to lower, respectively, this frequency and choose other aspects of the shape for reasons of comfort and performance.

5. The vocal tract: the upstream resonator

Benade [58] drew attention to the near symmetry between the up- and down-stream resonators in reed and brass instruments. Consider a valve that is driven by the difference between upstream pressure p_{mouth} and down-stream pressure p_{bore} and has flow U from mouth to bore. The impedance Z_{bore} 'looking' into the bore is the AC component of p_{bore}/U while that looking into the vocal tract is $p_{\mathrm{mouth}}/-U$ so that $(p_{\mathrm{mouth}} - p_{\mathrm{bore}}) = -U(Z_{\mathrm{mouth}} + Z_{\mathrm{bore}})$. For such a valve, the two resonators are thus effectively in series. In many cases, Z_{mouth} is substantially less than Z_{bore}, so the upstream resonances have relatively little effect. However, experienced players can produce peaks in the upstream impedances that may have magnitudes that are non-negligible in comparison with those of the bore, particularly in the higher range of the instrument where peaks in impedance become weaker.

One way of measuring the importance of the effect of the vocal tract is to measure simultaneously the pressures inside the mouth and the mouthpiece. From continuity, the flows into mouth and mouthpiece add to zero, so the ratio of the two acoustic pressures gives the ratio of the acoustic impedance of the two ducts [59]. This method has been used to show that, at the playing frequency, the magnitude

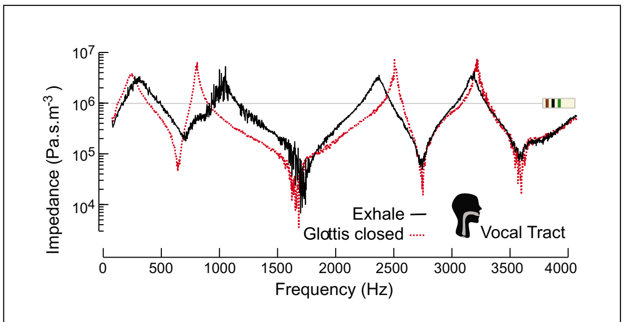

Figure 7. The impedance spectra of a vocal tract measured at the lips: glottis closed (dotted) and exhaling (solid) (from [68].)

of the impedance of the vocal tract can equal or even exceed that of the bore when playing the very high range of the saxophone [60] and the trombone [61, 62]; ranges where the peaks in Z_{bore} are weak. This very high range is usually available only to expert players. This pressure ratio method has the advantage of speed and relative simplicity, so that the time variation in this ratio in performance can be measured. Its disadvantage is that it samples the frequency domain only at harmonics of the note played.

It is also possible to measure the impedance spectrum in the vocal tract performance by injecting a known broadband acoustic current into the mouth. This has the disadvantage that notes must be sustained for a second or so, but the advantage that the resonances of the vocal tract are determined. This method has been used to study how impedance peaks in the vocal tract can control performance on the didjeridu [63, 64], saxophone [65, 66], clarinet [53] and trumpet [67].

Figure 7 shows two measurements of a vocal tract, one during exhalation and one with the glottis closed [68]. The high frequency behaviour is qualitatively similar to that of an open-closed rigid tube about 170 mm in length (cf. Figure 5 with a longer cylinder). The low frequency behaviour, which presumably is important for transients and possibly for low notes, is different, however, because of the finite rigidity and mass of the tissue bounding the tract. The peak at around 200 Hz corresponds to the mass of this tissue oscillating on the 'spring' of the contained air, which is approximately a compact object at this frequency. A minimum impedance at about 20 Hz, not clearly visible on the scale of Figure 7, is produced by the tissue oscillating on its own elasticity [68].

Briefly, experienced players of the single reed instruments produce and tune large peaks in Z_{mouth}. These can be used to bend notes below the frequency of the nearby bore resonance [53]. The saxophone, because of its largely conical bore, has peaks in Z_{bore} whose magnitude falls rapidly with increasing frequency (see Figure 5), with the consequence that notes in the highest range cannot be sounded without assistance from Z_{mouth}. To play these notes, experienced players tune the tract resonances near those of the desired bore resonance, as shown in Figure 8a [65].

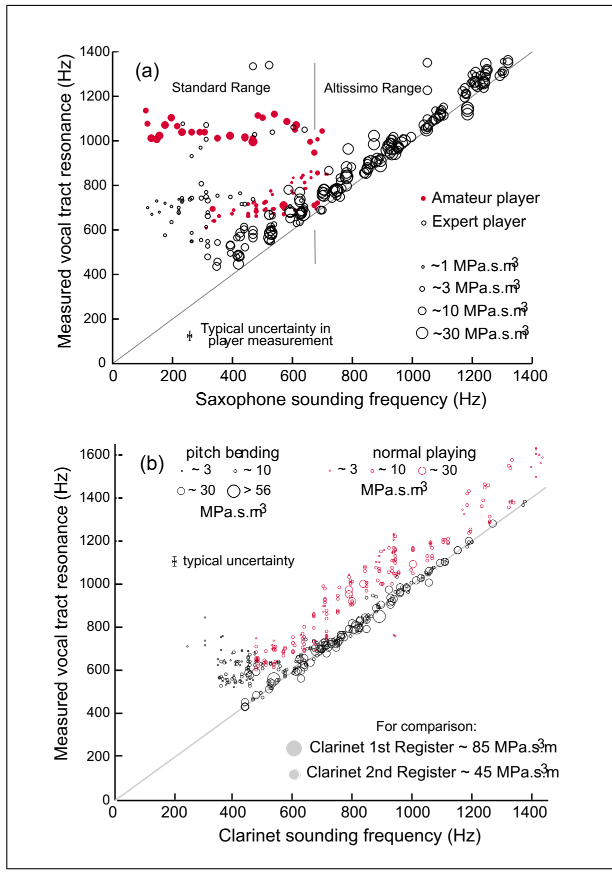

Figure 8. The relationship between the measured resonance frequency f_{res} of the vocal tract and the sounding frequency f_0, i.e. the fundamental of the note played, for the clarinet and tenor saxophone. In each figure the continuous line indicates the relationship $f_{\mathrm{res}} = f_0$. In Figure 8a, the open and filled circles indicate expert and amateuer players respectively. In Figure 8b the open and filled circles indicate measurements during normal playing and pitch bending respectively. In each figure the size of the symbol indicates the magnitude of the impedance peak. After [65] and [53] respectively.

In the normal range of the instrument, saxophonists show no consistent tuning of the tract impedance peaks (Figure 8a). Clarinetists, in their middle or 'clarino' range, appear to adjust an impedance peak of modest magnitude about 100 Hz or so above the playing frequency (Figure 8b).

In both single reed instruments, players tune vocal tract resonances for pitch bending and glissando: to play at a frequency away from that of the peak in Z_{bore}, for expressive reasons, or to play a glissando, such as that which begins Gershwin's *Rhapsody in Blue*. Tuning can also play a role in control of multiphonics and in bugling (i.e. successively sounding several different impedance peaks in Z_{bore}) [66].

Do brass players use similar techniques? Like the saxophone, brass instruments have very weak impedance peaks in the highest range of the instrument, a range usually accessible only to some experienced players. A study of trumpeters specialising in the high range showed no consistent vocal tract tuning (Figure 9, from [67]). A study

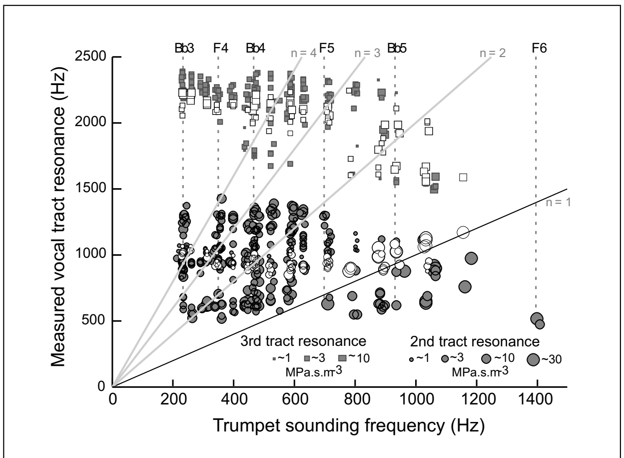

Figure 9. The relationship between the measured resonance frequencies f_{res} of the vocal tract and the sounding frequency f_0, i.e. the fundamental of the note played, for the trumpet. The continuous lines indicate the relationship $f_{\mathrm{res}} = nf_0$ where n is an integer. The circular and square symbols indicate the second and third measured resonance frequencies respectively. The open symbols indicate the results from a single player who undertook an extensive set of measurements, wheras the filled symbols indicate results from the other six players. The size of the each symbol indicates the magnitude of the impedance peak. The dashed vertical lines indicate the frequencies of the peaks in Z_{bore} for the open fingering (OOO) used in the experiment. From [67].

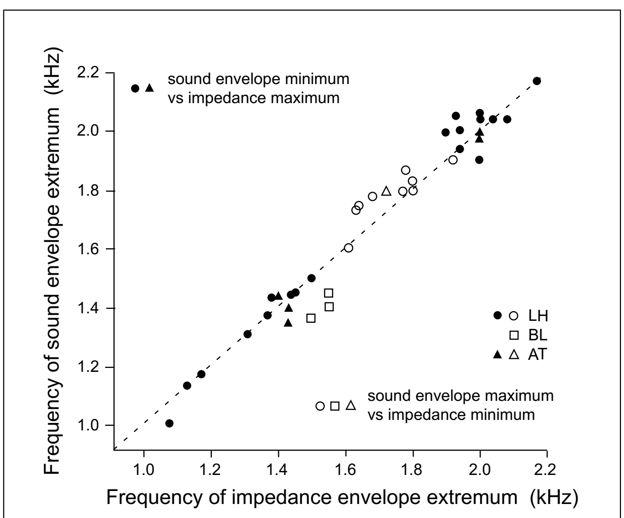

Figure 10. The frequency of maxima in the spectral envelope of the sound radiated by a didjeridu is plotted against the frequency of the minima in Z_{mouth} (hollow symbols). The frequency of minima in the spectral envelope of the radiated sound is also plotted against that of the maxima in Z_{mouth} (filled symbols). The dashed line shows when the frequencies of the extrema in the sound and impedance would be equal. From [64].

on trombone players using the pressure ratio technique gave results also consistent with an absence of tuning, but showed that the phase of the upstream impedance is important [61].

Another use of the vocal tract concerns the timbre. This is most spectacularly illustrated in the didjeridu, an Australian aboriginal lip-valve instrument. Usually, a single drone note is sounded continuously, and the musical interest comes from rhythmic variations in timbre produced by changes in the vocal tract configuration, including those required for the cyclic breathing technique that allows continuous playing. For the didjeridu, peaks in Z_{mouth} impede air flow between the lips. Consequently, little power is input to or radiated by the instrument at frequencies near these peaks. The remaining harmonics at frequencies between the peaks in Z_{mouth} produce formants in the output sound ([64]; see Figure 10).

Are similar tactics used to vary the timbre in other instruments? Studies using the pressure ratio method show that the ratio of the pressure in the mouth to that in the mouthpiece can vary [59, 60, 61, 62], indicating that changing Z_{mouth} can change the output sound. Li *et al.* [69] measured Z_{mouth} for saxophonists who played different timbres by using different vocal tract configurations. That study showed that harmonics in the output sound were not suppressed but enhanced at frequencies near the peaks in Z_{mouth}, indicating a completely different mechanism from that in the didjeridu.

6. Coordinated control and conclusion

The long sessions of practice that musicians spend in order to achieve subtle, coordinated control of embouchure, breath and fingers show just how difficult this is. That this overview can only tell the beginning of explanations of how these controls work shows that there is still much to do to understand how players interact with these instruments which, as Bach implied in the opening quote, do not play themselves.

Acknowledgement

The authors gratefully acknowledge support from the Australian Research Council and helpful suggestions from two anonymous reviewers and from Associate Editor Isabelle Cossette.

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