Introduction: Understanding Brass Instruments

Trevor Herbert

The purpose of this book is to help readers understand brass instruments – the instruments themselves as material objects, their players and the techniques they use, and the role of brass instruments in cultures and contexts in various parts of the world and historical periods. All such instruments fall into the class or category of instruments known as 'labrosones', in which sound is initiated by the vibration of the player's lips (see *Labrosones* and *Classification of brass instruments*).[1] So the class is defined not by the material of which the instrument is made, but by the process by which sound is generated. This descriptor is helpful as well as technically necessary because brass is just one of the materials from which instruments of the class have been made. For example, the first labrosones were made from natural objects such as animal tusks and horns, the sixteenth-century cornett (see *Cornett*) was constructed from wood and bound with leather, and in modern times, composites such as plastics have also been used extensively for the manufacture of lip-vibrated instruments. However, it is also important to make the obvious point that 'brass instruments' is the favoured term for this family of instruments because most, especially in Western culture, have actually been made of brass or some other metal. Furthermore, 'brass instruments' is the phrase in common use and it has stuck through custom and practice; for this reason and to side-step unnecessary pedantry it is used throughout this book as well as in its title.

It is likely that no class of melodic instruments has had a longer ancestry or has had a greater variety of musical and social purposes. Many examples of manufactured brass instruments survive from the ancient world, and a yet more abundant collection of images exists that hint with varying degrees of clarity at their cultural and social roles (see *Antiquity*). There is evidence of them in some form or other in almost every inhabited area of the world, and to the extent that we are able to tell, while there are usually distinctive local flavours, there are also some remarkable similarities that stretch across cultures. For example, wherever trumpets or trumpet-like instruments have been found, they appear to have been associated with expressions of secular or sacred power, and it is probably no accident that in English the word 'trumpet' (as in 'to trumpet') functions as a verb to denote a confident aspect of human behaviour.

All instruments of the class are essentially tubular, with a mouthpiece or opening at one end shaped so that the player's lips can be comfortably placed (usually but not always at the very tip of that end).[2] When blown through, the lips vibrate and the resultant periodic flow of air excites the vibration of an air column inside the instrument: the vibrating air in turn interacts with the player's lips, influencing their movement. The tube terminates in an opening to the ambient air, often with a marked expansion of the tube (known as the bell), that enables some of the internal sound energy to be radiated and heard (see *Acoustics*). With seashells, animal horns and tusks, much of the tube

[1] The word 'labrosones' was invented by the organologist Anthony Baines and first used in his book *Brass Instruments: Their History and Development* (1976b). On its first appearance he described it briefly in parenthesis as 'a handy term for lip-vibrated instruments' (1976b: 40).

[2] The distinction is necessary because while most brass instruments are blown through the very end of the tubing (end-blown instruments), a smaller proportion of vernacular instruments are blown from a point on the side of their sounding length (side-blown instruments).

wall is approximately conical, but with some vegetable material such as hollowed branches of trees the tube wall is approximately cylindrical. The internal shape of a labrosone, whether cylindrical, conical (or, as is more usual, with a subtle expansion), is one of the features that characterise its timbre, and surviving specimens, even from the ancient world, show signs of sophistication that must have been aimed at providing a range of pitches, colours and, by implication, expressive qualities.

More specimens of brass instruments survive from antiquity than from the Middle Ages and early Renaissance, but this does not completely compromise an understanding of their musical purpose in the medieval and early Renaissance periods. A few instruments survive, and contemporary images help us understand how they were used (see *Iconography*). For example, a broad consensus can be drawn from iconographical, musical and narrative sources about one of the most important moments in the history of the brass instrument family. At some time, probably in the very early fifteenth century, instrument makers, probably in Germany, incorporated a moveable telescopic slide to some trumpets (see *Slide trumpet* and *Middle Ages and Renaissance*). This could only have had one purpose: to increase the number of different notes that could be played on it; because one of the fundamental principles about the way brass instruments work is that if you increase or decrease the length of tubing that is being blown through, the player gains access to a different set of natural notes (see *Harmonic series*). This instrument, which is referred to in modern times as the 'Renaissance slide trumpet', was the raw prototype of the trombone, which, by at least 1480, had been equipped with the 'U'-shaped slide that has subsequently been the feature of all slide trombones.

At this point a clear distinction needs to be made between trombones, cornetts,[3] trumpets and horns. Trombones and cornetts were equipped to play almost all notes in their range, while trumpets and horns, devoid of finger-holes or slides, were restricted to those notes that could be naturally produced by blowing an instrument made of a fixed length of tubing. Horns of various types have a long ancestry as vernacular instruments, but they were not introduced into Western art music until the eighteenth century. Trumpets, even natural trumpets, have always been important in Western traditions; we know this not just from iconographical sources, but also from wages inventories that show trumpet players to have been employed in abundance in courts throughout Europe (see *Trumpet*). By the seventeenth century, trumpeters were using techniques that allowed access to a wide range of notes on natural instruments (see *Clarino*), and within a century the same was true of horn players. These techniques – the use of the high *clarino* range, hand-stopping (see *Hand-stopping*) and 'crooking' (see *Crooks and couplers*) – were presumably invented by players through trial and error, but they seem to have been commonly understood by players and composers across countries and even continents.

The major change in instrument design occurred in the closing years of the eighteenth century with the commencement of a series of developments, each of which was aimed at providing access to a true chromatic spectrum across the greater part of each brass instrument's range through the incorporation of some form of mechanical device. Slides, key mechanisms and valves of various types made this possible, and for a large part of the nineteenth century different instruments that incorporated keys, a slide or valves co-existed, but it was the valve that was to gain supremacy and revolutionise the world of brass instruments (see *Valve*). There were many different valve designs and it was some time before problems inherent in the manufacture of such instruments were solved. Many refinements and several totally new instruments were introduced, few of which were to endure after the white heat of invention that had prevailed in the Victorian period was over; just a small proportion of these entirely new instruments survived into the new century.

[3] The Renaissance 'cornett' and the valve 'cornet', which was invented in the nineteenth century, are quite different instruments. To avoid confusion, in this book we have distinguished between the two by consistently spelling them differently, but strictly speaking this expediency is ahistorical.

Studying Brass Instruments

The earliest published sources that were intended to explain how brass instruments work appeared early in the sixteenth century (see *Agricola (Sore), Martin*), but it was not until almost a century later that the theoretical sources became sufficiently explicit to cast a clear light on playing technique and idiom. This body of material includes major works on instruments in general (see *Praetorius, Michael* and *Mersenne, Marin*), the first written didactic treatise for the trumpet, material on ornamentation for the cornett and the earliest known source to explain how trombone slide positions were understood (see *Bendinelli, Cesare* and *Virgiliano, Aurelio*). While an abundance of musical sources survive from before the eighteenth century, the greatest number do not have their individual parts labelled, and this is why the didactic treatises, pictures, pay inventories and other sources that music researchers use are so important: they allow reasonable conjectures to be made about the musical idioms of brass instruments, the circumstances in which they were used and the musical and social conventions that their players understood.

The origin of modern research into such matters can be traced to the nineteenth century and to very broad scholarly concerns about the past. It seemed natural at that time for the starting point for such enquiries to be the acquisition of factual data and the ordering of it into categories and chronologies that could be easily understood. It is from this time that the great music thematic catalogues appeared, along with systems for the classification of musical instruments. Those who studied such matters in the nineteenth century would have regarded themselves as antiquarians and the majority were amateurs. Their descendants called themselves organologists or musicologists, but the foundations laid down by some of the stellar early pioneers continue to hold good (see *Organology* and *Societies and interest groups*).

In the twenty-first century, the questions that perplexed those early researchers continue to prevail and are joined by new concerns. Traditionally, brass instrument researchers have been interested in three fundamental and closely related channels of inquiry: *repertoires* – the music that performers played (written or unwritten); *performance* – the range of issues that impinge or have impinged on the way music has been played; and *reception* – the way brass playing has been heard, the expectations that audiences had of performers in different times and places, and the flow of continuities and changes that have occurred in musical tastes.

These three relatively straightforward topics prompt the need for several different avenues and methods of inquiry. A very substantial subset as far as brass instruments is concerned is organology, which is closely linked to musical curatorship, because so many organology projects are focused on large collections of musical instruments (see *Collections of instruments* and Appendix 4). The fact that so many historic brass instruments survive in good condition is the result of the endeavours of private and public collectors who were the first to identify the historical importance of such objects. The methodologies of organology are various, but they have always, to a greater extent than is the case with some other branches of musicology, been scientific, in the sense that they employ objective processes to evaluate and understand instruments. The similarities and differences across the family of brass instruments make it possible to gain some perspective of the patterns of continuity and change, not just of instruments as material objects, but also of the musical environments in which they existed. A more recent branch of organology that has provided important new insights into the ways that brass instruments can be understood has emerged from acoustical research.

Cultures and Audiences

Traditionally, understandings of the music of non-Western cultures have been separate from those of Western music, especially Western art music (see *Anthropology and ethnomusicology*). One of the achievements of ethnomusicologists has been to show that terms such as 'non-Western' and 'world music' fail to capture the diversity of non-Western cultures. Civilisations throughout the world have used brass instruments in ways that are distinctive and often eschew European values. This is true even in post-colonial cultures where Western instruments and even elements of repertoire have been

the subject of a type of hybridisation that often prioritises local traditions and values over Western tastes (see *Africa* and *Frozen brass*).

In Western music history, differences have also prevailed, but they are often obscured by modern approaches to performance. The history of brass playing shows that international mobility was common by the late fourteenth century, and while this may have caused some cross-fertilisation of performance styles, it is also clear that different performance conventions co-existed across Europe. This is a factor that is often hidden by modern tendencies to classify performance practices simply by chronologies, with the implicit assumption that common performance cultures prevailed. Such attitudes have partly been the result of expediencies that were in turn caused by processes such as globalisation and the developments that led to it: the introduction and distribution of audio and video recordings and other new media, especially radio, global publishing, mass manufacture of instruments by international corporations and the easy mobility of people. All this led to two basic changes that prompted a revision of the way we think about and understand music – including the role of brass instruments. The first is the development of styles and methods of playing that embrace musical languages that previously resided in separate and discrete cultural places; this phenomenon has been especially important since the nineteenth century in respect of the influence of various species of popular music, especially jazz. The second change has been one of public attitude. This change started in the nineteenth century, but it gained much greater momentum in the second half of the twentieth century. The musical preferences in previous music cultures favoured the repertoires of their own time, but this has changed. In the minds and tastes of most people in modern Western cultures, a belief has developed that ownership of all music from whatever time and place is fully at their disposal. To put it somewhat differently, for the first time in history, the music of our time is actually the music of all time.

This point prompts a reflection on the balance of modernity and history that is challenging to process, not least because it implies a need for brass performers of any worth to engage not just with modern repertoire but also with a studious approach to history, and to be aware of the many pitfalls to which historians are susceptible (see *Historical performance*).

Histories and People

It is tempting to see the history of brass instruments in Western culture as a single, relatively smooth incremental process in which the main changes have been prompted by developments to the instruments themselves, but this would be misleading. Leaving aside the fact that regional differences were once much greater than they had become by the late twentieth century, key structural 'moments' interrupted this continuum that were social and cultural and not just musical. These moments influenced the story of brass instruments and configured its path to modern times.

One such development occurred late in the eighteenth century when modes of learning moved away from apprenticeships, often conducted within family dynasties, to specialist educational institutions. The most important of these institutions was the Paris Conservatoire, but it was followed by similar institutions in Europe and eventually elsewhere. Their importance comes from what at the time was the innovative principle that these institutions should serve national needs and values, and that instruction should be delivered by a relatively small number of expert and exemplar performers. It stands to reason that such a focused and concentrated system created orthodoxies that defined taste and style in musical performance. These orthodoxies were further galvanised by the issue of new species of instruction manuals, often called 'method books', that systematically explained performance orthodoxies and the processes through which their inherent skills could be learned. While the conservatoires were the source for such ideas, it was the method books that had the widest influence because of the scope of their distribution. For example, the method written for the cornet by the instrument's first international virtuoso and a professor at the Paris Conservatoire, Jean-Baptiste

Arban, may have been the earliest didactic work written for a brass instrument that had a truly global influence and market (see *Arban, Jean-Baptiste*).

Part of the motivation for the foundation of the Paris Conservatoire came from the need to establish a centre for the training of musicians of the French National Guard. Though the Conservatoire was soon to assume a much broader role, the quality of military music was to remain an important concern which was addressed in a number of ways. Military music was a concern for most European governments because it was regarded as an essential ingredient in the way states were represented in ceremony: in effect the musical and visual aspects of ceremony were perceived as key elements in diplomacy (see *Military band* and *Kneller Hall*). The development of military bands in the nineteenth century also had crucial significance for brass instruments. The sheer scale of military music projects in most countries made it structurally important for musical commerce as well as culture. In 1894 Jacob Kappey, a German-born military bandmaster who directed some of Britain's leading military bands, and the author of the entry on 'Wind Bands' for the first edition of Grove's *Dictionary of Music and Musicians*, published a history of military music. He introduced his subject by calculating the number of full-time military musicians working in Western Europe at that time. His estimate, which was at least realistic and possibly conservative, was that the number exceeded 52,000.[4] The ramifications of the dominance of parts of the music business by the military were significant. A large proportion of the design improvements to brass instruments in the nineteenth century were aimed at improving military music; and related matters, such as the standardisation of musical pitch, had to take the needs of the military into consideration. A further and obvious corollary of all this was the massive increase in the number of brass players because of the need to populate so many military bands. In less than half a century the opportunities for employment for brass players shifted from a relatively few centres of aristocratic and civic patronage to a Europe-wide network (and by extension its colonies) of what were essentially state-sponsored music institutions. Almost all the personnel for these bands came from the lower social classes and were trained to high standards either within bands or in specialist institutions.[5]

The widening of the franchise of brass playing to the lower social orders was greatly increased by the acute growth of amateur music-making that occurred from the mid-nineteenth century (see *Brass band* and *British brass band*). While the expansion of military music was initiated by a perceived need to enhance national display, the development of amateur brass playing can be attributed to a different set of factors which included seemingly relentless urbanisation, and the perception of a worried dominant class that music participation was character-building and should be encouraged because it stimulated a sense of order; but the key factors were commercial – the ability of manufacturers to produce at scale and sell at low prices, and the introduction of financial devices (such as deferred payment schemes) that made it possible for working-class people to own and learn the instruments.

By the end of the nineteenth century, brass instruments were easily available throughout the world and were being played by people in a variety of different ways. Military band training had made it possible for brass players whose families had no prior connection with music to become professional performers, and audiences for band concerts far exceeded those for more traditionally elite forms of music. There were many consequences that resulted from the popularisation of instrumental music that occurred in the late nineteenth century, but by far the most important development as far as brass instruments were concerned was initiated in the south-east corner of the United States.

No musical or social occurrence has had a greater influence on the idiom of brass instruments than jazz (see *Jazz*). The origins and various subsequent phases of jazz have been well documented, but in the context of this book the importance of jazz lies in the performance techniques that were

[4] J. A. Kappey, *Military Music: A History of Wind-Instrument Bands* (London: Boosey & Co., 1893), 93.
[5] See Herbert and Barlow (2013).

invented by jazz musicians and the influence they subsequently had. From the start, the modes of playing of jazz brass performers were instinctive and invented rather than studiously learned. While the performance traditions of brass performance had been adjusted in the nineteenth century by the development of new types of instruments and the techniques their players introduced, the influence of jazz was of a yet different order. The effects created by jazz musicians were prescient of, and the inspiration for, what modernist art-music composers were to write and which became characterised as 'extended techniques': growling, flutter-tonging, the extensive use of mutes, explorations of the extremities of range – all had their origins in jazz (see *Extended techniques*).

Only one cultural development matches jazz as a revolutionary force in the recent history of brass instruments and it is much more recent. The last quarter of the twentieth century witnessed the dissolution of an idea that had stood for centuries: that brass instrument playing was an activity exclusive to males (see *Gender*). This idea was sustained by various notions: concepts of femininity, the idea that women were unable to cope with the physical demands of brass playing, structural elements such as those that prevented women from entering military bands, as well as broader social attitudes, protectionism and at times wilful prejudice. With astonishing speed from about the 1970s, these ideas were revealed as not just discriminatory but also hopelessly phoney. An obvious debt is owed to the feminist movement generally for this shift, but the greatest credit must be awarded to the many stellar female performers who, in a single generation, transformed a culture that had prevailed for as long as brass instruments had been played.

If this brief overview demonstrates anything, it is that at every stage in the history of brass instruments there has been an interplay of factors. Most obviously they include the ingenuity of instrument designers and the contribution of performers who have devised so many different idioms for this family of instruments, but there has always been a variety of other ideas at work: musical, social, cultural and economic. It follows that the entries in this book, determined as they are by the headlines on which its editors have settled, need to be seen and understood in their relationship to each other and to a wider range of contexts. The richest understanding of the book's content will be gained by following the cross-references and by consulting the readings that are suggested at the conclusion of each entry. This encyclopedia, as is typical of other volumes that are known by that name, should be seen as the beginning rather than the end of inquiry.

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Abblasen A term denoting the morning and evening performances of 'tower music' by municipal wind players in towns and cities in German-speaking regions during the seventeenth and eighteenth centuries. Collections of music by two Leipzig *Stadtpfeifer* comprise pieces composed expressly as *Abblasen* music: Johann Christoph Pezel's *Hora decima musicorum* (1670), which contains forty sonatas for two cornetts and three trombones, and Gottfried Reiche's twenty-four *Quatricinia* (1696) for cornett and three trombones. The fanfare shown in E. G. Haussmann's portrait of Reiche, though commonly titled *Abblasen*, is not known to have been performed in that context.

FURTHER READING
Smithers (1973), Collver and Dickey (1996), Green (2006)
ALEXANDER MCGRATTAN

Acoustics The science of sound.

The most important aspects of brass instrument acoustics concern the way in which sound is generated by the vibration of the player's lips, the interaction between the lips and the acoustic resonances of the column of air inside the instrument, and the influence of the shape of the instrument tubing on the musical properties of the played notes.

Sound generation in brass instruments

What is the essential acoustical feature which characterises a brass instrument? This encyclopedia contains entries on many instruments normally made from brass, including the trumpet, trombone and french horn, but there are also articles on the cornett, serpent, and alphorn, traditionally manufactured in wood. Conch shells, tusks and horns are also included. The unifying factor justifying the treatment of these diverse instruments as members of the 'brass' family is not the material of construction, but the method of sound generation. They are all lip-excited wind instruments (see *Classification of brass instruments*); in each case, the player generates the sound by blowing air through a slit-like aperture between the lips.

Studies using high-speed cameras and transparent mouthpieces have clarified the nature of the lip motion when a note is sounded on a brass instrument (Stevenson 2009; Bromage et al. 2010) (Figure 2). The player begins by shaping and tensing the lips to give them a natural resonance frequency close to that of the desired note (see *Embouchure* and *Slotting*). The muscles controlling the lungs are then used to increase the pressure in the mouth above its normal atmospheric level; the resulting pressure difference across the lip aperture causes air to flow out of the mouth. For sufficiently small values of the mouth pressure, the air flows smoothly and continuously through the gap between the lips. When the mouth pressure reaches a critical threshold level, there is a dramatic change in the behaviour of the lips: instead of remaining a fixed distance apart, they start to vibrate, opening and closing the lip aperture periodically. The lips are then operating like a valve controlling the airflow from the mouth, regularly turning it on and off with the same frequency as the lip vibration (Campbell 2004).

It is possible for an experienced brass player to sound a note at a definite pitch without an instrument or even a mouthpiece, simply by forming an embouchure and generating a large enough pressure in the mouth. Lip-buzzing in this way is often used as part of the practice routine of the player. If the buzz has a pitch of A4, for example, the high-speed camera confirms that the lips open and close 440 times every second. Fortunately, it is not necessary for the player to manipulate the lips consciously at this high frequency; all that is required is the correct embouchure and blowing pressure.

Figure 2 A cycle of motion of a brass player's lips (frontal view, obtained with a high-speed camera and transparent mouthpiece).

It is an inherent property of resonant structures like the brass player's lips that under certain circumstances the rest position of the structure becomes unstable, resulting in a transition to a state of steady vibration (Cullen et al. 2000). In the case of the lips, the agent which triggers the transition is the flow of air through the aperture.

Coupling between the lips and the instrument

When the lips are buzzed on a mouthpiece attached to an instrument, another important factor comes into play: the feedback from the resonances of the air column inside the instrument exerts a powerful influence on the lip vibration. A series of pressure pulses created in the mouthpiece by the periodic opening of the lips travels down the air column as a wave, like ripples travelling across a pool. It might be expected that when this pressure wave reaches the bell it would simply spread out into the atmosphere; in fact this happens only if the vibration frequency is higher than a cut-off frequency determined by the bell shape. Most of the notes in the playable range of the instrument have frequencies below the cut-off; for these frequencies the pressure wave is reflected before reaching the exit of the bell and travels back up the air column. If one of the reflected pressure pulses reaches the mouthpiece at the same time as a new pulse starts its journey, the two pressures add together, stabilising and reinforcing the vibration of the lips. The frequencies for which this reinforcement occurs are the resonance frequencies of the instrument, which correspond closely to the frequencies of the natural notes which can be easily sustained by the player.

Air column resonances and natural notes

Brass instruments typically have many resonances, whose frequencies are determined by the details of the internal geometry of the instrument. From measurements of the bore profile, a curve showing the variation of the tube diameter along its length (see *Bore*), it is possible to calculate the 'input impedance', defined as the pressure at the mouthpiece entrance divided by the volume flow of air into the mouthpiece at a particular frequency. The input impedance can also be measured by generating a known oscillating airflow in the mouthpiece and recording the resulting pressure. Since the resonances of the air column occur at frequencies for which the mouthpiece pressure is largest, a curve plotting the input impedance over a range of frequencies has a peak at each resonance frequency. A measured trombone input impedance curve is illustrated in Figure 3.

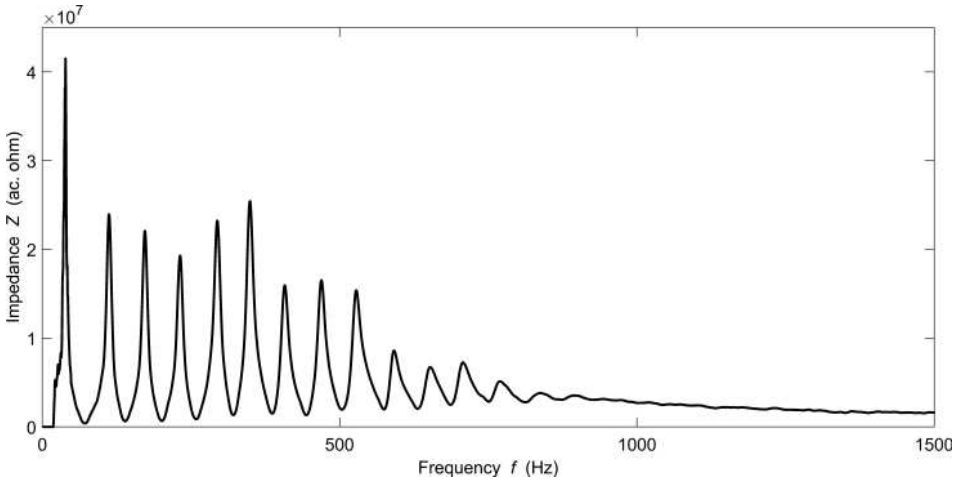

Figure 3 Measured impedance curve for a Conn 8H tenor trombone with the slide in first position.

Although the natural notes of a brass instrument are commonly described as 'harmonics' (see *Harmonic series*), they never form an exact harmonic series; the actual frequency ratios depend on the nature of the bore profile. Instruments whose profile is close to conical, such as the alphorn, show only small deviations from true harmonics (see *Alphorn*). In contrast, the cylindrical hosepipe frequently used as a novelty demonstration by brass players has the much more widely spaced set of resonances corresponding to a series containing only the odd numbered harmonics. Although the trombone has a substantial proportion of cylindrical tubing, most of the impedance curve peaks occur at frequencies which are very close to integer multiples of 58 Hz, the expected harmonic series for an instrument with a fundamental pitch B♭1. The tendency to widened spacing introduced by the cylindrical section is compensated in two ways. The high-numbered resonances are lowered by an appropriate choice of mouthpiece dimensions. The lower-numbered resonances are raised by the design of the bell section, which reflects the forward-going wave back towards the mouthpiece at a distance inside the bell which increases as the frequency is reduced; the tube thus appears shorter to the lower-numbered resonances. This low-frequency correction is inadequate for the first resonance, as can be seen from the fact that the first impedance peak in Figure 3 is not at 58 Hz but at 39 Hz.

Pitch-changing techniques

The player chooses which of the natural notes to sound by forming an embouchure whose lip resonance frequency is close to that of the appropriate air column resonance. The pitch of the played note can be significantly raised or lowered without jumping to a different air column resonance. This can be done by changing the lip resonance frequency, a procedure commonly described as 'lipping the note' (see *Lipping*). The shape of the mouth cavity can also be changed to modify the acoustic resonance upstream of the lips (Fréour et al. 2015). These two techniques are often employed simultaneously.

To achieve a chromatic compass on a brass instrument it is necessary to bridge the pitch intervals between the natural notes. In modern instruments this is done by increasing the tube length, either continuously by extending a slide or discretely by activating valves. A length increase of 5.9 per cent lowers the pitch of the higher numbered natural notes by one semitone. Since the change usually involves an increase in the proportion of cylindrical tubing in the bore profile, the decrease in pitch is slightly greater for the lowest natural notes. In historical instruments with finger-holes such as the cornett and the serpent, the effective sounding length of the tube is reduced by opening one or more side holes. For the lowest numbered natural notes, opening a side hole is approximately equivalent to

cutting the tube a short distance below the open hole. This venting becomes ineffective above a cut-off frequency which depends on the geometry of the hole, resulting in increased irregularity in the fingering of scales in the highest register.

Centring of played notes

In the apparatus used to measure the input impedance of an instrument (*ARTIM* 2017), a sinusoidal airflow is created in the mouthpiece, and the resulting pressure signal also has the form of a sine wave. This is a typical property of a linear system in which the output and input signals have the same form. The situation is different when the oscillating volume flow is generated by the vibration of the player's lips, since the coupling between the lip motion and the air column resonances results in a non-linear relationship between airflow and mouthpiece pressure. The musically important consequence is that the mouthpiece pressure in a played note does not normally have a sinusoidal waveform. Since any regularly repeating signal is mathematically equivalent to a simultaneous set of sine waves which are exact harmonics of the repetition frequency, the effect of the non-linearity of the lip-excitation process can also be viewed as the generation of a set of harmonic components in the mouthpiece pressure. The number and strength of these upper harmonics increases during a crescendo.

A note is described as 'centred' if the player's lips are firmly guided towards the desired pitch by the feedback from the instrument (see *Slotting*). This feedback is reinforced if there are air column resonances at frequencies close to the harmonics of the played note, since each component of the mouthpiece pressure is then strengthened by coupling to the corresponding resonance. Playable notes can be found even at pitches for which there is no resonance to support the fundamental, provided that the upper harmonics receive enough reinforcement (see *Factitious notes*); an example is the pedal B♭1 on the tenor trombone, which can be sounded strongly with a repetition frequency of 58 Hz although there is no air column resonance close to this frequency. Above the bell cut-off frequency there is no significant feedback to the lips from the air column. Notes in this high register are not strongly centred, and continuous lip glissandos are possible.

An apparent paradox in the functioning of brass instruments is that good centring of notes appears to require that most of the sound energy arriving at the bell is reflected back to the mouthpiece, while the minimisation of player effort seems to demand efficient radiation of sound energy from the bell. This paradox is resolved by the frequency dependence of the pressure transfer function, defined as the frequency–dependent ratio of the pressure outside the bell to the pressure in the mouthpiece. The pressure transfer function for most brass instruments is very low at frequencies well below the bell cut-off frequency, while the amplitudes of the mouthpiece pressure harmonics at these frequencies are relatively large. This results in strong centring of most of the playable notes, whose fundamental frequencies lie in this range, while the small fraction of the sound energy which is radiated is still enough to generate a powerful sound. The pressure transfer function rises steadily as the frequency is increased, allowing the higher and weaker harmonics in the internal sound field to radiate more efficiently. Above the bell cut-off frequency nearly all the sound energy is radiated; these high harmonics contribute to the brightness of the sound, but their absence in the feedback to the lips does not significantly affect the centring of the notes.

Why some instruments have a brassy timbre when played loudly

A characteristic feature of many brass instruments is the bright, hard timbre of notes played loudly. Although this sound is often described as 'brassy' (Fr. '*cuivré*'), it is not caused by vibration of the metallic bell of the instrument, but by a physical phenomenon in the air column known as non-linear sound propagation. Linear acoustics, which predicts that a sine wave travelling through air will gradually lose energy but will retain its sinusoidal waveform, is an approximation based on the assumption that the change in air pressure due to the passage of the wave is a small fraction of the static atmospheric pressure. This assumption is not valid in the case of a trumpet played *fortissimo*, since the amplitude of the mouthpiece pressure oscillation can be as high as 20 per cent of an