Characterization and Taxonomy

of

Historic Brass Musical Instruments

from an

Acoustical Standpoint

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Abstract

The conceptual bases of existing classification schemes for brasswind are examined.

The requirements of a taxonomy relating to the character of brass musical instruments as experienced by players and listeners are discussed.

Various directly and indirectly measurable physical parameters are defined.

The utility of these parameters in classification is assessed in a number of case studies on instruments in museums and collections.

The evolution of instrument design since 1750 in terms of these characterization criteria is outlined.

Declaration

I declare that this thesis has been composed by me and that the work is my own.

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Contents

Chapter 1

Introduction

1.1 Scope

The scope of this study is the whole field of what may be called 'European' brass instruments made for musical purposes. This includes instruments made in the European tradition on other continents, but excludes purely signalling instruments and instruments of folk traditions that have not been to some extent integrated into the mainstream of 'art' music.

General criteria for consideration are:

1. The instrument is essentially tubular, sounded by a player exhaling through vibrating lips applied to one end of the tube. The terms 'brasswind' and 'brass instruments' do not denote the material of construction, which can be metal, wood, plastic, etc. or composite.

2. The instrument is designed to play a range of notes, typically over one to four octaves.

2. The instrument is designed to play notes which are intended to be 'in tune' with the prevailing conventional framework of pitch standards and temperament.

3. The instrument is normally assigned a nominal pitch (Myers 1994), i.e. is *in* a key such as B♭.

Thus discussed in this study are all the brass instruments used in orchestras and bands playing from written music, with the addition of instruments only occasionally so used but built with this possibility, e.g. bugles in B♭, alphorns in G♭. By analogy with woodwind instruments, a term which is not normally used for signalling whistles and folk flutes and reed-pipes, the instruments satisfying these criteria may be termed 'brasswinds'.

Excluded are instruments such as the short English hunting horn, burgmote horns and oliphants (not designed to play a range of notes); didgeridoos (not intended to be assigned a nominal pitch); and ancient instruments such as the buccina, carnyx, lur (pitch framework and playing range not adequately known). The instruments of the Russian horn band, though each designed to play a single note, might be considered as a group to meet the criteria - however no set was readily available for study.

There are inevitably some of the many hundreds of kinds of brasswinds past and present with some kind of established identity which have not been mentioned because of lack of availability. However, the types most commonly used in music making since the period of the Renaissance have been studied, and there is no reason to believe that the methods of classification investigated here will not be applicable to any of the other kinds.

1.2 Basic Acoustics of Brass Instruments

The acoustics on which this study is based is thoroughly dealt with in textbooks such as Campbell and Greated (1987) and Fletcher and Rossing (1991), and may be summarised as follows.

All brass instruments consist of a tube, at one end of which is a mouthpiece shaped so that the player can make an air-tight seal when the lips are placed against it. The acoustical properties of brass instruments depend on the interactions of the player (in particular the oral cavities and lips), the air column inside the instrument, and the ambient air at the other end of the instrument. The column of air inside the tube is set into vibration when it is excited by the player buzzing the lips, which are placed against the mouthpiece. A sustained sound on a brass instrument requires 'standing waves', i.e. soundwaves travelling from one end to the other and reflected from each end like water waves in a bath. Although the player opens the lips by blowing air through them, because the lips are buzzing they are effectively closed for enough of the time to reflect most of the sound waves travelling towards them through the instrument. Whether the other end of the instrument terminates abruptly (as in a bugle) or terminates in a flaring bell (as in a trumpet), sound waves are reflected by the bell mouth or by the flare. The sound inside an instrument is much more intense than the sound produced by the instrument in the surrounding air. The bell of an instrument has to be carefully designed so that it reflects enough sound to allow standing waves to build up, yet allows enough sound to escape to be audible at an appropriate intensity to be useful in music. For this reason, brass instrument bells are of a limited range of patterns - one shaped like a gramophone horn, for example, would not work.

The standing waves lose some of their energy to the ambient air as audible sound, some in friction with the walls of the instrument, and also a small part to the player's lips, which are coerced to vibrate at a frequency to some extent dictated by the instrument. At the same time, the player adds energy to the vibrating air column at just the right frequency by blowing through the buzzing lips to replace the sound energy being dissipated.

The air inside a brass instrument, which is effectively closed at one end by the lips and open at the other, can sustain standing waves at certain quite well-defined frequencies, known as the frequencies of the 'modes of vibration' of the air column. If the frequency of the wave is a very slightly higher or slightly lower than one of these frequencies, standing waves are still possible, but will be weaker. These mode frequencies form a series which is more extensive for a narrow tube such as in a french horn or a natural trumpet than for a wide tube such as in a bugle or an ophicleide. For a perfectly conical tube, the frequencies would correspond numerically to a harmonic series, which is defined as a series of numbers (here, frequencies) which are exact integer multiples of the lowest member (the fundamental). For a perfectly cylindrical tube, the frequencies would correspond to the odd-numbered members of a harmonic series. Real brass instruments are neither perfectly cylindrical nor perfectly conical, and the modes of vibration depend on the internal shape of the instrument. Tubes are musically most useful if several of the frequencies of several of the modes of vibration approximate to members of a harmonic series. In the case of instruments with large cylindrical portions of tubing such as trumpets and trombones, the mouthpiece and bell need to be carefully designed to make this possible. Even so, the lowest one or two members of the series of modes of vibration of trumpets and trombones diverge considerably from the harmonic series. The art of the brass instrument maker is to give the modes the most advantageous frequencies, strengths and tolerances.

When a sustained sound is produced on a brass instrument, not only does the air inside the instrument vibrate at the frequency of vibration of the players' lips, but also at exact integer multiples of this frequency. These are the spectral components of the sound, sometimes called 'overtones'; the lowest component (whose frequency is that of the lip vibration) is the fundamental. The frequencies of the spectral components of the sound when a sustained single note is being played without vibrato form a harmonic series. The sound which escapes from the bell of the instrument also contains these spectral components, and it is the relative strengths of these components that determine the timbre of a sustained sound on the instrument. However, different notes played on the same instrument will have different spectra: a high note may have a significant amount of acoustic energy in only two or three components whereas a low note may have a rich spectrum with significant amounts of energy at fifteen or more frequencies. It is always easier to distinguish two brass instruments by comparing low notes than high. Loud notes not only have energy at each spectral component, but also a more extensive spectrum. Because of this, a recording of a loud note can be recognised as such even if reproduced at low volume.

The series of fundamental frequencies of the notes which can be sounded by a player form only an approximation to a harmonic series, though they are sometimes loosely called 'the harmonics'. If the frequencies of the modes of vibration of the air column formed a harmonic series, then the 'note centre frequencies' available to the player would also form a harmonic series [Figure 1.1]. However, this is an ideal case and the behaviour of real instruments is more complicated. In order for the instrument to 'speak' and produce a 'well-focused' sound, several of the overtones (harmonics) of the note being played need to resonate with modes of vibration of the tube. In most cases, the fundamental of the note is very close to one of the mode frequencies; in addition, to produce the tone quality expected of brass instruments, its spectral components (harmonics) also resonate with higher modes of vibration of the air column inside the tube. The interaction of the harmonic components of the sound with the air column, termed a 'co-operative regime', is a strong effect. On one hand, a co-operative regime can allow a sustained sound even if the fundamental does not match a mode of vibration of the air column - this is how a trombonist can sound a pedal note or a tuba player can sound 'factitious' notes not in the usual series [Figure 1.1]. On the other hand, if the modes of vibration have a poor match with the overtones (harmonics) of a note a player is sounding, the note will be 'stuffy' in quality, difficult to produce, and possibly out of tune. Since the air column can sustain standing waves at frequencies very slightly higher or slightly lower than the mode frequencies, the player has some latitude to 'lip' a note up or down in pitch and to use pitch vibrato.

Figure 1.1: *The pitches of the first 20 modes of vibration of air at 25° C in an ideal cone of length 2.645 metres (approximately 8ft): the mode frequencies departing most from the equally-tempered scale are indicated in black. A well-in-tune instrument pitched in 8-ft C will allow a portion of this series of notes to be played without extending a slide, operating valves or opening tone-holes, depending on the bore proportions and the ability of the player. An ophicleide, for example would normally use members 1 to 6; a natural trumpet can sound members 3 to 20.*

In the case of wide-bore signalling instruments such as a bugles, there are only a small number of modes of vibration of the air column which are of sufficient strength to contribute to the generation of sustained sound; therefore the 'co-operative regimes' are less extensive than those which allow in-tune production of the lower notes of narrow-bore instruments such as the french horn and the trombone; as a result many instruments of the bugle family are not well in tune. In the case of instruments with tone-holes such as cornetts and serpents, the situation is complex: the series of notes which can be produced with a given fingering are not generally a close approximation to a harmonic series. On these instruments, for example, a note and a note an octave higher usually have different fingerings (Campbell 1996).

So far, only sustained sounds have been discussed. In order to sound a note, the brass player has to set the lips in vibration, sending a pulse of sound towards the bell. By the time the initial pulse is reflected back and can interact with the lips to establish a stable sustained sound, the lips will have gone through at least one cycle (many cycles for high notes). A large part of the skill of the brass player consists of the ability to buzz the lips at the right initial frequency; it is to acquire this ability that many teachers recommend practice on the mouthpiece alone. The length of unsupported time is longer for a given note on, say, a natural trumpet in 7-ft D than a piccolo trumpet in 2¼-ft B♭. With a longer tube length, the nearest playable notes above and below the desired note are closer in pitch than with a short tube length. For these reasons, the trend in instrument design since the invention of the valve has been to make shorter instruments.

The sound characteristics of instruments depend to a large extent on their behaviour in the initial build-up of a note. If tape recordings have these 'starting transients' cut out, it is almost impossible to identify the instrument being played, sometimes even to tell if it is wind or string. Another characteristic of an instrument can be the presence of formants. These are regions of the spectrum where the components are consistently strong regardless of the exact fundamental frequency of the note being sounded. Formants are the mechanism whereby vowels can be recognised in speech and song; they make an important contribution to woodwind character, and are less important for brass but still significant (Meyer, 1978).

Opinions differ as to the importance of the material of a brass instrument. The vibration of the walls has little effect on the sound spectrum produced by a brass instrument, and the character of what the listener hears is principally determined by the shape of the bore profile of the instrument and of the oral cavities of the player. Factors such as material and wall thickness may in some cases have effects that can be sensed by the player, who is in physical contact with the instrument and who perhaps hears sound radiated from the body of the instrument. The bore profile, however, is the principal determinant of the character if the instrument - for example whether it is a french horn, a flugelhorn or a saxhorn.

Mode number	Frequency (Hz)	C_2	C_3	G_3	C_4	E_4	G_4	C_5	D_5	E_5	G_5
1	42.2	66.4									
2	124	133	133								
3	198	199		199							
4	265	265	265		265						
5	332	332				332					
6	395	398	396	398			398				
7	461	465									
8	529	529	529		529			529			
9	599	597		597					597		
10	663	664	664			664				664	
11	732	730									
12	801	796	796	796	796		796				796
13	872	863									

Figure 1.2: *Example of Mode Frequencies and Spectral Components. The second column shows the frequencies of the modes of vibration of a bass trumpet in 8-ft C by Alexander (Model 19) with a Bach 7C mouthpiece belonging to W.A. Giles, the tuning-slides fully closed and with no valves operated, measured at 18° C using the capillary input impedance method as described by Campbell (1987). The other columns show the spectral components (harmonics) of the notes playable on this instrument with no valves operated [Figure 1.1]. The pedal note, C_2, which is rarely used on the bass trumpet receives no support for its fundamental, and can be sounded only because of the support of modes 3 - 13 for its harmonics 3 - 13. The second mode (124 Hz) is a semitone flatter than the fundamental of the note C_3 (133 Hz), which note can therefore be sounded only because of the support of modes 4, 6, 8, 10 and 12 for its harmonics 2 - 6. On this instrument, modes above the 13th are not strong enough to help a player 'centre' on a desired note. In fact, the compass of the bass trumpet is not usually regarded as extending above G_5. The playable notes are a little sharp compared with the pitch standard A_4 = 440 Hz (middle C = 265 Hz is equivalent to A_4 = 446 Hz), and will be sharper still when the instrument is warmed up; however, the instrument is normally used with the tuning-slide drawn.*

1.3 Historical Background

The history informing this study is based is dealt with in detail in textbooks such as Baines (1976) and Heyde (1987b); the phenomenon of the proliferation of brasswind models may be summarised as follows.

Through the eighteenth century and the early years of the nineteenth, both the trumpet and the horn were increasingly used in orchestral and band music. Despite the widespread use of hand-stopping in horn playing and the rarer use of slide trumpets or keyed trumpets, composers and arrangers were very restricted in the kind of music they could write for brass instruments. Makers had to provide sets of crooks - up to four or five for the keys commonly used for trumpet music and ten or eleven for horns. Parts written for these instruments were closely related to the natural series of notes; and if the music changed into a different key, time had to be allowed for the player to change crooks.

These limitations prompted the invention of the valve, which had the effect of an instantaneous change of crook. The first successful valve was that of the musicians Heinrich Stölzel and Friedrich Blühmel in Prussia in 1814. Other designs followed; these achieved a similar effect by different mechanisms. It was soon realised that valves, when mechanically capable of being operated with sufficient speed, could be used not merely to change crook simply and rapidly, but to play tunes and ensemble parts with great facility - more evenly and easily than by handstopping a horn and with greater rapidity than with the slide of a trombone or slide trumpet.

Not only did the invention of valves revolutionise horn and trumpet technique, but it also permitted the development of new kinds of brass instrument. The use of a slide in a trombone or in a trumpet necessitated a bore profile that included considerable lengths of cylindrical tubing. The use of finger-holes or keys for the cornett, serpent, keyed bugle and ophicleide was most satisfactory for instruments with an almost purely conical bore profile. The use of handstopping was effective only with instruments of the bore profile of the french horn - narrow at the mouthpipe, wide at the bell throat and pitched not too far from F (12-ft tube length). With valves, however, instrument makers had complete freedom to introduce instruments with any bore profile that resulted in an instrument that was acceptably in tune with itself.

Within a few years of the invention of the valve, instruments in various sizes and shapes were being produced, particularly in Germany, which were the forerunners of the cornet, the tuba and other instruments. In the course of nineteenth century the adoption of the valve led to a proliferation of viable bore profiles for acceptable brass instruments. In addition to unambiguously new instruments such as the tuba, many types of instruments with intermediate bore profile were developed, such as the saxhorn. The established repertoire for existing instrument types (especially the horn and the trumpet) required instrument designs capable of performing this repertoire, with sufficient performance characteristics remaining intact through each design development. This study is an investigation of the properties which continued through the evolution of established types to the present day, and which distinguish them from the newly invented models of the nineteenth century.

Before the nineteenth century, instruments were made by hand-craft techniques, and makers are considered to have used instrument designs incorporating proportions expressible by the ratios of small integers, as will be discussed in Chapter 2, Section 2.2. Generally, these methods were replaced in the nineteenth century by mechanised techniques, an empirical approach to design and factory production; in the twentieth century there has been some practical application of acoustical theory.

One important technique which has continued throughout is the use of mandrels in instrument making. A mandrel is a piece of iron or steel of the exact shape required for the interior of a part of an instrument, on which that part can be worked to bring it into its correct shape. If not actually made by the instrument maker, mandrels are made to the maker's specification. The mandrels form an essential, but usually unwritten, part of the 'recipe' for making an instrument. The mandrel on which the bell is made is particularly important, since it determines exactly the shape of the bell flare of the instrument and much of its acoustic character, as will be discussed in Chapter 6. Mandrels can be used for many years, allowing continuity in the production of individual models of brass instrument design over time.

Several manuals (Nödl 1970, Bahnert et al 1986, Dullat 1989) provide detailed descriptions of brass instrument construction techniques, including many measurements of components of contemporary instrument models. However, comparable measurements are not readily obtainable for historic instruments, and for consistency fresh measurements have been made for this study on old and new instruments alike using the same techniques and equipment.

Chapter 2

History of classification

2.1 Simple Classifications

Classification, the systematic grouping of objects or ideas to facilitate their treatment, has been used by authors to arrange material in books, and by museums to arrange displays and catalogues. The best-known musical instrument classification is the Hornbostel-Sachs classification of 1914 (Hornbostel and Sachs 1914, translation into English 1961). Its treatment of brasswind [Figure 2.1] is rather superficial: the purpose of the scheme is to allow curators to arrange objects even if they know nothing about the music or culture of origin. Such a classification may, however, lead to discoveries about the migration of instrument types from one region or people to another.

423	Trumpets	
423.1	Natural trumpets	
423.12	Tubular trumpets	
423.121	End-blown trumpets	
423.121.1	Straight end-blown trumpets	
423.121.12	With mouthpiece	
423.121.2	End-blown horns (tube is curved or folded)	
423.121.22	With mouthpiece	
423.2	Chromatic trumpets	
423.21	Trumpets with fingerholes	*cornetti, key bugles*
423.22	Slide trumpets	*trombone*
423.23	Valve trumpets	
423.231	Valve bugles (conical tube throughout)	
423.232	Valve horns (predominantly conical tube)	
423.233	Valve trumpets (predominantly cylindrical tube)	

Figure 2.1: *Western brass instruments in the Hornbostel-Sachs classification, 1914.*

Here all brass instruments are 'trumpets', coming in the general class 423. The primary division is into natural and chromatic, divided morphologically (natural instruments) or by mechanism (chromatic instruments). These are the easiest attributes to be recognised by someone with no specialist knowledge of kinds of brass instrument. For valved instruments only, however, there is a simple categorization by bore profile. This classification would (for example) separate natural, slide, keyed and valved trumpets which might at one time have been used for the same repertoire.

This division into three classes by bore profile has been adopted by several present-day writers on musical acoustics such as Eargle (1990). Here, a euphonium is regarded as a valved bugle, almost entirely conical. B$\flat$ and F horns are predominantly conical, and trumpets and trombones are cylindrical. It is not immediately obvious where to place some modern instruments, such as a Wagner tuba or a cornet, let alone historical instruments.

A division into five families [Figure 2.2] has been outlined by Edward Tarr (1984) which he attributes to the collector Wilhelm Bernoulli. This is based on subtler distinctions between bore profiles and bore diameters.

Wide conical bore absent or minimal bell flare	*cornett, serpent, bass horn*
Narrow mainly cylindrical bore medium bell flare medium throat wide mouthpipe	*trumpet (except modern piston valve trumpet), trombone*
Narrow half conical half cylindrical bore medium bell flare medium throat narrow mouthpipe	*cornet, post horn*
Narrow to wide conical bore absent or minimal bell flare very large throat formerly wide, now narrow mouthpipe	*flugelhorn, ophicleide*
Very narrow, slightly conical bore very large bell flare medium throat very narrow mouthpipe	*horn*

Figure 2.2 *Five families of western brass instruments (Tarr, 1984).*

A much more detailed scheme was proposed by Adam Carse (1939) This introduces mouthpiece profile as a principle of division. Note that modern french horns are now 'mainly conical' and the intermediate class is given to cornets. There are consistent designations for natural and modern trumpets. This classification is satisfactory for many purposes. However, in the Carse scheme [Figure 2.3], the Wagner tuba is still unplaced, and many other distinctions are not made, such as the difference between a valve trombone and a bass trumpet.

No mechanism
- Mainly cylindrical bore
  - Narrow bore
    - Cupped mouthpiece — *Old trumpets*
    - Deeper cupped mouthpiece — *Cavalry and fanfare trumpets*
- Conical bore
  - Wide bore
    - Various mouthpiece — *Bugles*
  - Narrow bore
    - Cornet or bugle mouthpiece — *Coach and post horns*
    - Cone or funnel mouthpiece — *Hand horns and French hunting horns*

Finger-hole or key-hole (shortening mechanism)
- Conical bore
  - Wide bore
    - Cup mouthpiece — *Cornetts*
  - Very wide bore
    - Cup mouthpiece — *Serpents*
  - Wide bore
    - Intermediate mouthpiece — *Bass-horns, Keyed bugles, Ophicleides*

Valve (lengthening mechanism)
- Mainly cylindrical bore
  - Narrow bore
    - Cup to intermediate mouthpiece — *Valve trumpets*
    - Intermediate mouthpiece — *Valve trombones*
- Conical and cylindrical bore
  - Narrow bore
    - Intermediate mouthpiece — *Modern cornets*
    - Conical (lily-shaped) mouthpiece — *Old cornets*
- Mainly conical bore
  - Narrow bore
    - Cone or funnel mouthpiece — *Valved french horns*
  - Wider bore
    - Intermediate mouthpiece — *Flügelhorns, alto, tenor and baritone saxhorns and bugle-horns*
  - Wide bore
    - Intermediate mouthpiece — *Euphoniums, tubas or bombardons*

Slide (lengthening mechanism)
- Mainly cylindrical bore
  - Narrow bore
    - Cup mouthpiece — *Slide trumpets*
    - Intermediate mouthpiece — *Slide trombones*

Figure 2.3: *Carse's 1939 classification.*

Carl Schafhäutl (1854) introduced the concepts of 'whole-tube' and 'half-tube' brass instruments, the former being able to sound the pedal notes and the latter only the octave of the pedal note and higher members of the series of natural notes. This criterion depends, however, to a large extent on the abilities of individual players, and is not strictly related to musical practice. For example, the pedal notes of bugles and other soprano brass instruments may be able to be sounded, but they are not much required in the usual musical repertoire.

Nicholas Bessaraboff (1941) in his catalogue of musical instruments in the Boston Museum of Fine Arts collection which includes much of Canon Galpin's Collection, gives considerable attention to the taxonomic problems of brasswinds. Bessaraboff was an engineer by training, and was perceptive about the nature and roles of brass instruments. He realises the limitations of the 'whole-tube' and 'half-tube' concepts, but retains them as a tertiary principle of division. A further failure of the 'whole-tube' and 'half-tube' division which he recognised is that a french horn crooked in 12-ft F or lower cannot readily sound the pedal but a french horn crooked in 11-ft G or higher can, so this principle of division separates two very closely related instruments. Worse still, a tenor trombone in position 1, 2 or 3 can sound the pedal but a tenor trombone in position 4, 5, 6 or 7 cannot, so this instrument changes its class in the course of being played. (Players of modern wide-bore trombones, it should be mentioned, can and do play pedals in all positions, and even notes an octave below the pedal as 'privileged notes' on occasion.)

In Bessaraboff's classification [Figure 2.4], the primary principle of division is into conical and cylindrical instruments; his secondary principle is into 'two-octave', 'three-octave' and 'four-octave' instruments, depending on the highest in the series of natural notes available to the player. This also, of course, depends to some extent on individual playing abilities. Sounding tessituras do not necessarily vary much in practice: trumpets and french horns, for example, have been built in widely differing tube lengths to play the same orchestral parts. With band instruments there has been a tendency for instruments to be used with a 2½-octave range. Thus Bessaraboff's divisions cut across families and even the identity of individual instruments.

A. Conical		
	1 Two-octave	*Shofar, Oliphant, Forester's horn* *Cornett, Serpent, Bass horn* *Key bugle, Ophicleide*
	2 Three-octave	
	i With pedal tone	*Bugle, Lur, Alphorn*
	ii Without pedal tone	*Cornet, Post-horn, Ballad horn*
	3 Four-octave	
	i With pedal tone	
	ii Without pedal tone	*Hunting horn (trompe), french horn*
B. Cylindrical		
	1 Two-octave	
	2 Three-octave	
	With pedal tone	*Trombone, Trumpet*

Figure 2.4: *Bessaraboff's 1941 classification.*

Herbert Heyde (1975, 1987a) proposed a classification of instruments following Linnean taxonomy. His scheme uses successive division into *Komplex*, *Abteilung*, *Stamm*, *Bereich*, *Ordnung*, *Gruppe*, *Familie*, *Gattungskries*, *Gattung*, and *Art*; these levels being subdivided or omitted as necessary. The principles of division for 'Labialinstrumente' are:

Lengthening, shortening or no mechanism
Overall bore profile ('*Kornoide*' or '*Tromboide*')
Bell shape (flared, funnel or 'hyperbolic')
Degree of cylindricality (weak or strong)
Type of mechanism

The classification can be considered to be an outline only, since the terms are not sufficiently well defined and not enough examples are given to apply the scheme without establishing further rules. It has not been developed in Heyde's later work, discussed in Section 2.21 below.

These broad-brush classifications have no precisely stated criteria or tests. The terms 'conical' and 'cylindrical' have intuitive meaning but are not satisfactorily defined. Simple schemes may distinguish satisfactorily between the types of instrument in use before the invention of the valve, but fail to give clear places to new types such as the cornet, the bass tuba, the saxhorn, the bass trumpet and the Wagner tuba.

2.2 Heyde's bore characterization

The greatest body of detailed and consistent measurements so far made of brasswind has been for the series of catalogues by Herbert Heyde of the museums in Eisenach, Halle, Leipzig and Frankfurt an der Oder (Heyde 1976, 1980a, 1980b, 1982, 1989). These collections together hold most types of German brasswind from all periods, including early examples by Nuremberg makers. As well as the lengths of the various conical, cylindrical and flaring sections, Heyde has measured the bore diameter at certain points. Among the measurements he gives are:

d = the minimum diameter, usually a short distance in from the mouthpiece receiver

D = the bell diameter and

D3 = the tube diameter in the bell at the depth of one bell diameter.

Heyde has found that when expressed in terms of the units in use at the time and place of the instrument's making, the measurements of pre-industrial instruments are frequently simple numbers and the various lengths often turn out to be related by simple proportions. For example, in a Viennese trombone of 1794 in Edinburgh University Collection of Historic Musical Instruments (EUCHMI 3205) examined by Heyde in 1991, the upper section is two-fifths of the total tube length, the slide section three-fifths. The diameter of the cylindrical tubing is 5 Viennese *Linien* (five-twelfths of a *Zoll* or Viennese inch). D3 is three-and-a-half times d. The end of the bell divides the overall length by the golden section. These observations may have little acoustical significance, but they could point us to the models, the design ideal, adopted by the makers.

Heyde designates the relative lengths of the conical, cylindrical and flaring sections of an instrument the *Anteilverhältnis* or *AV*, and in his catalogues gives this as two or three fractions whose sum is unity. The 1794 trombone for example, is seven-ninths cylindrical plus two-ninths 'hyperbolic'. This proportion is often cited as the principal distinction between a trombone and a trumpet. However, a simple plot of this ratio against nominal pitch for the trumpets and trombones described in Heyde's catalogues shows consistency among Renaissance and baroque examples but reveals that both trumpets and trombones have evolved to contain less cylindrical tubing. The picture presented by valved instruments is not so simple. What was a valid distinction between, say, an alto Renaissance trombone in 6½-ft E♭ and a natural trumpet in 6½-ft E♭ is not so straightforward when we look at valved instruments. There are other limitations of this measurement as a guide. A trombone is still a trombone, whichever position the slide is in. As the slide is extended, however, the effect is to increase the proportion of cylindrical tubing. Similarly, operating the valves of a trumpet increases the proportion of cylindrical tubing, but does not make the instrument sound like an alto trombone.

Heyde has suggested that the ratio of D3 to d is particularly valuable. It is a measure of the increase in diameter over the tube length up to the start of the final flare. This ratio can be plotted against D for some different kinds of instrument. Considering instruments widely used before the invention of keys or valves, the different kinds occupy different areas (Figure 2.5). With specimens immediately prior to the general adoption of valves, an altered pattern appears (Figure 2.6). Considering instruments of the valve era (Figure 2.7) there is a proliferation of bore profile design made possible by the invention of the valve.

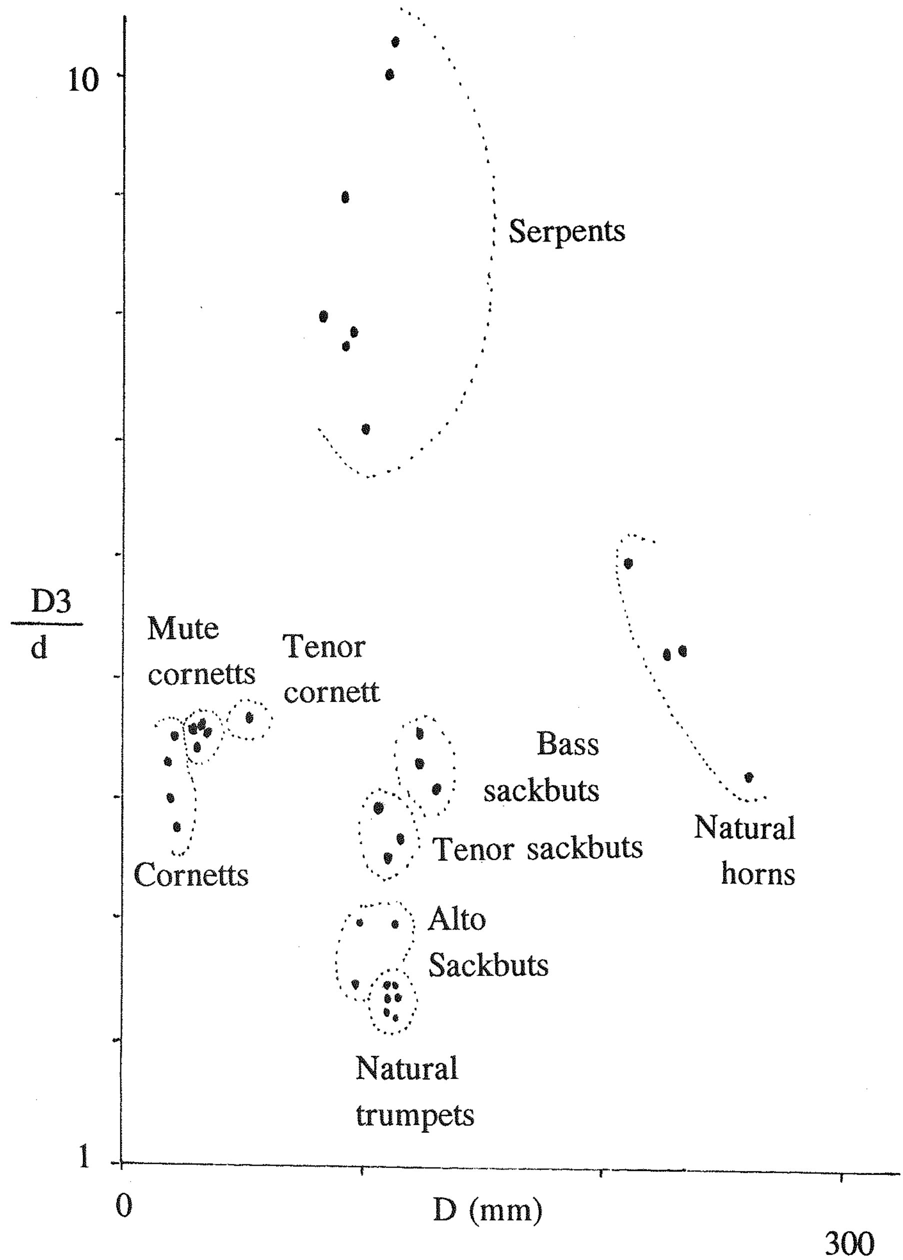


Figure 2.5: *Plot of D3/d against D (millimetres) for early instruments.*

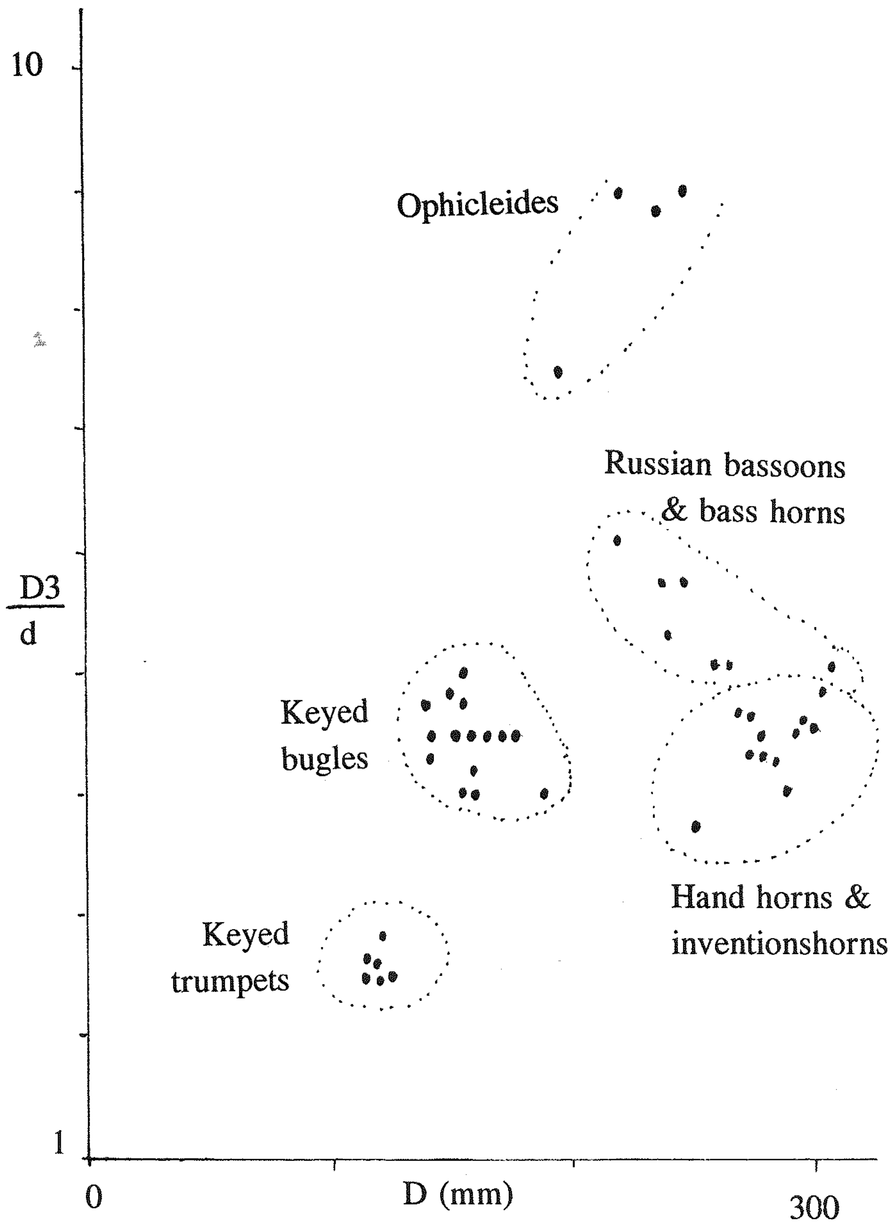


Figure 2.6: *Plot of D3/d against D (millimetres) for pre-valve era instruments.*

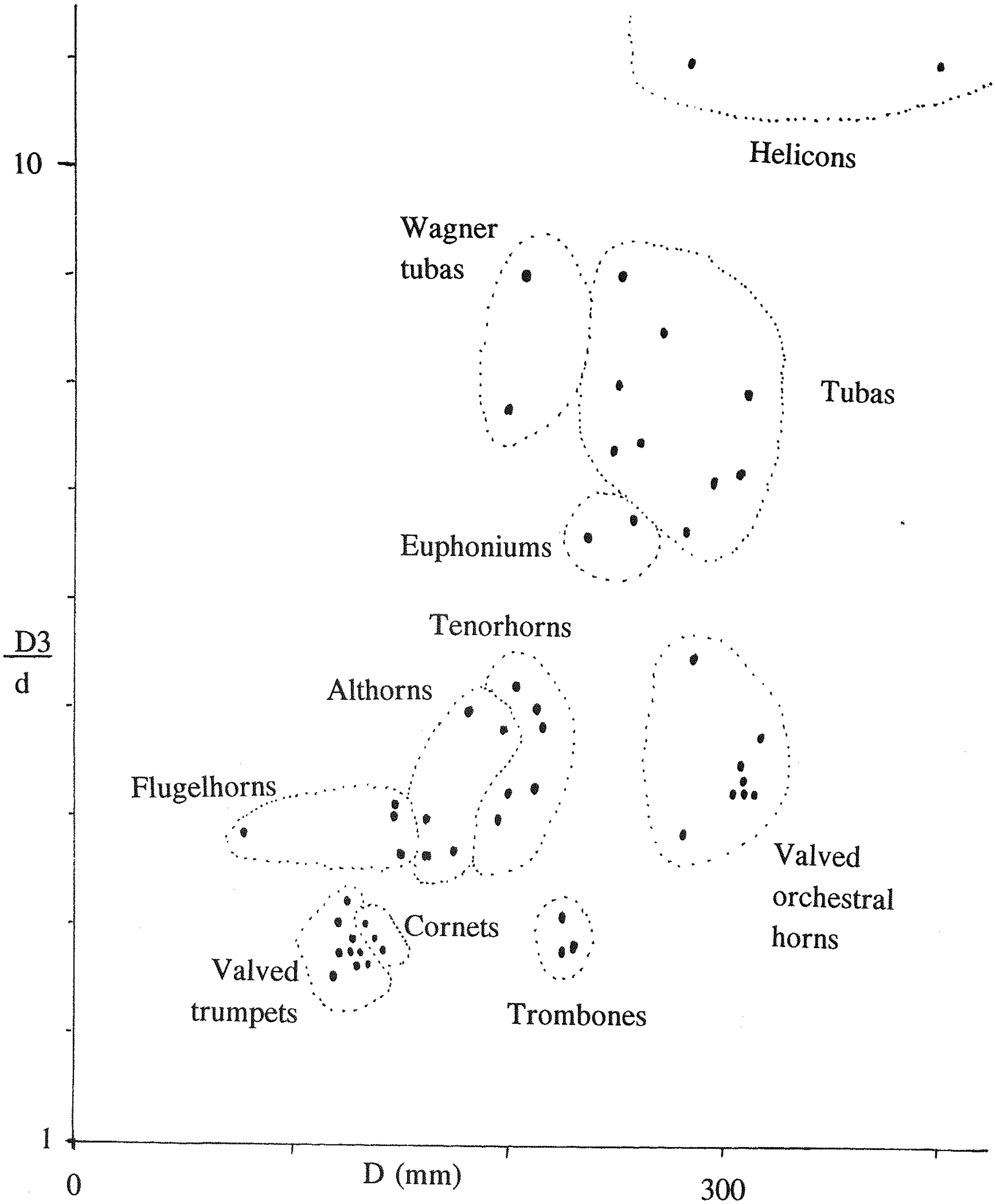


Figure 2.7: *Plot of D3/d against D (millimetres) for valve era instruments.*

Although prior to the invention of valves, signalling instruments such as posthorns could be made with any viable bore profile, instruments for musical purposes were restricted to those with usable high registers (french horns and natural or keyed trumpets) those with slides (necessarily with much cylindrical tubing), horns that could be hand-stopped (long and with a pronounced bell-flare) or those playable with finger-holes or keys (conical throughout). The valved versions of these are in Figure 2.7 along with cornets, tenorhorns, tubas etc.

However, the wide-bore trombone, the design introduced by Sattler and adopted by Wagner, has moved some way from the Renaissance trombone. The main orchestral instruments have changed a considerably. At each point of change they have carried with them an established repertoire, and enough of their character for the new design to be recognised as being in the same class as the old. If, however, someone had invented the modern valved trumpet without the intermediate evolutionary steps, one feels it would hardly share the same name as the old natural trumpet.

Figure 2.7, of course, omits other designs made possible by the invention of valves such as the ballad horn, the cornophone, the tenor cor and many others.

Chapter 3

Purpose and expectations of taxonomy

3.1 Uses of Classification

Classification of instruments has been used for many purposes (Kartomi 1990). These can include managing material in catalogues and text books, the main purpose of the systems discussed in Chapter 2 Section 2.1. A cultural or functional approach could be appropriate for ethnographic purposes (Kartomi 1990, Devale 1990). A classification by playing technique as proposed by Kvifte (1989) might be useful in pedagogic work. Other purposes may require classifications that place emphasis on instruments' value, their museum conservation requirements, their overall size or weight, or even their sculptural qualities. The acoustical standpoint of this study is only one of many valid approaches, and taxonomy as discussed below is only one purpose.

3.2 The Taxonomic Problem

How many different types of brass instrument are there ? A typical nineteenth-century maker's catalogue offers an impressive choice. For instance, Henry Distin's catalogue of 1857 lists 76 kinds [see Appendix A]; although some models are stated to be the same instrument but in differently wrapped forms for cavalry use etc, it is not explicitly stated that they are made using the same mandrels but differently bent afterwards. Similarly, the Zimmermann catalogue of forty years later (Zimmermann 1899) includes 79 varieties of brass instrument, counting in each case raw brass and silver-plated versions as the same instrument. In preparing the first edition of the catalogue of the brass instruments in the Edinburgh University Collection of Historic Musical Instruments (Lewis, Myers and Parks 1992; Myers and Parks 1993; Myers and Parks 1994) it was found necessary to use 185 type names. In several cases the same name can be applied to instruments that are separated by an appreciable evolutionary distance, such as the varieties of tenor trombone in B♭.

It is a valid question whether these hundreds of nominally different instruments really all respond to the player and sound differently. After discussing valved brass instruments in some detail, Carse (1939, p.315-6) states provocatively:

> "No doubt other instruments, all in varying degree akin to the cornet, bugle or ophicleide, could be found if the records, catalogues and patent files of last century were searched and the museums ransacked. The collection of varied types could be enlarged by including some solitary instruments made only in one size and named according to register, kinship to type, or perhaps with the idea of perpetuating the name of some optimistic inventor. Most of these would probably fail to establish a claim to any individual existence, for the field is limited, and there is not room for any great variety between the tone-quality of the cornet and that of the bugle, whether large or small; nor does the admixture of trumpet-, horn-, or trombone-bore, and their characteristic mouthpieces, supply sufficient variety to provide very many new and clearly different tone-qualities. Many claimants to a separate existence within this restricted field have had to give up their pretended individuality and throw in their lot with the common types that are in use today. The flügelhorns and contralto saxhorns, the tenorhorns and baritones, the tubas and bombardons may be differently named in each country, or may even be differently named in the same country, but their nomenclature is always more varied than their tone-qualities. Different widths of bore and diversity of mouthpiece-cup will give variety of tone-quality within a certain radius, but that radius is limited in extent. In the highest register, the field of brass instruments in high E flat, it matters little to the hearer whether the instrument be a trumpet, cornet, saxhorn or flügelhorn. In the contralto or B flat register, there is room enough for the cornet and the flügelhorn, but hardly for anything in between the two. So it is in the tenor or E flat register, the baritone and the bass registers; we can admit instruments which are large-sized cornets or large-sized bugles, but anything between these two makes the distinction too fine for ordinary ears, and therefore too fine for practical use ..."

Carse may be correct in suggesting that 'ordinary ears' can distinguish no more than two differing types of brasswind in each register. A psycho-acoustic survey of the general population to test this contention is outwith the scope of this study. There is no doubt that trained musicians can recognise more than two types, if not as auditors then certainly as performers. The continued production by individual manufacturers of a wide range of instruments as well as differing models of the most popular instruments, nominally the same type, is commercially justified only by purchasers perceiving differences.

The use of the word 'taxonomy' implies, of course, an analogy with biological scholarship. In the field of natural history, taxonomists do not merely wish to classify species for convenient handling of museum specimens and written descriptions, but also to suggest the evolutionary relationships between species. With artefacts, as opposed to natural entities, there is no requirement for a new species to have evolved from a previous species: objects can be new inventions. However, completely new musical instruments are rare. Although some brasswind types such as the keyed bugle, cornet, ophicleide and tuba could have been claimed to be new, many developed while keeping the name and some of the character of a predecessor. The instruments designed for the purpose of performing, say, orchestral trumpet parts have been very varied, but each (if successful) has to do justice to the existing trumpet repertoire. The concepts of evolution and taxonomy are more than metaphor in this situation.

Taxonomy can be regarded as reflecting a classification by sound ideal. To belong to the same taxa, instruments should convert a similar output from a player into a similar input for a listener.

We should distinguish between classification and taxonomy for the purposes of this study. There are many possible ways of classifying musical instruments; taxonomy is only one form of classification.

3.3 Requirements of Taxonomy

We require principles of division consistent with acoustical theory, for economy involving the minimum necessary number of parameters. The parameters should relate to factors under the control of instrument makers (e.g. properties of their patterns and mandrels), to the audible character of the instruments (e.g. the radiation characteristics of the bell flare) and the feel to the player (e.g. the input impedances).

We would seek some quantity that is constant for all sizes of the family of saxhorns, for instance, or for all trombones from soprano to contrabass. One would expect this quantity to remain constant, or at least to change slowly and continuously with time, when an instrument undergoes an 'evolutionary' change.

Although direct measurements of the acoustical behaviour of instruments, and indeed playing them, are useful for testing taxonomic criteria, for historical purposes we require criteria that can be applied to museum instruments. These are often fragile, damaged or even incomplete, and thus not amenable to acoustical testing. A taxonomy would ideally be applicable to surviving fragments, also to surviving mandrels and designs.

Although acoustically measured quantities may provide the key to consistent characterization of instruments, direct physical measurement should be sufficient to identify the maker's model. Manufacturers have offered ranges of instruments made to certain specifications: it should be possible to ascertain these specifications in recent history, and to reconstruct those of earlier periods. Performers have chosen certain instruments for a particular repertoire; organological research aims to identify what instruments have been used for the various parts in music of interest to us.

Such a measurement-based taxonomy should prove useful to instrument makers, performing musicians, composers, organologists and museum curators.

Chapter 4

Factors and ranking of factors

4.1 Factors of possible taxonometric significance

As in other areas of musical acoustics, it is a delicate task to prioritise the many factors which can, in different circumstances, appear important to instrument makers, players and audiences. Some of these factors may be used to distinguish between good instruments and bad, but in attempting a rigorous taxonomy, it is a greater priority to distinguish, say, a bass trumpet from a valve trombone than to distinguish between a superb french horn and a poor one.

For nearly all brasswind, it is possible to consider the bore divided into mouthpiece, main length of the tube, and the bell. Very generally speaking, the mouthpiece shape governs the coupling with the player, the main body determines the playing pitch, and the bell controls the radiation of sound and thus the character of what the listener hears. This model is too simple for any detailed analysis, but may serve for taxonomic purposes.

The factors considered by various authors to affect the character of brasswinds include:

1. Bore profile (which can be varied in one instrument by use of slides, valves or placing the hand in the bell). In Chapter 2, authors of published classification schemes used various principles of division: cylindrical/conical; degree of flare in bell; narrow/wide mouthpipe; whole tube / half tube; compass. These issues are discussed in Chapters 6 and 8.

2. The profile of the mouthpiece proper to the instrument. In Chapter 2, authors of published classification schemes distinguished between cupped and funnel cup shapes. This is discussed in Chapter 7.

3. The properties of a particular player's lips and vocal tract. This is undoubtedly a very significant factor in the character of brasswinds, but since performing technique is entirely dependent on the player and completely independent of the instrument, it cannot form part of a taxonomic scheme.

4. Wall thicknesses, particularly in the bell flare. This is considered to be a noticeable factor by some players. The effect of wall thickness, particularly in the bell section of trombones has been investigated by Smith (1981) and Watkinson and Bowsher (1982) and is at most a second-order factor in determining tone quality. How the brass is stress-relieved or coated (Pyle 1981) may make the difference between a good trumpet and a bad, but not the difference between a trumpet and a horn.

5. Bends in the tubing. It would be useful to be able to take as a premise that the most important determinant is the interior profile of mouthpiece and instrument bore viewed as if the instrument were straightened out, so that the taxonomy did not depend on the shape a tube is coiled in (the 'wrap'). Although from an ethnographic and organological viewpoint the manner of folding, looping or coiling instruments may be significant, it will be suggested in Chapter 5 that the wrap is of second-order importance in the acoustical behaviour of instruments.

6. Bore perturbations (e.g. water-keys, dents, valve misalignments). Widholm (1989) also discusses the effects of valve type on transitions between notes in legato passages.

7. Temperature and humidity; thermal gradients.

8. The steady (or unsteady) flow of air through the instrument.

Several of these factors have been investigated in previous research and can be discounted as forming primary principles of division in a taxonomy. Pratt & Bowsher (1978a) ranked the factors determining the perceived tone quality of trombones as (1) the instrument (2) the player and (3) the mouthpiece.

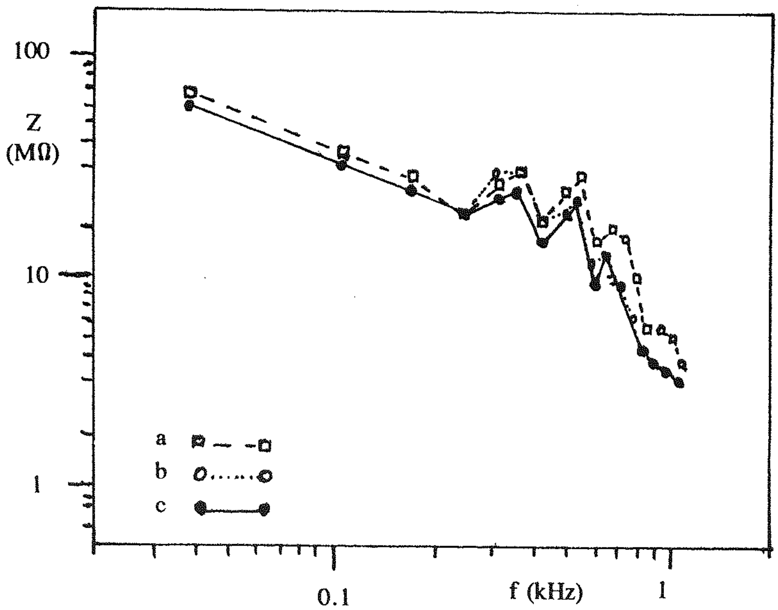
4.2 Impedance measurements on trombones

In order to test the hypothesis that the bore profile of the bell flare is of prime importance, the acoustic impedance of a considerable number of trombones of different sizes and models was investigated. This continued the work of Campbell (1987) and relates directly to relevant work reported elsewhere (Backus 1976, Pratt & Bowsher 1978b, Pratt & Bowsher 1979, Caussé et al. 1984). The trombone has been used with a wider variety of mouthpiece than other brass instruments, ranging from the shallow cup of the jazz era to the deep cone of the nineteenth-century French trombone; this makes it particularly suitable for investigation.

The experimental part of this study has consisted of input impedance measurements of trombones of various sizes (alto, tenor, bass and contrabass) and various styles and periods (reproduction Renaissance models, baroque, nineteenth-century and modern). The apparatus was that described by Campbell (1987), similarly calibrated. Peak envelopes were similarly derived. The instruments measured included:

FT	Alto Renaissance model trombone in E♭ (Tomes)	bore 11.0mm.
EUCHMI 2782	Alto trombone in E♭ (Besson, London, c 1940)	bore 11.5mm.
SSC	Tenor Renaissance model trombone in B♭ (Tomes)	bore 12.0mm.
EUCHMI 3205	Tenor trombone in B♭ (Huschauer, Vienna, 1794)	bore 10.8mm.
EUCHMI 606	Tenor trombone in B♭ (Courtois, Paris, c 1880)	bore 11.2 - 11.5mm.
EUCHMI 214	Buccin trombone in B♭ (probably France, c 1840)	bore 11.1 - 11.4mm.
CEB	Tenor trombone in B♭ (Boosey & Hawkes Imperial model)	bore 12.4mm.
EUCHMI 3207	Tenor trombone in B♭ (Schopper, Leipzig, c 1920)	bore 13.0 - 13.3mm.
DMC	Tenor trombone in B♭ (King 2B model)	bore 12.2 - 12.5mm.
AM 159	Tenor trombone in B♭ + F (King 3B model)	bore 12.9mm.
AM 171	Tenor trombone in B♭ (Conn 8H model)	bore 13.8mm.
AM 960	Bass Renaissance model trombone in G (Tomes)	bore 12.0mm.
EUCHMI 3671	Bass trombone in G (Higham, Manchester, c 1935)	bore 12.0mm.
EUCHMI 3255	Bass trombone in G + D (Boosey & Hawkes wide bore model)	bore 13.4mm.
AM 764	Bass Renaissance model trombone in E♭ - D (Meinl)	bore 13.0mm.
EUCHMI 3208	Contrabass trombone in E♭ + B♭ (Germany, c 1925)	bore 13.5mm.

The input impedances were measured with each instrument equipped with an appropriate mouthpiece and in several cases with alternative mouthpieces. It was found that the peak envelope is seriously disturbed only if a mouthpiece of radically different volume is used. A deep conical traditional French mouthpiece (virtually a scaled-up french horn mouthpiece) gave a peak envelope differing little from that given by a shallow jazz era mouthpiece [Figure 4.1]. Campbell (1987) discussed the effect of using a reproduction Renaissance model trombone mouthpiece of much smaller cup volume.



(a) □- -□ conical traditional French mouthpiece
(b) ○····○ jazz era mouthpiece
(c) ●——● modern American mouthpiece

Figure 4.1: *Peak envelopes of Courtois narrow-bore trombone with (a) Courtois deep cone mouthpiece EUCHMI 3100, (b) Selmer 23D jazz mouthpiece EUCHMI 665, (c) Bach 6½ AL mouthpiece of greater volume than (a) or (b), AM 189.*

The tenor and bass Renaissance model trombones by Tomes are equipped with removable tapered leadpipes. The tapered leadpipe is not an authentic feature of the Renaissance sackbut, but this maker supplies them for present-day players who find the instruments speak more readily when the leadpipe tapers as does that of the modern trombone. It was found that the taper has the effect of levelling the peak envelope slightly, raising the peaks of modes 3-7 and lowering the peaks of modes 8-12 [Figure 4.2].

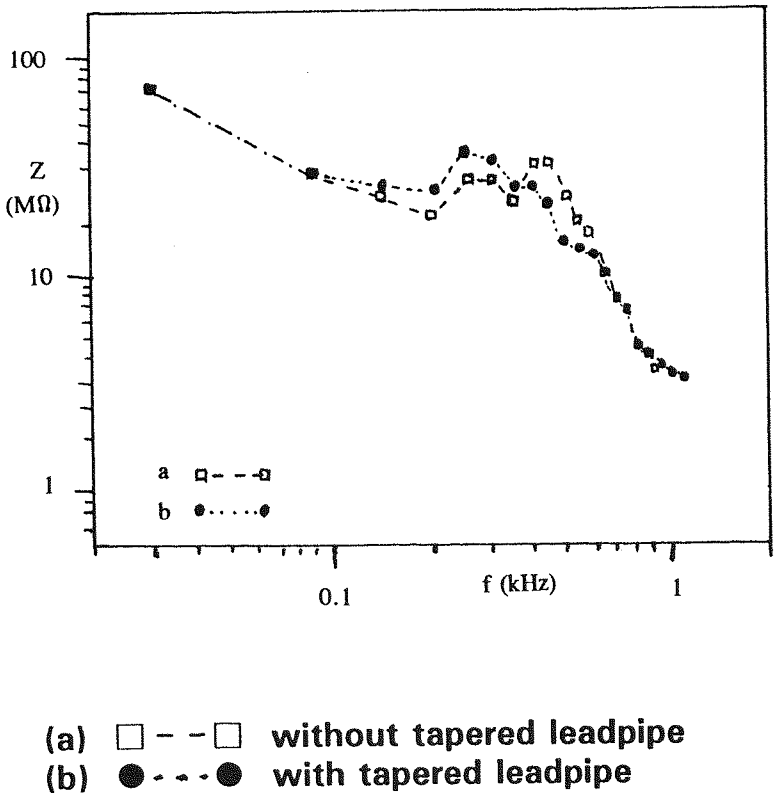


Figure 4.2: *Peak envelope of Tomes bass Renaissance model trombone in G (a) without tapered leadpipe and (b) with tapered leadpipe.*

The effect of moving the slide on the trombone is more pronounced than the effects discussed above. A slide shift of 500mm, increasing the tube length by 1m, gives approximately the player's sixth position on a B♭ trombone (in practice, a trombonist varies the position from one note in sixth position to another). The introduction of so much extra cylindrical tubing into the instrument constitutes a drastic modification of bore profile, which has the effect of lowering the peaks of the first six to eight modes and raising the peaks of the higher modes; the use of the thumb valve lowering the overall pitch by a perfect fourth has a comparable effect [Figure 4.3]. This effect can be regarded as that of a formant at the resonant frequency of the mouthpiece; moving the slide lowers the frequencies of all the modes, the mouthpiece formant at constant frequency subsequently enhancing peaks of higher mode number. Also, the increase in the proportion of cylindrical tubing increases the frequency intervals between the lowest modes. This is not so noticeable to the player because of the accompanying enhancement of the higher mode peaks which can support co-operative regimes; for a trombone in sixth position, the lowest three tones should be regarded as 'privileged' notes [Figure 4.4].

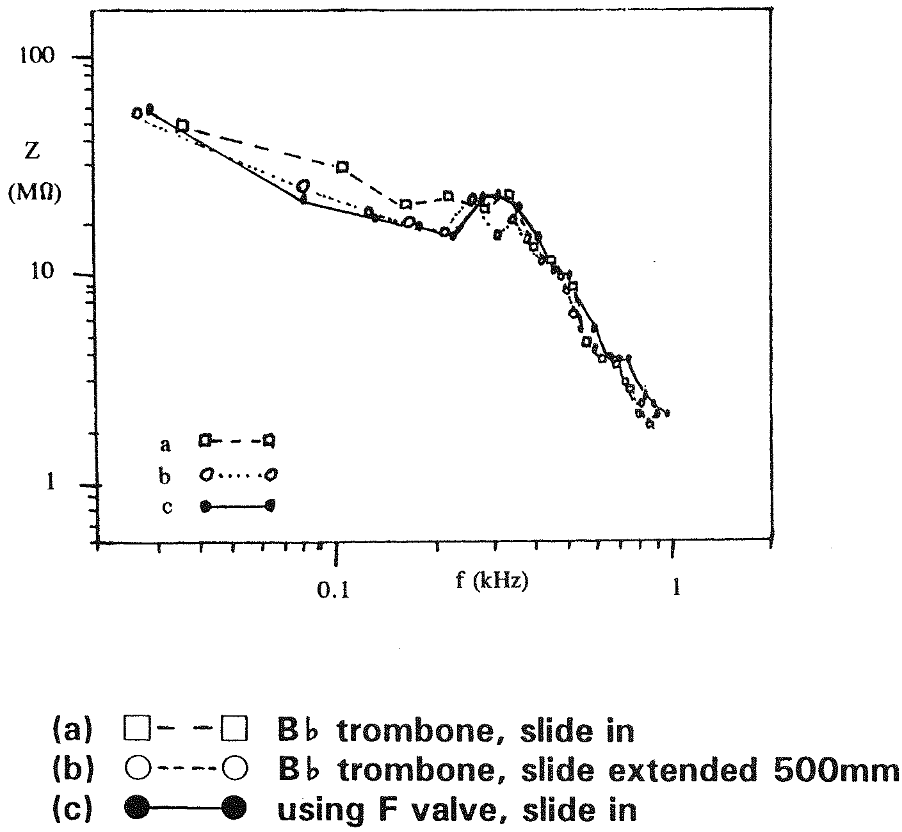
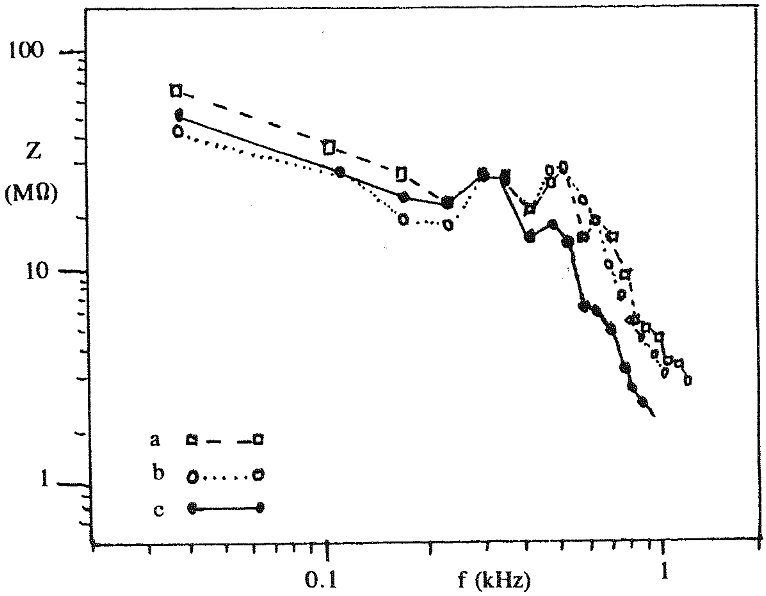


Figure 4.3: *Peak envelope of King 3B trombone with (a) slide in, (b) slide extended 500mm and (c) thumb valve used to put instrument into F.*

	a	b
1	5089	6972
2	3282	4495
3	3099	4288
4	2951	4083
5	2947	3970
6	2961	3958
7	2942	3975
8	2947	3988
9	2988	3947
10	2998	3979
11	2957	3972
12	2970	4012
13	2973	4010
14		4015
15		3970
16		3977
17		3972

Figure 4.4 *Table of effective cone lengths (in millimetres) of trombone by Joseph Huschauer, Vienna, 1794 (a) slide in and (b) slide out 500mm.*

The greatest and most irregular variations in peak envelope are found between trombones of different model, especially those of different bore size. The Tomes E♭ alto Renaissance model trombone has a similar envelope to that of the Besson alto trombone; the King 2B tenor trombone has a similar envelope to that of the King 3B model; the Tomes G bass renaissance model trombone has a similar envelope to that of the Higham G bass trombone. The main traditional schools of trombone design, however, show distinctive peak envelopes [Figure 4.5].



(a) □– –□ narrow bore traditional French trombone
(b) ○····○ medium-wide bore traditional German trombone
(c) ●——● wide bore modern American trombone

Figure 4.5: *Peak envelopes of (a) Typical narrow-bore French trombone (Courtois), (b) Typical Sattler model German trombone with wide bore and bell (Schopper), (c) Typical modern wide-bore orchestral trombone (Conn 8H); all with appropriate mouthpiece and with slides in.*

Thus investigations of the input impedances of a varied sample of trombones suggest the hypothesis that the bore profile of the bell flare is a factor of great significance in characterizing brass instruments: it will be discussed further in Chapter 6. Other features such as the presence of a tapered leadpipe and the mouthpiece shape are also factors, but second-order. The input impedance curve can act as a 'fingerprint' of instrument design, if like slide and valve positions are compared. The effect of extending the slide on the trombone is pronounced, and can give a peak envelope similar to that of a different instrument with slide in closed position.

Compared with completely different instruments, the peak envelopes of the trombones have much in common. Figure 4.6 shows the envelope for an instrument with a pronounced conical bore. A study comparable with the above treatment of trombones was made by Krüger (1983) for natural and valved trumpets.

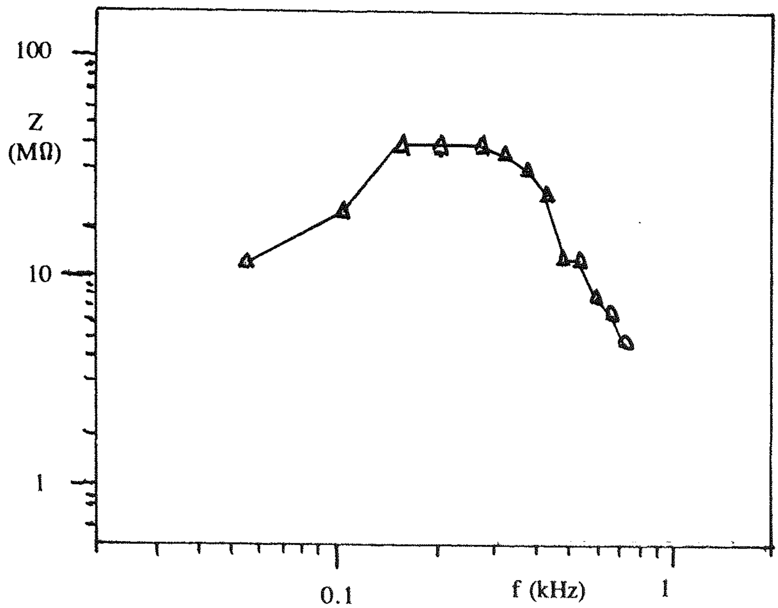


Figure 4.6: *Peak envelope of ophicleide in B♭ (EUCHMI 2158) with mouthpiece by Higham (EUCHMI 2159), all keys closed except the lowest (the open-standing A key).*

Chapter 5

Air column bends

5.1 Effects of tube bends

In order to compare and classify instruments, it would be helpful to be able to discount the effects of the bends in the tube. The bows in trumpets and the coils in french horns are sufficiently accounted for by the practicalities of holding and transporting the instruments, and do not need to have any acoustical purpose.

In general, when faced with a historic brass instrument in a museum, it is necessary to know how to measure round the bows, loops and other bends so that it can be usefully compared with another instrument which might for example, have fewer, more gentle, or differently spaced bends.

This raises two other questions: how, acoustically, does a bend affect the response of the instrument, and how, practically, does bending a straight tube affect its length ? Instrument makers have long been concerned to reduce the sharpness of bends in valve pistons and rotors, an area currently being re-visited by trombone makers with 'open-wrap' B♭+F trombones and revivals of nineteenth-century concepts such as disc valves and Blühmel's wide-rotor valves. In this chapter, the effects of tube bending are assessed in practical terms, leaving until Chapter 6 the problems of measuring flaring tubes and the acoustical effects of flare.

Different authors have assumed different answers to these questions. Most, in measuring the sounding length of a wind instrument, calculate the path which follows the centre of the bore: we might call this the 'mid-line' approach. Webb (1991), for practical instrument-making purposes, has measured along the outer surface of the tube following its outside extreme round bends. Albertson (1984) following a suggestion of Cary Karp takes a more subtle approach by calculating the lengths of lines in the bore on both the

inside and the outside of the bend and then taking the geometric mean. One can also consider measuring the shortest path from one end of an instrument to the other: threading inelastic string through the instrument, pulling it tight, and measuring.
The acoustical theory has been presented by Keefe and Benade (1983), who also tested it by experiments using highly bent tubing (series of baritone horn tuning-slide bows joined end-to-end). Brindley (1983) also carried out practical tests. The effect of a bend in a tube is to reduce the wave impedance and to increase the phase velocity. The speed of sound is increased, so the result of the bend is to make the air column effectively shorter than its mid-line length. This effect is greater for higher frequencies, so the 'in-tuneness' of the air column's modes of vibration is potentially affected and hence the instrument's response to the player. The effect is, as one would expect, greater for more acute bends. Keefe and Benade define a 'bend parameter' to measure the severity of a bend [Figure 5.1]. For a tube of radius r_0 bent so that the 'mid-line' has a radius of curvature R_0, the bend parameter B is defined as

$$B = \frac{r_0}{R_0} \tag{5.1}$$

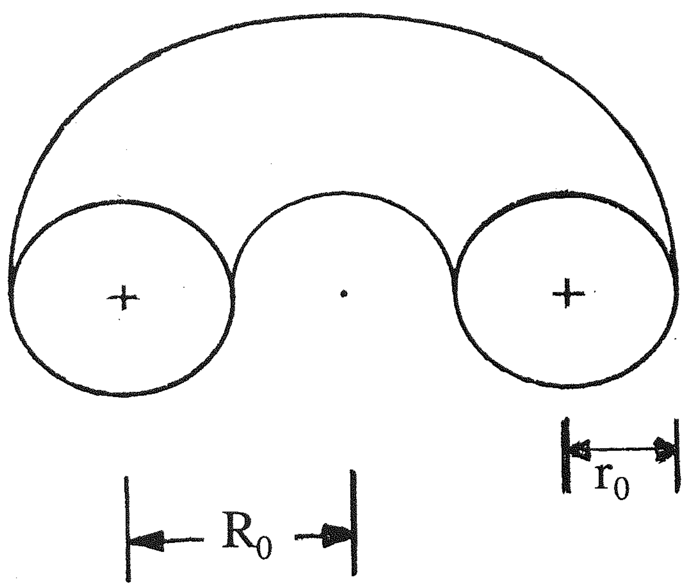


Figure 5.1: *Bow of radius R_0 in a tube of radius r_0.*

The bend parameter can be calculated for some instrument components:

French horn D crook: B = 0.06

French horn A crook: B = 0.11

Trumpet crook (described below): B = 0.16

Trumpet 2nd valve tuning-slide bow: B = 0.57

Baritone horn tuning-slide bow: B = 0.73 (Keefe and Benade's test specimen)

Ophicleide large bow: B = 0.76

E♭ bass tuning-slide with L.P. 'kink': B = 0.91

The shortening effect also depends on the position of the bent section in the whole tube. However, the shortening effect is not large. Even for Keefe and Benade's experimental highly curved tube, it was found that the effects of the curvature were less than the effects of the rise in temperature caused by handling the tube.

For taxonomic purposes, therefore, the mid-line convention remains satisfactory. The geometric mean calculation of Albertson and the 'shortest path' technique both over-correct the very slight shortening of the path (or increase in the speed of sound) round a bend.

5.2 Practical tests

In order to test further the practical effects of tube bending, some experiments were carried out using a straight trumpet in 4½-ft B♭ by Hawkes & Son (EUCHMI 877). This particular instrument has a detachable central section stamped "B♭"; the model was quite possibly originally provided with an alternative piece for A, but this specimen lacks this 'corps de rechange'. The Scottish brasswind specialist, Stewart Benzie, was commissioned to make two new sections with matching internal diameter and the correct external diameters for fitting into the instrument. Various tests were carried out to see if they could be distinguished - both by laboratory measurements of acoustic impedance and also by playing tests. No difference could be detected, though it was possible to detect small differences in response between either of the two new A sections and the trumpet with the B♭ section and the second valve operated, which gave approximately the same tube length.

Mr Benzie was then asked to bend one of the tubes into a loop, using the conventional method of filling with metal, pitch (as in this case) or ice and bending round a form. The joint-fitting ends were removed while the bending took place, and carefully re-fitted afterwards in the same positions on the tube. The looped A section has two approximately semi-circular bows, and is the shape of a standard D crook for a trumpet in 6-ft F. Measurements on the looped corps de rechange showed that the external length of the tube on the outside had, at the bends, increased by 23%; the external length of the tube on the inside had, at the bends, decreased by 17%; and the length of the bent sections along the mid-line had increased by 3.5%. The length of tube actually bent was 200mm, the total length of instrument and mouthpiece some 1500mm, so the overall effect on the instrument of looping the crook was a lengthening of the air column by 0.45%, equivalent to a flattening of 8 cents. Acoustic impedance tests showed no perceptible difference between the bent section and the unbent section, and playing tests showed no significant difference: the shortening acoustical effect of bending was cancelled out by the increase in tube length.

If a maker chooses to make a much-coiled instrument such as a post-horn or a trompe de Lorraine by starting with a straight version and bending it, however, he could expect the length to increase, although the effective acoustical length will not increase as much as the mid-line length.

Mention could also be made of the tendency of the cross section in a bowed tube to become slightly elliptical with bending. Since the internal volume of a bend does not change, the cross-sectional area decreases slightly. This may also have an effect on the acoustical length of the air column.

There are, of course, other ways of bending a tube. A century ago, the makers Silvani and Smith (1895) developed a method for bending without heating or cooling the tube at all, by inserting a flexible steel mandrel. Today, the large manufacturers make bows by hydraulic expansion of the tube in a mould.

In the above we have been considering the 'steady state' behaviour of air columns with bends and finger-holes or other vents. The pitches of the notes that can be satisfactorily sustained on an instrument depend on the resonance frequencies of all the modes, not just the mode with frequency closest to the fundamental frequency of the note being played. These pitches are relatively little affected by bends, but much affected by openings. However, the response of an instrument to the player's attack, the 'starting transient' of a note, is another matter, as also is playing at such high volume that the wave propagation is non-linear, the 'tearing linen sheet' effect when a narrow-bore trombone is played loudly (Hirschberg et al. 1996). The effects of bends do not appear to have been investigated in the non-steady state case, but they may account for trombonists' problems with the common rotary valve.

Chapter 6

Considerations of the horn function

6.1 The horn function

Bell designs fall between two extremes, the virtually conical and the acutely flaring, approached, for example, by the alphorn and the natural trumpet respectively. If a small section is cut off the end of a conical bell, the pitch of the instrument is raised but the tone quality is hardly affected; if a small section is cut off a bell that goes beyond an acute flare and approaches a flat disk, such as a sousaphone's, the pitch is unaltered, the only effect being to change very slightly the sound radiation properties of the bell.

For taxonomic purposes it might be desirable to find parameters for measuring bell flares that relate to their acoustical function and which would place them on a scale ranging between these two extreme cases. One well-established parameter is the *Horn Function*, introduced by Benade and Jansson (1974) and further discussed by Amir et al (1993). The horn function is defined as U in Equation 6.1 where r is the 'radius' of the tube - not the geometric radius but the distance from mid-line to tube wall measured over the surface of a wavefront, shown in Figure 6.1.

$$U(z) = \frac{1}{r}\frac{d^2r}{dz^2} \tag{6.1}$$

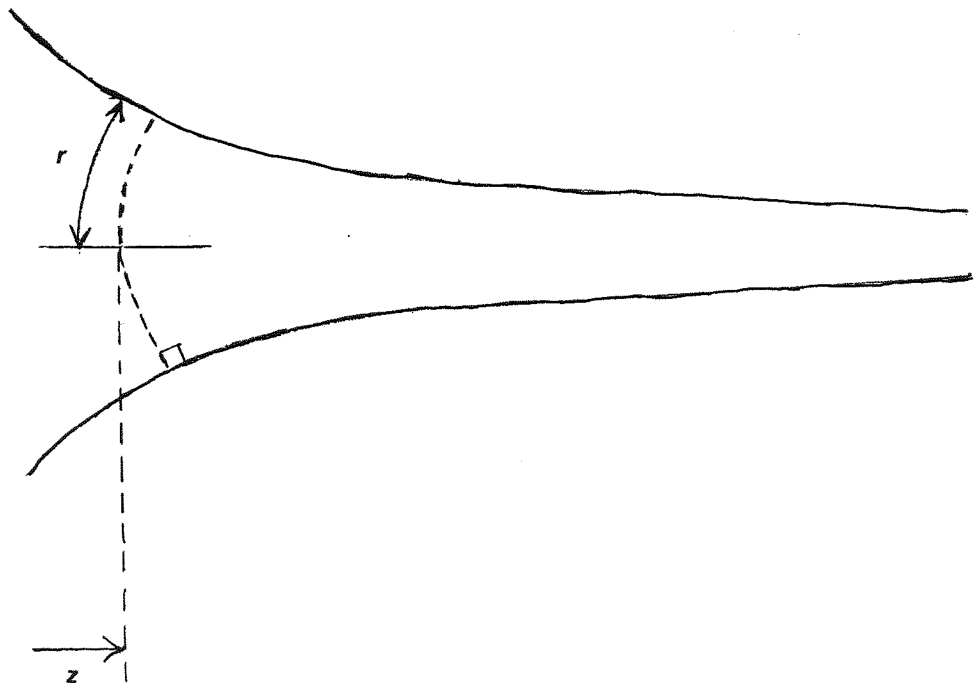


Figure 6.1: *A spherical wavefront in a bell flare for a tube with a circular cross-section, like most brass instrument bells.*

In a region where the bore is not expanding too rapidly, a good approximation to the value of the horn function is the product of the two curvatures which characterize an axially symmetrical flare given in Equation 6.2 where in Figure 6.2, K_L is the reciprocal of the longitudinal radius and K_T is the reciprocal of the geometric radius of the tube (Benade and Jansson 1974).

$$U \approx K_T K_L \tag{6.2}$$

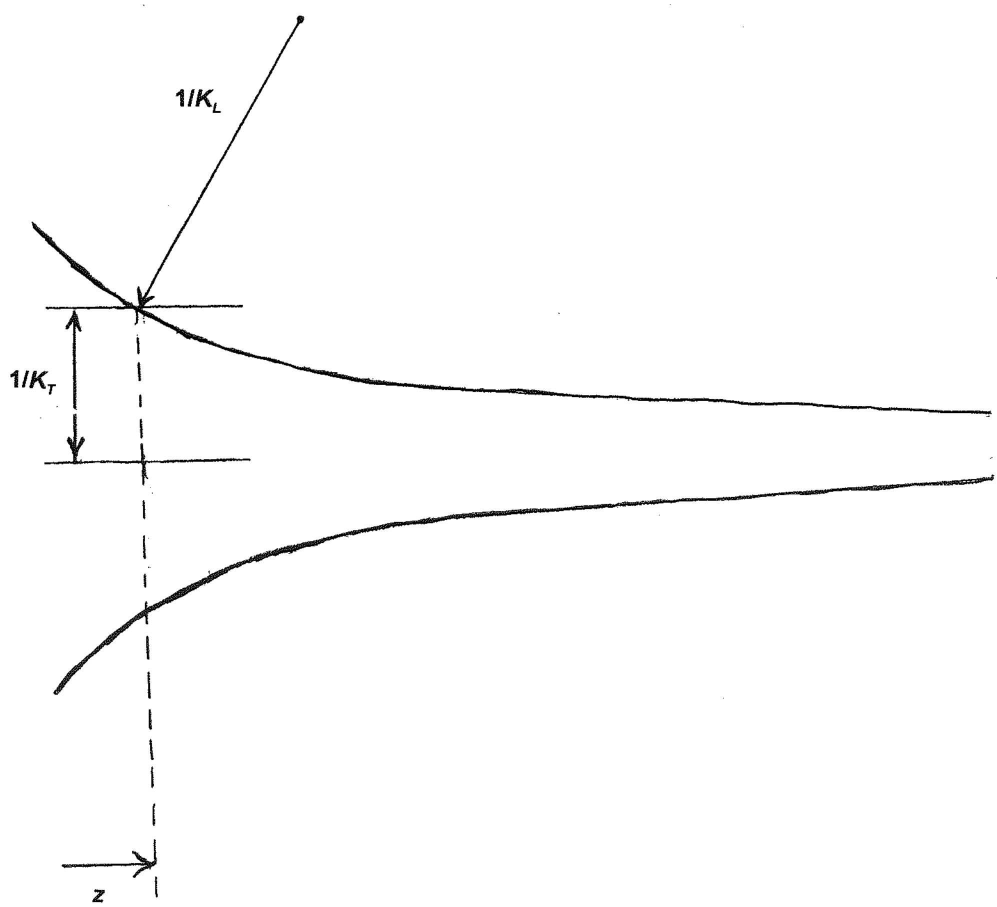


Figure 6.2: *The radii of curvature of an axially symmetrical horn.*

This is an approximation assuming that the wavefronts are spherical; Jansson and Benade (1974) found that actual wavefronts in brass instruments fall between plane and spherical surfaces. The advantage of making the approximation in Equation 6.2 however is that it gives the horn function entirely in terms of the geometry of a bell flare.

The horn function varies along the length of a brass instrument, and for instruments with a developed flare there is a peak value a short distance before the end of the bell. For example, the bell of the trumpet by Joseph Huschauer of 1794 in the Edinburgh University Collection of Historic Musical Instruments is shown (dashed line in Figure 6.3) with a plot of its horn function (solid line). The horn function reaches a peak of 615 m^{-2}. Similarly, the bell of a trombone by Robert Schopper of c 1910, also in the Edinburgh University Collection of Historic Musical Instruments, is shown (dashed line in Figure 6.4) with a plot of its horn function (solid line). The horn function reaches a peak of 312 m^{-2}.

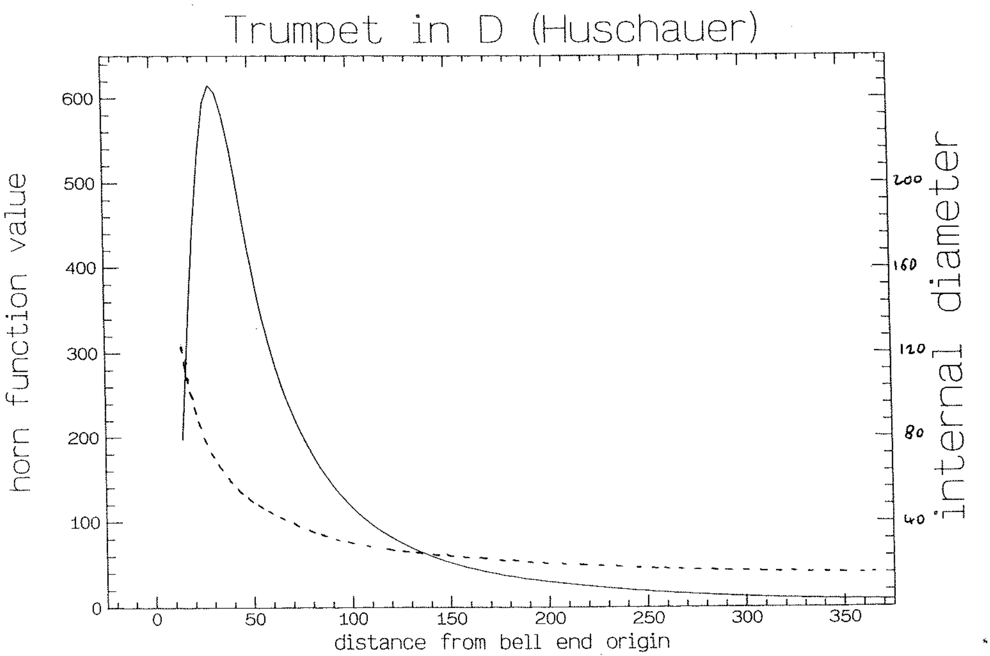


Figure 6.3: *Bell of a natural trumpet (EUCHMI 3247), bore diameter in millimetres, with plot of horn function (m^{-2}). The curves stop at the end of the bell: this is not the origin of co-ordinates, for reasons explained in Section 6.2.*

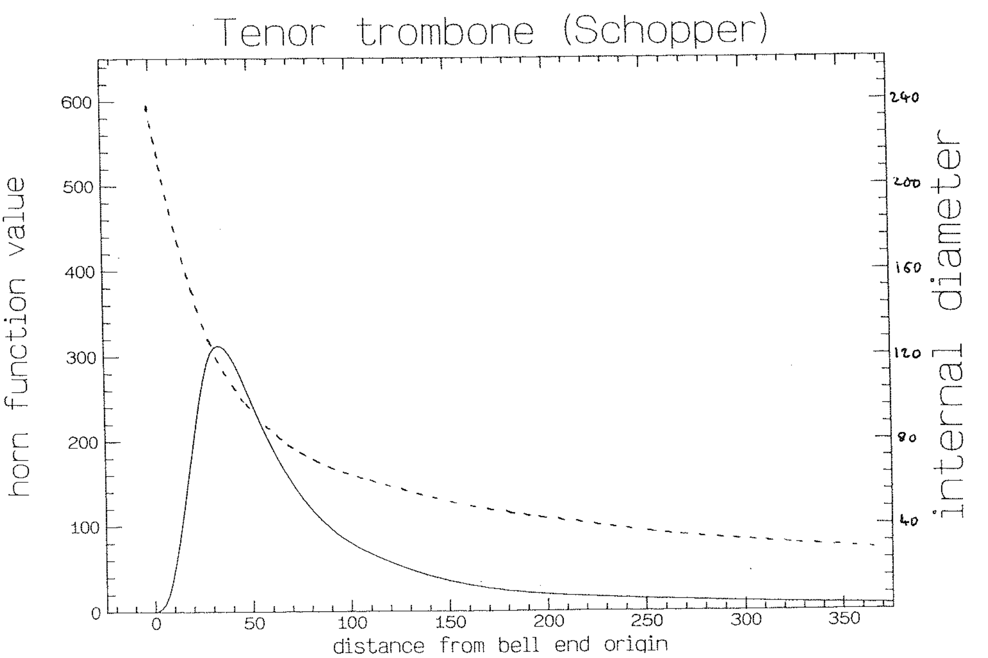


Figure 6.4: *Bell of a trombone (EUCHMI 3207), bore diameter in millimetres, with plot of horn function (m^{-2}). The curves stop at the end of the bell: this is not the origin of co-ordinates, for reasons explained in Section 6.2.*

A flare reflects sound waves of different frequency to a different extent. A low frequency wave is almost completely reflected in a region of instrument tube with a high value of the horn function, whereas a high-frequency wave is hardly affected by a flare. The effect is analogous to the potential barrier effect in quantum physics. The peak value of the horn function corresponds to a *cut-off frequency*, given by

$$\textit{cut-off frequency} = \frac{c}{2\pi}\sqrt{U} \qquad (6.3)$$

where c is the speed of sound in free air (typically 346 ms^{-1}) and shown schematically in Figure 6.5 (Fletcher and Rossing 1991). Sound waves of frequency higher than the cut-off frequency are not reflected by the potential barrier; waves of lower frequency are reflected rather than transmitted to a degree depending on how far they have to 'tunnel' through the barrier and the height of the barrier. This reflection of waves at different places is required in instruments such as trumpets and trombones with substantially cylindrical sections of bore in order to bring the frequencies of the modes of vibration into an approximation to a harmonic series, necessary for centred, in-tune notes.

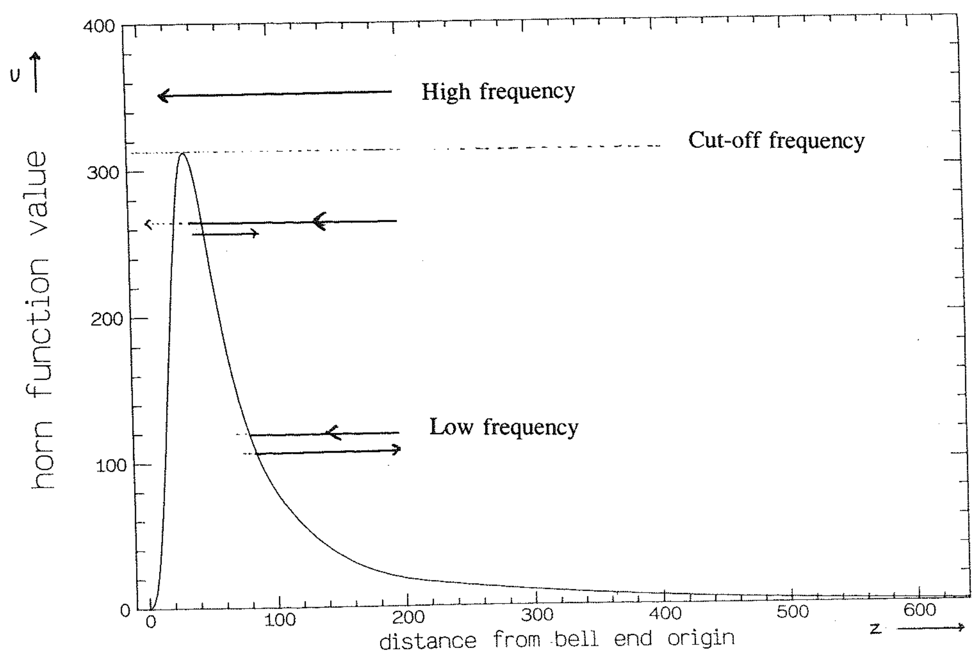


Figure 6.5: *Schematic diagram of the barrier effect of a horn function peak and the cut-off frequency. For a peak value of horn function of 312 m^{-2} as shown here, the cut-off frequency is 970 Hz.*

6.2 Bessel horns

In order to compute the horn function (and thus the cut-off frequency), for actual historic instruments, some mathematical model is needed in order to smooth out the local irregularities common in old instruments and which would unduly affect the peak value of the horn function. It has been suggested (Pyle 1975) that the bore profile of a flaring bell can be modelled by a 'Bessel horn' for which the radius R of the horn at a distance z from the origin of co-ordinates is given by

$$R = R_F^{1+\alpha} z^{-\alpha} \tag{6.4}$$

where R_F is a characteristic radius of the horn and α is a dimensionless 'flare parameter'. (Typical values of α are 0.5 for a baroque trumpet, 1.0 for a modern trombone and 1.5 for a french horn.)

No actual brass instrument exactly follows the profile of a Bessel horn, since the mandrels used by instrument makers have always been designed by trial and error, not by plotting the curve of Bessel horn. Nevertheless, a Bessel horn can usually be found which fits closely a portion of a real bell flare; for the purpose of this study, close fits have been found for the portion of the bell flare containing high values of the horn function and thus virtually all of the 'potential barrier'. Applying the approximation of Equation 6.2 to the Bessel horn of Equation 6.4 gives the horn function in terms of the characteristic radius and the flare parameter:

$$U(z) \approx \frac{\alpha(1+\alpha)}{z^2}\left[1+\alpha^2\left(\frac{R_F}{z}\right)^{2(1+\alpha)}\right]^{-\frac{3}{2}} \tag{6.5}$$

In practical terms, the computation of the horn function is achieved by taking measurements of the bore diameter and depth at a series of different depths into the bell of an instrument. The interior of a bell mouth is measured using a logarithmically graded series of rod probe gauges, each made from perspex rod to a tolerance of 0.1mm. These are attached in turn to a prepared rule allowing the depth of insertion to be read directly. Where possible, areas of obvious denting are avoided. Normally, the maximum and minimum depths of insertion of each rod gauge are made; these generally occur at orientations approximately 90° to each other. The average of the two depths is recorded as the axial distance from the bell end, and half the difference (plus a basic tolerance in the measurement of 1mm) is recorded as the spread in the axial distance measurement. An isolated high spread value can thus be interpreted as a discrepancy due to a minor dent or ripple in the bell wall surface, whereas consistently high spread values result from an overall ellipticality (squashing) of the bore. If the bell rim itself is squashed, the subsequent readings will have high spread values (unless the effect is cancelled out by ellipticality in the opposite sense further into the bell mouth); any systematic error in determining the position of the end of the bell is eliminated by the subsequent data processing: a discussion of the accuracy of the process is given in Appendix B.

The results can be presented as a table with four columns. As an example, the bell flare of the ex- Galpin trombone by Neuschel in the Kunsthistorisches Museum, Vienna (extensively used as a model for reproductions) has the bell flare of Figure 6.6

Location	Interior diameter	Axial distance from bell end	Spread in axial distance	Tolerance in interior diameter
Bell end	102.5	0	0.1	1.5
	99.48	5	2	0.1
	90.17	19	2	0.1
	81.45	34	2	0.1
	73.70	47	2	0.1
	66.69	59	2	0.1
	60.43	71	2	0.1
	54.60	85	2	0.1
	49.40	101	2	0.1
	44.70	120	3	0.1
	40.45	140.5	3.5	0.1
	36.60	163	3	0.1
	33.12	189	5	0.1
	29.96	219	4	0.1
	27.12	250	3	0.1
	24.23	282.5	2.5	0.1
	22.20	317	2	0.1
	20.08	346	4	0.1
	18.17	387	9	0.1
	16.44	434	5	0.1

Figure 6.6: *Bell flare measurements for trombone by J. Neuschel dated 1557 (WSAM 706), all in millimetres. With this measuring technique, the diameters are fixed and the depth of insertion is the dependent variable.*

The overall diameter at the very end of the bell has been ignored in most of the horn function computations in this study, and only the measurements made by the gauges used, i.e. with the measurements starting at a depth of a few millimetres from the end of the bell. To each depth measurement has to be added a distance z_0 since bell flares never extend to the origin of co-ordinates (at the asymptotic plane of the Bessel horn) where the diameter would be infinite. (Typical values of z_0 are 10mm for a modern trumpet, 30mm for a trombone and 100mm for a french horn.) The depths are then transformed logarithmically, and the logarithms of the augmented depths plotted against the logarithms of the diameters. It is necessary to adjust z_0 until the logarithmic plot is as near as possible a straight line for a substantial portion of the bell, an iterative process. The slope and intercept are computed for the least-squares fit to this portion of the bell. Then the two Bessel horn parameters can be taken from the slope and the intercept of the straight line fitted to the transformed data. The least-squares curve fit will minimise the influence of the various dents and squashes picked up by most old instruments.

A plot of ten or eleven appropriately spaced points can be sufficient to cover the region where the horn function is significantly high. It is necessary to take at least twenty-two bore measurements from an instrument to achieve a satisfactory fit of eleven points. Figures 6.7 to 6.10 show two examples of the fit of a Bessel horn to actual bore profiles. The bell of the Huschauer natural trumpet in D of 1794 in the Edinburgh University Collection of Historic Musical Instruments (EUCHMI 3247) is closely fitted by a Bessel horn of flare parameter 0.6983 and characteristic radius 49.35mm. The fit is good from the end of the bell as far as the ball sleeve, 200mm from the bell end. Figures 6.7 and 6.8. show linear and logarithmic plots respectively of the actual bell measurements (dotted line) and the Bessel horn (solid line).

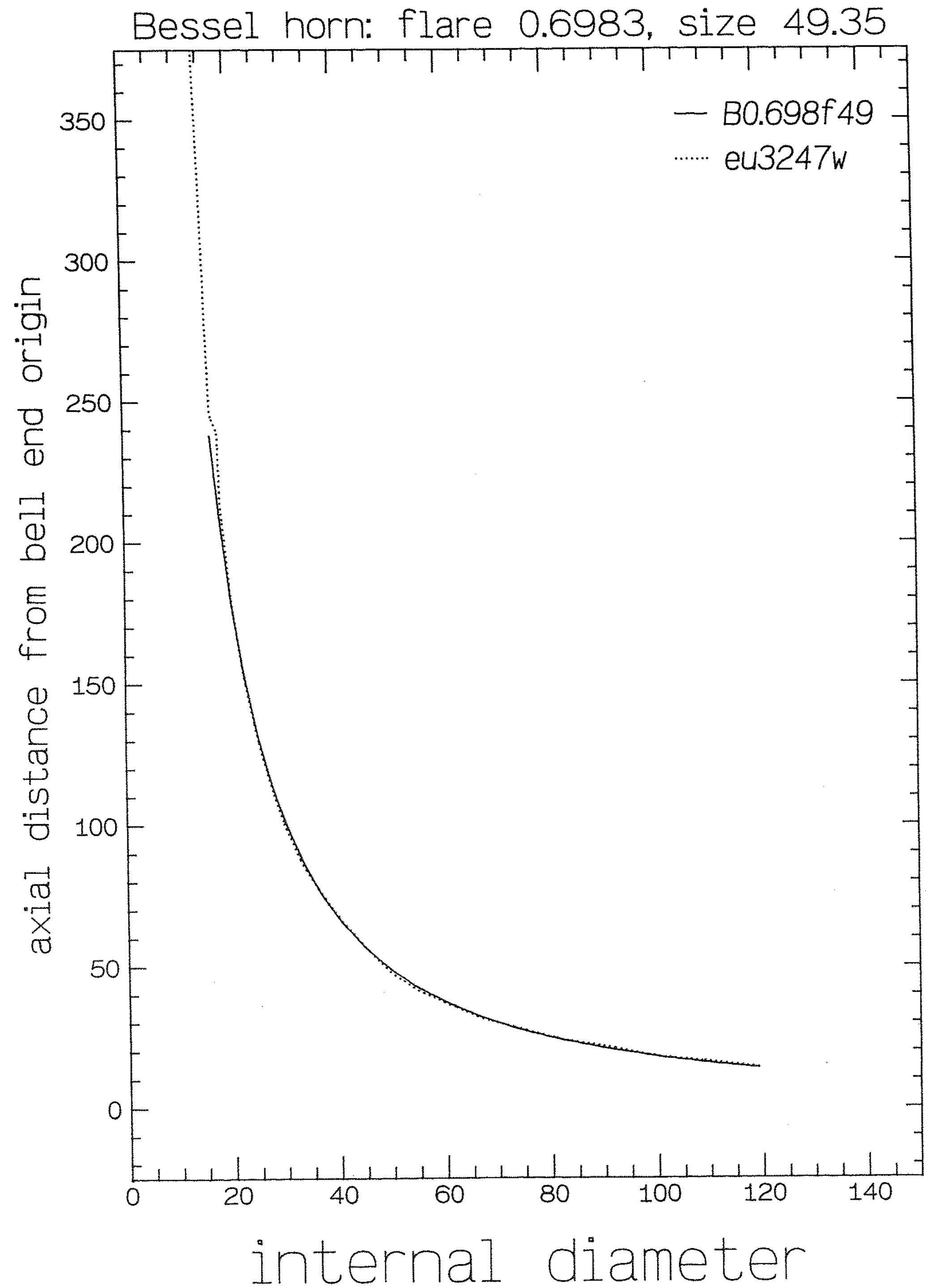


Figure 6.7: *Bell of a natural trumpet (EUCHMI 3247) with plot of fitting Bessel horn, axial distance and bore both in millimetres, linear co-ordinates.*

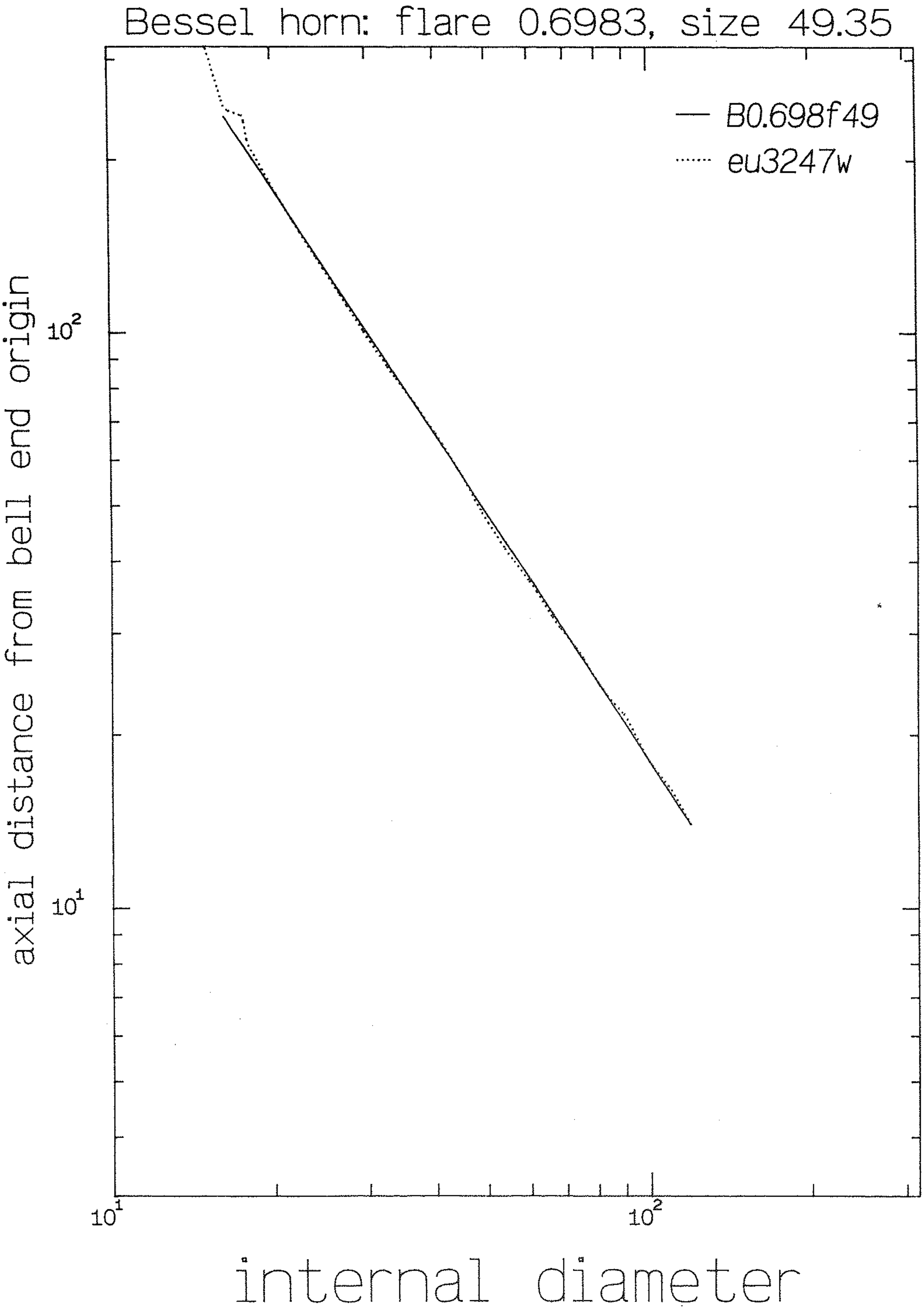


Figure 6.8: *Bell of a natural trumpet (EUCHMI 3247) with plot of fitting Bessel horn, axial distance and bore both in millimetres, logarithmic co-ordinates.*

The Bessel horn flare parameter and characteristic radius are stated precisely at this stage; rounding of figures to reflect the accuracy of the measurement is done later (see Appendix B).

The bell of the B♭ valved trumpet by Vega is less closely fitted by a Bessel horn. Nevertheless, a useful fit can be obtained over the region 15.5mm from the bell end to 148mm from the bell end by a Bessel horn of flare parameter 0.426 and characteristic radius 41.69mm: Figures 6.9 and 6.10 show respectively the linear and logarithmic plots of the actual bell measurements (dotted line) and the Bessel horn (solid line). The failure of a Bessel horn to model the whole of a brass instrument's bell section is the reason that the flare parameter and the characteristic radius cannot themselves be used to classify instruments.

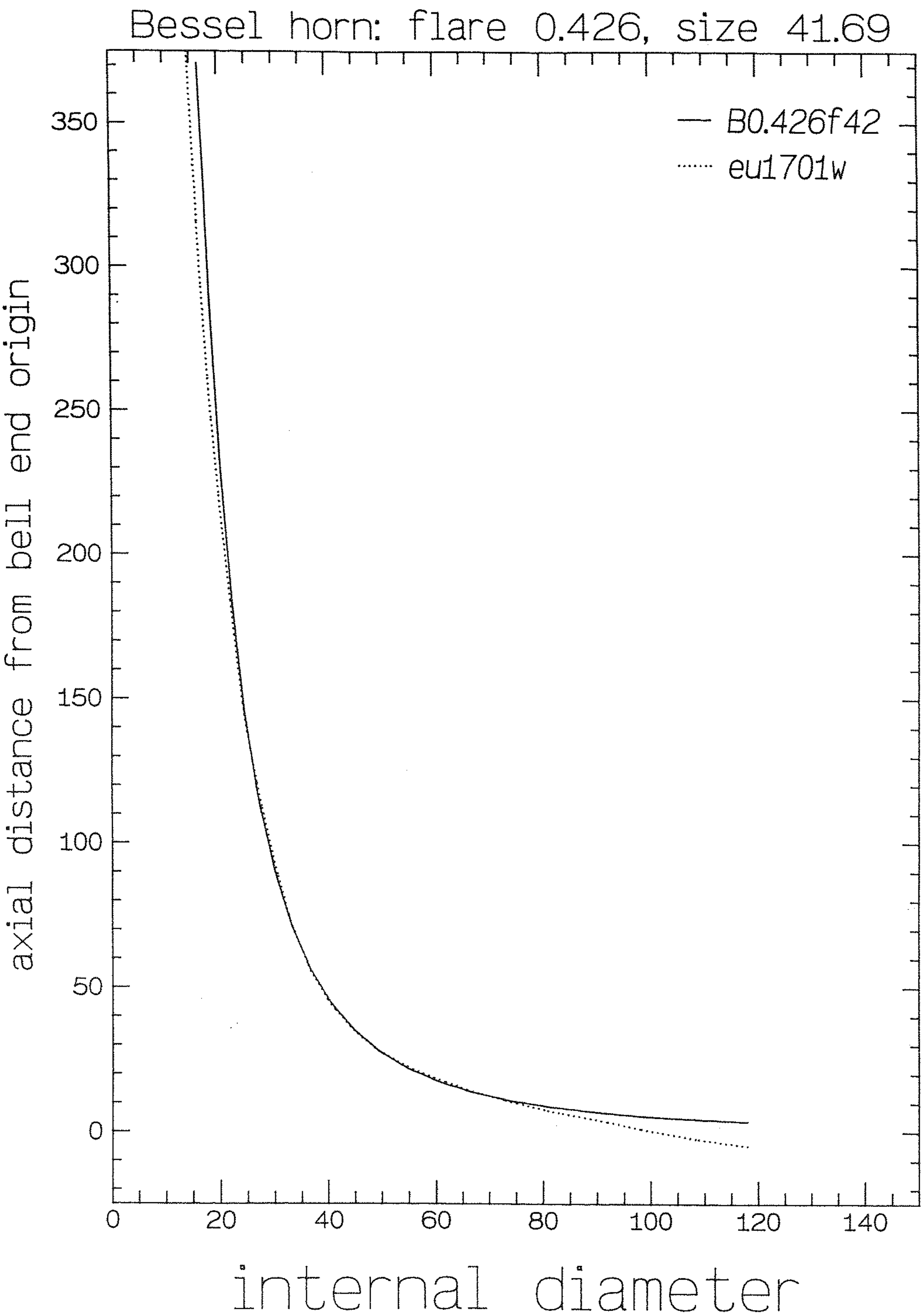


Figure 6.9: *Bell of a modern trumpet (EUCHMI 1701) with plot of fitting Bessel horn, axial distance and bore both in millimetres, linear co-ordinates.*

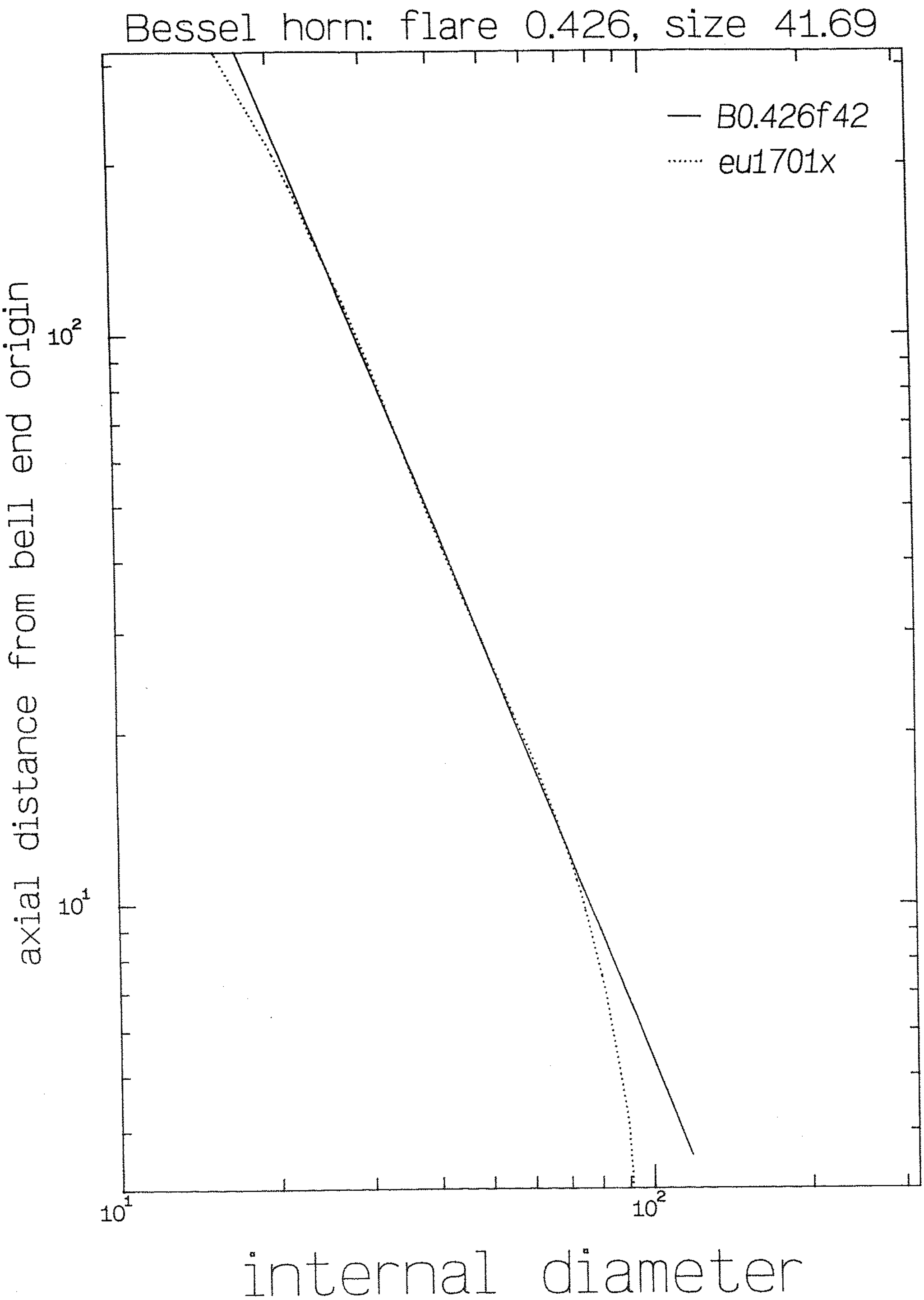


Figure 6.10: *Bell of a modern trumpet (EUCHMI 1701) with plot of fitting Bessel horn, axial distance and bore both in millimetres, logarithmic co-ordinates.*

The peak horn function and thus the cut-off frequency can then be calculated by inserting the Bessel horn parameters numerically in the appropriate expressions. The position z_{PEAK} of the maximum value of the horn function is obtained by differentiating the right-hand side of Equation 6.5 with respect to z which is then zero when

$$z_{PEAK} \approx \left(\alpha^2 \cdot \frac{3\alpha+1}{2}\right)^{\frac{1}{2(\alpha+1)}} \cdot R_F \qquad (6.6)$$

If this does not fall well within the portion of the bell used for curve-fitting, then a sequence of measurements either nearer to or further away from the bell end has to be used instead, and the process repeated. When the best-fit Bessel horn matching the portion of the bell which comfortably includes z_{PEAK} has been found, the maximum value of the horn function is then given by

$$U_{PEAK} \approx \frac{\alpha(1+\alpha)}{z_{PEAK}^2}\left[1+\left(\frac{(3\alpha+1)}{2}\right)^{-1}\right]^{-\frac{3}{2}} \qquad (6.7)$$

Appendices B and C show some of the results of these calculations and include a note on the sensitivity to errors in measurement. These results are mostly for museum instruments; but some modern instruments have also been measured for comparison. The results presented in Appendices B and C are those from mainstream brasswind: they can be used for comparison when investigating unusual or experimental instruments.

We can see, for example, that the highest cut-off frequency found so far is (not surprisingly) for a piccolo trumpet. For instruments such as the alphorn which have negligible bell flare, the sound is reflected by the abrupt termination rather than by any flare. The value of the horn function is low overall (a maximum of only 7 m^{-2} at the bell end), and does not reach a peak before the distal termination (bell end) of the instrument. It has generally been found that the instruments with acutely flaring bells, and thus those with the highest horn function values, are those best modelled by Bessel horns. Instruments with little flare such as alphorns or with a significant flare only at the very end of the bell such as the Swedish kornett and most tubas are not well modelled by

Bessel horns.

For an instrument with a truncated flaring bell, such as the 1594 Schnitzer trombone in the Edinburgh University Collection, the horn function [solid line in Figure 6.10] does not quite reach what would, in a longer flare, be its peak value, and the maximum is anyway not as high as that of a modern tenor trombone. This lower potential barrier reflects high-pitch components less effectively, thus contributing to the Renaissance trombone's mellower sound.

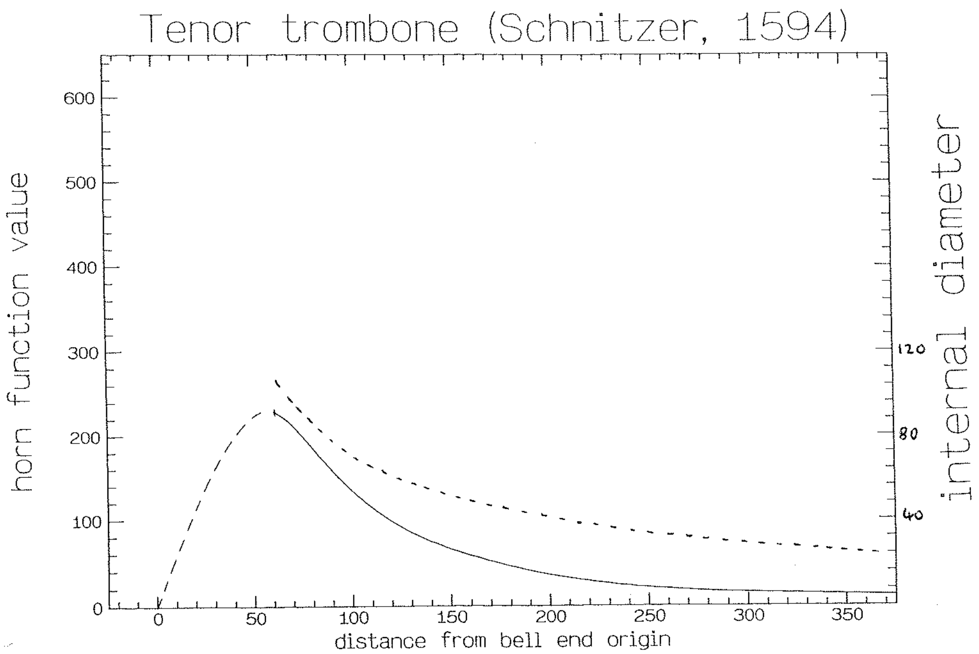


Figure 6.11: *Bell of a Renaissance trombone (EUCHMI 2695), bore diameter in millimetres, with plot of horn function* (m^{-2}).

The cut-off frequency is not found to have a precise value for recognised types of instrument, but a spread of values which overlaps to some extent with those of other types of instrument [see Appendix C]. Thus it cannot be the sole criterion in a taxonomic scheme. However, it can be one element: instruments with drastically differing values of U_{PEAK} cannot be expected to respond similarly to the player or sound the same to an auditor.

The diameter (or cross sectional area) of the bell at the point of maximum horn function value is sufficiently well-defined to be a taxonomic parameter [Appendix B], and could well give a more satisfactory measure of bore size at the distal end of a brass instrument than the parameter *D3* of Heyde (Chapter 2).

Modelling bell flares as Bessel horns can also allow the position of maximum bell wall curvature to be computed. In terms of the characteristic radius R_F and the dimensionless 'flare parameter' α, the distance z_{MC} of the point of maximum curvature from the asymptotic plane is given by

$$z_{MC} = R_F \left(\frac{\alpha^2 + 2\alpha^3}{2+\alpha} \right)^{\frac{1}{2+2\alpha}} \qquad (6.8)$$

By the definition of the horn function, this point is always nearer to the end of the bell than the point of maximum horn function. Although it corresponds to a feature of a flare which is visible to the eye, it has no known acoustical significance and has not been systematically computed in this study.

Chapter 7

Considerations of the mouthpiece volume and profile

No topic is discussed more by brass players than mouthpiece preference, especially by trumpet and trombone players. However, the subtleties of mouthpiece design are features of musical instruments which are of no interest to audiences or even to other musicians. The lay person can appreciate the distinction between, say, a trumpet and a cornet, and the difference between one model of mouthpiece and another can have an effect on the sound comparable to the effect of such a change of instrument. In this chapter the acoustical functions of the mouthpiece are briefly reviewed and parameters are suggested which can be used to characterize mouthpieces, together with priorities in the use of these parameters.

There are specialists in matching mouthpieces to players, in making tiny adjustments to the design, or selecting a mouthpiece from a finely graded commercially-produced series. These 'clinicians' satisfy a recognised need of student and other players. In this study, however, answers are sought to questions such as whether particular mouthpiece associated with an instrument is likely ever to have been supplied with it or for it, or how to identify what possible instruments an unattached mouthpiece might have been made for.

The problem is that to describe a mouthpiece fully requires a great number of measurements. Even to specify a mouthpiece that performs the same acoustical function (but does not necessarily look the same) requires many measurements. An analytical approach to mouthpiece taxonomy is very much needed.

7.1 Methods of mouthpiece description

The exact shape of the mouthpiece is considered by most players of brass instruments to be critically important in performance, both for the tone quality achieved and for the player's endurance. The design of the mouthpiece is often believed to be more important than the design of some of the features of the instrument such as leadpipe taper or bell flare. The study of brasswind mouthpieces has mostly been subjective in nature, based on clinical experience in selecting mouthpieces matched to players' individual anatomies and desired playing styles. Such an account of mouthpiece 'tailoring' criteria has been given in publications and brochures by many mouthpiece manufacturers, for example Bach (1952), Elliott (1995), Hall (1963), Himes (1982), Schilke (1952) and Stork and Stork (1989); these writers discuss the relative benefits of different sizes of cup and bore and of different profiles of rim and throat. The concepts introduced by most writers of such mouthpiece lore do not stand up to scientific scrutiny. It has to be admitted, however, that acoustical investigation has yet to yield an analysis of mouthpiece function which reflects at all adequately the fine control of detail in design which makers exercise. Specialist mouthpiece makers will offer a range of, say, a dozen slightly different cornet mouthpieces or a similar variety of trombone mouthpieces. Developments in mouthpiece design have been neglected by most historical organologists: most written histories of instruments rarely go further than the most obvious differences such as those between early and modern trumpet mouthpieces or between cornopean and modern cornet mouthpieces.

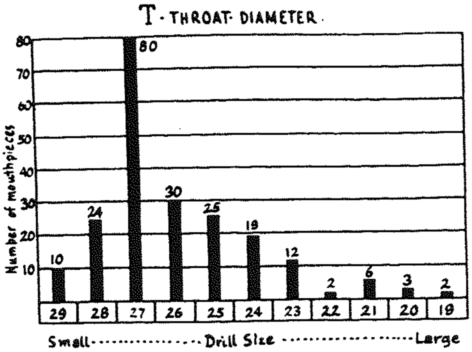
Previous accounts of systematic measurement of mouthpieces have been given for a wide range of instruments by Heyde (1980, pp.196-204 and 1982, pp.199-211), for early British trumpets by Halfpenny (1967, 1968, 1971) for modern trumpets and cornets by Rohner (1952, 1953).

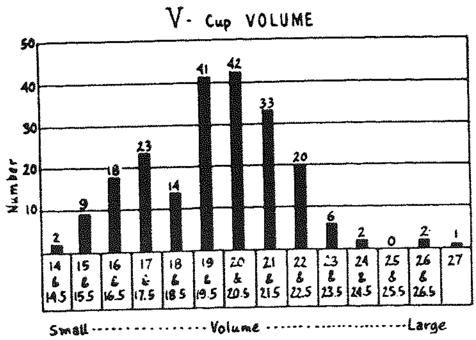
Rohner (1952) suggested a standardised system of describing mouthpieces using seven parameters, the measurements being graded and given code numbers (the T-V-D CRIB code, Figure 7.1) which he proposed should be stamped on mouthpieces by manufacturers.

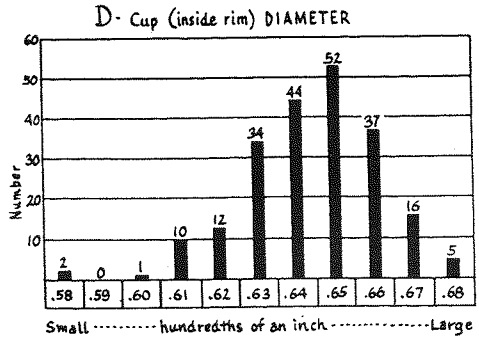
"Throat-Volume-Diameter-Curvature-Rim thickness-Impression-Bite"

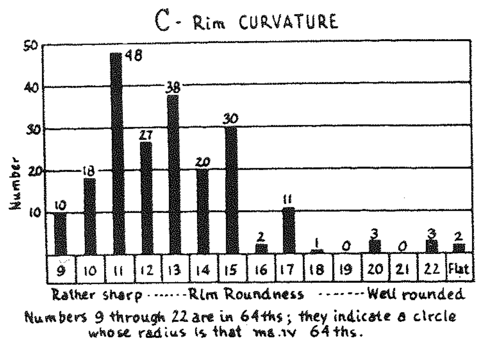
CODE →	0	1	2	3	4	5	6	7	8	9
T- THROAT	29	28	27*	26	25	24	23	22	21	20
V- VOLUME	15	16	17	18	19*	20	21	22	23	24
D- DIAMETER	59	60	61	62	63	64	65*	66	67	68
C- CURVATURE	9	10	11	12	13*	14	15	16	17	18
R- RIM THICKNESS	19	20	21*	22	23	24	25	26	27	28
I- IMPRESSION	76	77	78	79	80	81*	82	83	84	85
B- BITE	—	—	2	3	4*	5	6	7	8	—

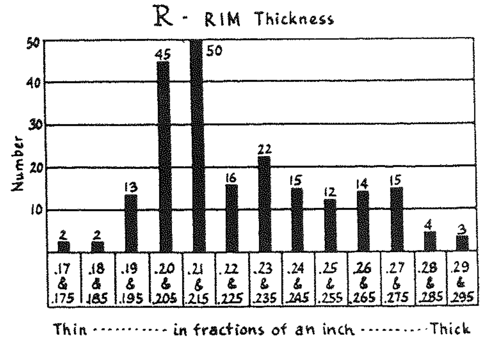
* Median above and below which are an equal number of mouthpieces.

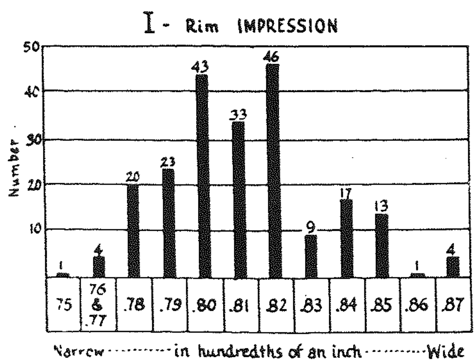












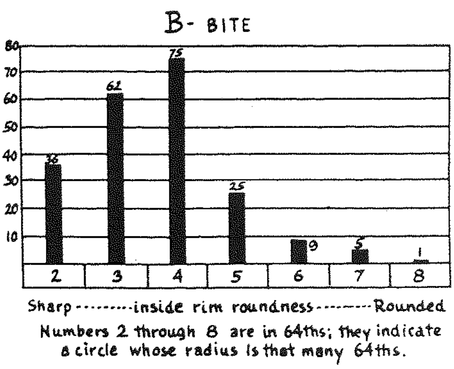


Figure 7.1: *The T-V-D CRIB code of Rohner (1952, from* The Instrumentalist *7 Nov-Dec 1952).*

However, the range of graded measurements covered only trumpet and cornet mouthpieces, and his code numbers were unfortunately not adopted by any of the manufacturers, who have continued to use their own inconsistent and idiosyncratic code numbers and letters. Moreover, his method of cup volume measurement (the average of the cup depths at two fixed distances from the axis) cannot be transferred to mouthpieces for other sizes of instrument. Halfpenny used ten measurements to describe trumpet mouthpieces, but conveyed information about cup shape, rim contour and 'bite' (meaning the curvature of the edge between rim and cup) solely by illustration. Heyde provided a useful diagram of 28 cup shapes, which enabled him to assign the mouthpieces in the Leipzig University collection to 28 classes. He used six measurements, from which he extracted ratios expressing cup conicity and cup depth as a proportion of overall length.

7.2 The acoustical functions of the brass instrument mouthpiece

A mouthpiece is necessary to provide support for the player's lips, so that the player can make an air-tight seal when the lips are placed against it, and so that a suitable area of lip is coupled with the instrument air-column. However, the acoustical functions are rather more complex than this. A review of mouthpiece acoustics is given by Campbell and Greated (1987).

The behaviour of the air in the mouthpiece cavity depends on the frequency of the component of the sound being considered. Further, the function of the mouthpiece is not solely dependent on its own physical properties, but also depends on the bore profile of the rest of the instrument. To a first approximation, for low frequency waves in a conical-bore instrument such as an alphorn, the primary effect of the mouthpiece cavity volume is to compensate for the fact that the cone is truncated at the narrow end.

The cavity itself has a resonance frequency of its own, the so-called Helmholtz resonance frequency. In the case of a cavity vented by a cylindrical tube, the square of the resonance frequency is proportional to the cross-sectional area S of the cylinder and inversely proportional to the volume V of the cavity and the length L of the cylinder (Fletcher and Rossing 1991)

$$f_{res} = \frac{c}{2\pi}\sqrt{\frac{S}{VL}} \quad (7.1)$$

where c is the speed of sound in free air.

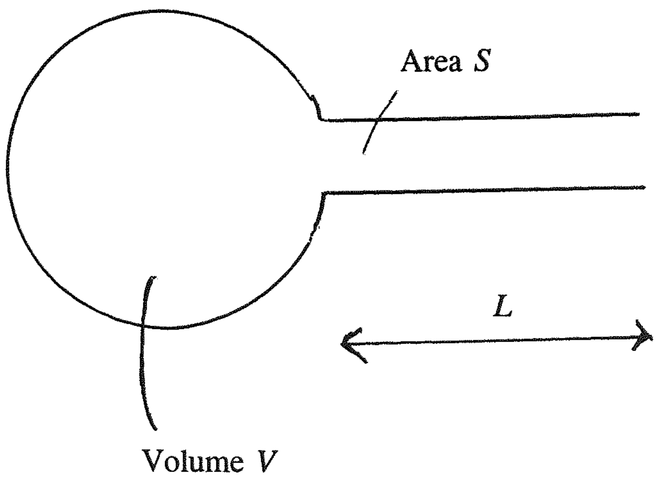


Figure 7.2: *The Helmholtz resonator, a simple mouthpiece model.*

When a mouthpiece is placed in the instrument for use, the backbore of the mouthpiece continues into and forms part of the bore of the instrument. In some instruments the taper of the backbore is continued (after the inevitable small discontinuity) by the taper of the leadpipe. The resonance frequency of the cavity depends to some extent on the bore profile of the whole instrument. The acoustic impedance response of a detached mouthpiece follows an approximately Gaussian curve as does a Helmholtz resonator [Figure 7.3].

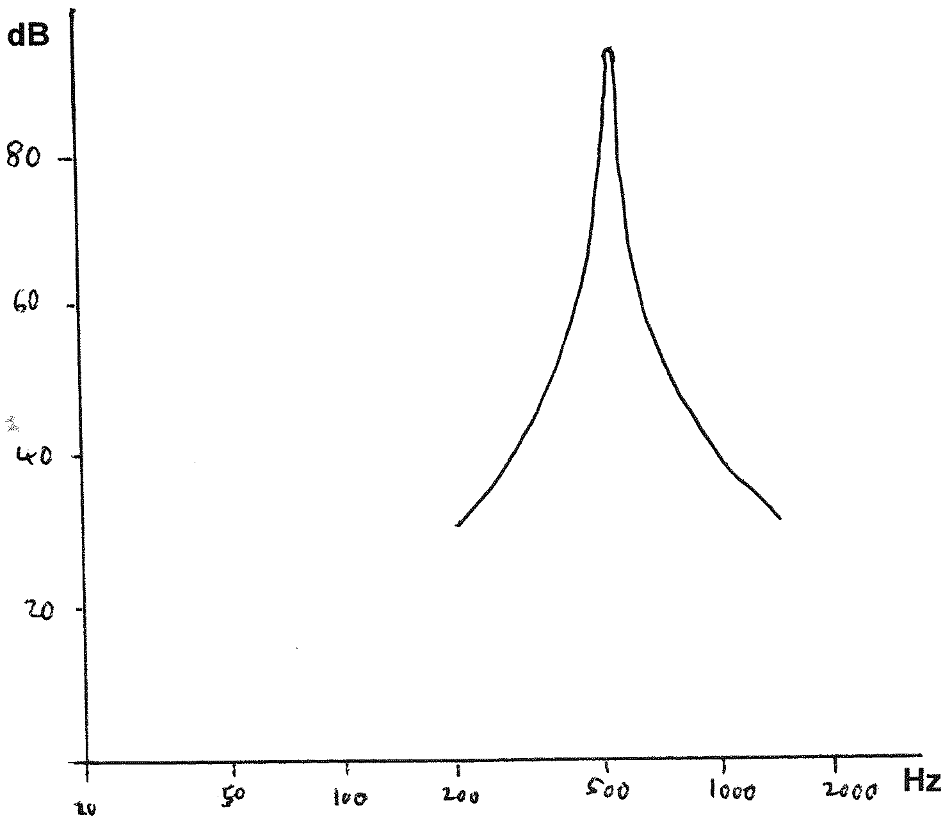


Figure 7.3: *Acoustic input impedance for a trombone mouthpiece by Besson (EUCHMI 2830) with a peak or resonance frequency at 565 Hz, measured at 19° C using the capillary input impedance method as described by Campbell (1987).*

The resonance frequency is usually in the range of the fundamental frequencies of the notes in the normal tessitura of the instrument. For notes near the mouthpiece resonance frequency, the mouthpiece cavity boosts the response of the instrument and affects the exact positions of the resonance frequencies of the whole air column. A mouthpiece with a suitable resonance is essential for the design of an instrument capable of being played well in tune. The parameters reflecting the behaviour of a mouthpiece as a Helmholtz resonator are:

1. Cup volume
2. Minimum cross-sectional area
3. Length and shape of throat
4. Shape of backbore and instrument

7.3 The anatomy of the mouthpiece

An essential requirement of a mouthpiece is that it mechanically fits into the instrument, so the first (though not the most interesting) parameter is the minimum shank diameter. Interchangeability of mouthpieces is generally desirable; also the bore in the instrument just beyond the end of the mouthpiece shank is itself acoustically significant, so each kind of instrument tends to have mouthpieces with a narrow range of shank diameters. There are exceptions, such as the few models of trumpet which are designed to take cornet mouthpieces. Appendix D gives the minimum shank diameters for the 435 mouthpieces in the Edinburgh University Collection (Myers and Parks 1996a and 1996b).

The parameter most often cited is the cup diameter, because of its great influence on the embouchure and the feel to the player. It varies from 12mm or less in cornettino mouthpieces to 30mm or more in the largest tuba mouthpieces, limits dictated by the size of the human lip rather than by the nature of the instrument. Its taxonomic role may, therefore, be accomplished better by cup volume and shape, parameters which might have a greater effect on timbre and response and are not constrained in any way by the size of the human lip.

At least one manufacturer of mouthpieces (Denis Wick) uses a further categorization, backbore shape. This is classified as either barrel, v-type, medium or open. Although the shape of the backbore is important, continuing as it does the profile of the instrument's leadpipe, its description has not formed part of this study.

A deficiency of existing museum catalogues is lack of information on the nature of the association between mouthpiece and instrument. A trumpet mouthpiece may be known to have been supplied with the trumpet when new, may be known to have been used by a former player with the trumpet, or may have been known to have been 'thrown in with' the trumpet when it was last sold. This information, even when known to the catalogue author, is rarely given.

7.4 Method of mouthpiece cup profile measurement

The purpose of the measurements of brass instrument mouthpieces of all kinds for this study has been to generate data of sufficient quality to allow direct comparison of acoustically significant parameters. The bite has been measured at its maximum curvature using a set of curvature gauges; the minimum radius of curvature has been measured to the nearest 0.25 millimetres. For the purpose of cup profile measurement, the bite cross-section is modelled as the quadrant of a circle having as radius the minimum radius of curvature of the bite, and the inside cup diameter is measured by caliper at a depth of one bite radius [Figure 7.4].

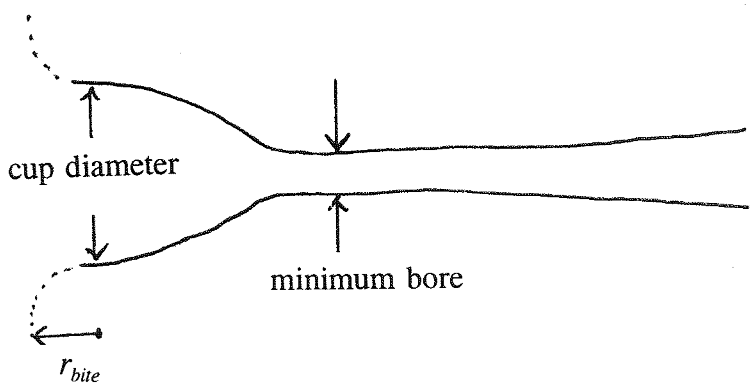


Figure 7.4: *Anatomy of a mouthpiece cross-section (solid line) showing minimum bore, bite as modelled by a quadrant (broken line), bite radius* r_{bite}, *and the inside cup diameter.*

For each mouthpiece studied, the minimum bore diameter and its position have been measured using an expanding bore gauge. The cup profile has been measured using a set of simple plug gauges, a series of aluminium cylinders with logarithmically graded diameters, $e^{1.3}$ (3.67), $e^{1.4}$ (4.06), $e^{1.5}$ (4.48) ... $e^{3.4}$ (29.95) millimetres. The tolerance in diameter is $\pm$ 0.02 mm; the depth of insertion is measured with a spread of 0.2 mm. The gauge measurement can be presented as a table with two columns as in Figure 7.5.

Internal diameter in millimetres	Axial distance from rim in millimetres
6.69	17.36
7.39	17.26
8.17	17.00
9.02	16.87
9.97	16.67
11.02	16.50
12.18	16.45
13.46	16.15
14.88	15.92
16.44	15.37
18.17	14.61
20.09	13.62
22.20	12.10
24.53	10.21
27.11	6.83
29.97	0.23

Figure 7.5 *Cup profile of mouthpiece for serpent (probably France, c 1750; EUCHMI 3304) as measured by plug gauges. With this measuring technique, the diameters are fixed and the depth of insertion is the dependent variable. The tolerance in internal diameter is 0.1 millimetre or less; the spread in axial distance is less than 0.25 millimetres. Since the data are used in subsequent calculations, they are not rounded at this stage.*

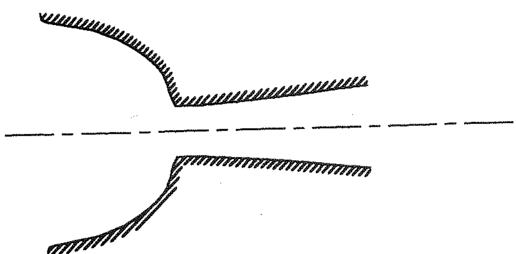


Figure 7.6 *Plot of cup profile of mouthpiece for serpent (probably France, c 1750; EUCHMI 3304) as measured by plug gauges. The minimum diameter measured by an expanding bore gauge is 6.7mm ± 0.1mm at a depth of 17.35mm ± 1mm; the bite radius as measured by a curvature gauge is 0.75mm ± 0.25mm, and the cup diameter at a depth of 0.75mm as measured by a caliper is 29.5mm ± 0.1mm.*

The data for a number of mouthpieces have been manipulated using a computer-aided drafting software (AutoCAD). For each, a cone has been constructed which touches the mouthpiece rim and throat. The point where this reference cone touches the rim is a small distance into the mouthpiece cup, a little less than a depth of one bite radius. In cup-shaped mouthpieces, there is an annular part of the cup volume which lies outside this cone; for a conical cup shape, there is no annulus. For a cuspoidal cup shape there is no throat - the cone apex is placed at the point of minimum bore; the cup walls lie inside the reference cone and the annulus volume can be regarded as taking a negative value.

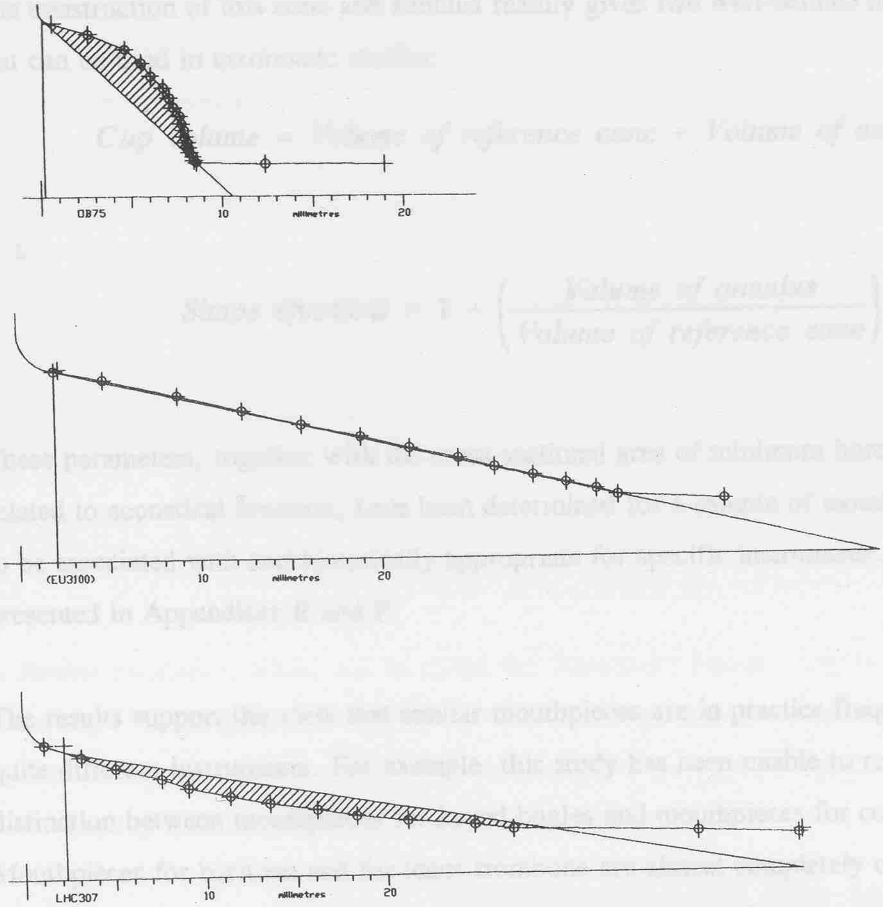


Figure 7.7: *The three types of mouthpiece cup shape with reference cone and annulus.*

The volume of the cone plus the annulus volume is adopted as a measure of the acoustically effective volume of the mouthpiece. The fact that the cone terminates at a point a small distance into the mouthpiece cup rather than on the face of the rim can be regarded as an allowance made for the fact that a player's lips occupy part of the volume of the mouthpiece. The protrusion of the lips into the mouthpiece varies considerably from one player to another and from embouchures for high notes to embouchures for low notes; inspection of embouchure formation with transparent mouthpieces confirms that this allowance is of the right order of magnitude. That the apex of the cone is not exactly at the point of minimum bore reflects the fact that the position of minimum bore is often not well defined and can be at some distance from the throat.

7.5 Taxonomic parameters

The construction of this cone and annulus readily gives two well-defined measurements that can be used in taxonomic studies:

$$Cup\ volume = Volume\ of\ reference\ cone + Volume\ of\ annulus \quad (7.2)$$

$$Shape\ Quotient = 1 + \left(\frac{Volume\ of\ annulus}{Volume\ of\ reference\ cone}\right) \quad (7.3)$$

These parameters, together with the cross-sectional area of minimum bore, all directly related to acoustical function, have been determined for a sample of mouthpieces known to be associated with and historically appropriate for specific instruments. The results are presented in Appendices E and F.

The results support the view that similar mouthpieces are in practice frequently used for quite different instruments. For example, this study has been unable to reveal any distinction between mouthpieces for keyed bugles and mouthpieces for cornopeans. Mouthpieces for baritone and for tenor trombone are almost completely overlapping categories. Similarly, no distinction can consistently be made between mouthpieces for bass trombone and for euphonium.

Whereas the function of the mouthpiece cup in supporting modes of resonance is well known and generally accepted, the 'popping frequency' (Benade 1973) of the mouthpiece in isolation can be only such a rough indication of the Helmholtz resonance frequency of the mouthpiece when in the instrument that it is more likely than not to be misleading. The pitch of the sound obtained by slapping the mouthpiece cup on a surface such as the palm of a hand does not only depend on the cup volume and throat cross-sectional area, but also on the length and shape of the backbore. This can be simply tested by extending the backbore with a shank or even a rolled slip of paper. The 'popping frequency' can be considerably lowered by a small extension of the backbore, and therefore depends in an unmeaningful way on the length and shape of the backbore. When a mouthpiece is placed in the instrument for use, the backbore of the mouthpiece merges into and forms part of the bore of the instrument. In most instruments the taper of the backbore is continued (after the inevitable small discontinuity) by the taper of the leadpipe. The column of air inside the backbore in isolation is not a critical feature of the whole system of instrument, mouthpiece and player.

The mouthpiece backbore is not in general cylindrical, but the popping frequency will clearly depend strongly on backbore length. When the mouthpiece is in place in the instrument, the calculation of the cavity resonance is not simple: the resonance frequency associated with the cup volume is substantially lowered, as the effective length of the backbore receives an additional contribution from the leadpipe and to some extent from the main air-column. Caussé, Kergomard and Lurton (1984) report such discrepancies between popping frequency and the frequency of peak support for the modes of resonance of various mouthpieces attached to cylindrical tubes.

A further parameter, which can be called the 'Resonance Factor', may be useful in taxonomy. This is derived from the cup volume and the minimum cross-sectional area, related as they would be in calculating the Helmholtz resonance frequency, but not involving any measure of length of grain or backbore:

$$\textit{Resonance Factor} = \frac{\textit{Minimum area of bore cross-section}}{\textit{Cup volume}} \qquad (7.4)$$

This parameter has the dimensions of inverse length and values can conveniently be given in m^{-1}. For a mouthpiece of given backbore length, an increase in the Resonance Factor will increase the resonance frequency. Appendix G shows a degree of correlation between Resonance Factor and normal playing tessitura of the associated instrument.

7.6 Measurements of resonance frequency

In order to check the assumptions made above, the resonance frequency was obtained directly for several mouthpieces using the capillary techniques of acoustical impedance measurement described in Campbell (1987). If the actual backbore of a mouthpiece were replaced by a cylindrical tube of diameter equal to the mouthpiece's minimum bore diameter, the equivalent length L_{EC} of this cylindrical tubing is that required to give the same resonance frequency as the actual mouthpiece. Using the cup volume as calculated using equation 7.2 and direct measurement of the minimum bore, the equivalent length L_{EC} can be calculated using Equation 7.1 [Equation 7.5]

$$L_{EC} = \left(\frac{c}{2\pi f_{res}}\right)^2 \left(\frac{Minimum\ area\ of\ bore\ cross\text{-}section}{Cup\ volume}\right) \qquad (7.5)$$

The equivalent cylinder length is over-estimated because the end-correction has been ignored, and also because the experimental apparatus uses the complete cup volume to the plane of the mouthpiece rim, whereas the calculated cup volume makes allowance for the protrusion of the player's lips and is smaller. However, since the backbore is mostly larger in cross-sectional area than the minimum cross-sectional area, the actual backbore length can be expected to be longer than the equivalent cylinder length. The results given in Figure 7.8 show that L_{EC} is of the same order of magnitude at the backbore length, though the correspondence is imperfect.

		Instrument	Maker	Place	Date	Popping f	Equiv Cyl L	Backbore L
EU	2469	Bugle	Honsuy	Spain	1985	920	32.0	51.3
EU	2344	Bugle	Honsuy	Spain	1984	868	35.7	54.0
EU	993	Bugle			1.19	866	37.1	44.8
EU	3019	Post-horn		Germany	1.19/e.20	848	35.6	45.7
EU	904	Bugle		Germany	c 1914	825	36.2	51.6
EU	906	Cornet	Higham	Manchester	c 1900	798	35.6	35.7
EU	672	Trumpet			1.19/e.20	676	51.0	54.7
EU	866	French horn		Germany (?)	1.19/e.20	669	40.9	38.2
EU	2696	Sackbut	Büchel	Germany	1.20	620	82.5	65.4
EU	2962	Tenor trombone	Salvation Army	Luton	m.20	617	70.8	50.8
EU	3100	Tenor trombone	Courtois	Paris	1.19/e.20	580	49.7	37.5
EU	1586	Tenor trom / Tenorhorn		Austria	e.20	578	45.3	57.3
EU	2830	Tenor trombone	Besson	London	1.19/e.20	565	56.1	48.2
EU	665	Trombone	Selmer	London	m.20	539	57.4	56.7
EU	2825	Alto trombone		Britain (?)	1.19/e.20	529	63.7	54.5
EU	3206	Tenor trombone		Austria (?)	19	515	47.9	64.0
AM	189	Trombone	Bach 6½AL	USA	c 1975	510	60.5	59.4
EU	3256	G Bass trombone	Boosey & Hawkes	London	c 1951	491	54.5	54.7
AM	192	Trombone	Remington	USA	c 1977	481	46.9	64.6
AM	688	Bass sackbut	Thein	Germany	c 1980	455	91.4	78.5

Figure 7.8: *The popping frequency (Hz), equivalent cylinder length (millimetres) and measured backbore length (millimetres) for some mouthpieces.*

A further source of error is that backbore lengths have been measured assuming in many cases that the cup ends and the backbore begins at the point of maximum curvature at the throat (further discussed in Myers and Parks 1996a or Myers and Parks 1996b); the measured backbore lengths cannot necessarily be given to an accuracy better than a few millimetres.

The effect of mouthpiece cup resonance on the sound quality is also more complex than a simple dependence on cup volume and throat cross-sectional area, though these are factors. For low notes on an instrument, the support given by the mouthpiece cup resonance for the upper harmonics in the sound spectrum will indeed be significant. For high notes, however, the Helmholtz frequency will be not far removed from the fundamental frequency of the note being played; here the effect of the mouthpiece cup resonance is to support the production of the fundamental of the note, and the support to its overtones (harmonics) will be negligible. This is confirmed by subjective experience as a listener: it is difficult to distinguish the sounds of brass instruments of the same basic size playing high notes; instruments show their own character much more when playing low notes.

The listener's perception of 'brightness of sound' also depends on the starting transient characteristics as well as on the spectrum of the sustained sound, and throat shape seems likely to affect transients even if steady state sound is largely independent of cup shape detail. Some players consider that throat curvature affects the response of the system to the 'attack' of a note. This is an area very ripe for further research.

Chapter 8

Considerations of mid-length bore

In Chapters 6 and 7 methods of characterization of brasswind by parameters relating to the acoustically-important proximal (mouthpiece) and distal (bell) terminations of the bore were discussed. However, these parameters alone do not unambiguously characterize all the instruments investigated, and it has been necessary to consider the overall profile of instrument bores although the relevant acoustical theory is not as amenable to yielding readily determinable parameters.

8.1 Data from pulse reflectometry

Many historic brass instruments are so constructed that substantial parts of the air column are inaccessible to direct measurement. Recent advances in the use of pulse reflectometry for bore reconstruction (Sharp, Myers, Parks and Campbell 1995; Sharp 1996; Sharp, Myers and Campbell 1997) in particular compensation for losses and allowance for multiple reflections, have provided a useful tool for measurement of historic musical instruments.

The question of musically inconsequential leaks having a disproportionate effect on the bore reconstruction is a potential problem. The bandwidth of the pulse spectrum utilised in reflectometry does not necessarily match the range of frequencies employed in musical use of the instrument. It has been found that these techniques require instruments to be leak-free to a higher degree than players require, so they are clearly not applicable to many museum instruments. However, for those that are (or can safely be made) leak-free, the resulting degree of accuracy, the completeness of the view of the effective interior, and the reduction in tedious direct physical measurement make the investment in pulse reflectance apparatus an attractive option.

The bore profiles which have proved to be viable for brass instruments have at one end a mouthpiece, which may be cupped or funnel-shaped, followed by the narrowest part of the windway, the 'mouthpiece throat'. From the throat, the windway passes through the mouthpiece backbore, the mouthpipe or leadpipe, any tuning-slide or valves, finally coupling with the free air at the widest part of the tube, the bell. The area of cross-section in most cases increases monotonically, although there can be some localised narrowing (e.g. at slides and at valves, or due to some slight damage). The traditional bore cross-section is circular; where (rarely) a deliberately elliptical cross-section is introduced, or in the slight deformation at bends in the tube, the bore profile can for most purposes be considered to be equivalent to that of a cylindrical tube of the same cross-sectional area.

Much of the sounding length of the instrument can, however, pose severe problems for direct physical measurement, particularly in instruments with many coils. In Chapter 5 it was established that for the purposes of comparison between instruments, a coiled instrument can be treated as equivalent to a perfectly straight instrument with the same cross-sectional area at each point along a line drawn through the geometric centre of the bore, the 'mid-line'. The bends encountered in the great majority of actual instruments will give rise to second-order discrepancies only.

The extension of the pulse reflectance techniques for bore reconstruction already in use in the medical field (Marshall, 1990) to brass instruments is a potentially useful means of investigating brass instruments for the purposes of classification. Existing applications to musical instruments (Krüger 1979, Smith 1988, Watson and Bowsher 1988, Bowsher 1989) have been directed to other purposes. A particular advantage would be in establishing the bore profile of instruments with substantial portions of coiled tubing without the difficulties of making large numbers of precise physical measurements of curved tube: a smaller number of direct physical measurements could be made and bore reconstruction techniques used for interpolation.

8.2 Results for certain historical models of instrument

Figure 8.1 shows the bore profile of a B♭ cornet by Rudall Carte without mouthpiece (EUCHMI 2988), without any valves operated. The directly measured profile and the profile reconstructed from reflectance measurements are superimposed. The initial dip is the mouthpiece receiver taper, and does not represent part of the sounding bore when a mouthpiece is inserted. The small-scale fluctuations in the reconstructed bore are mostly accounted for by features such as water-keys and small discontinuities at the ends of tuning slides and at the valves; no attempt was made to measure the cross-sectional area at these features physically.

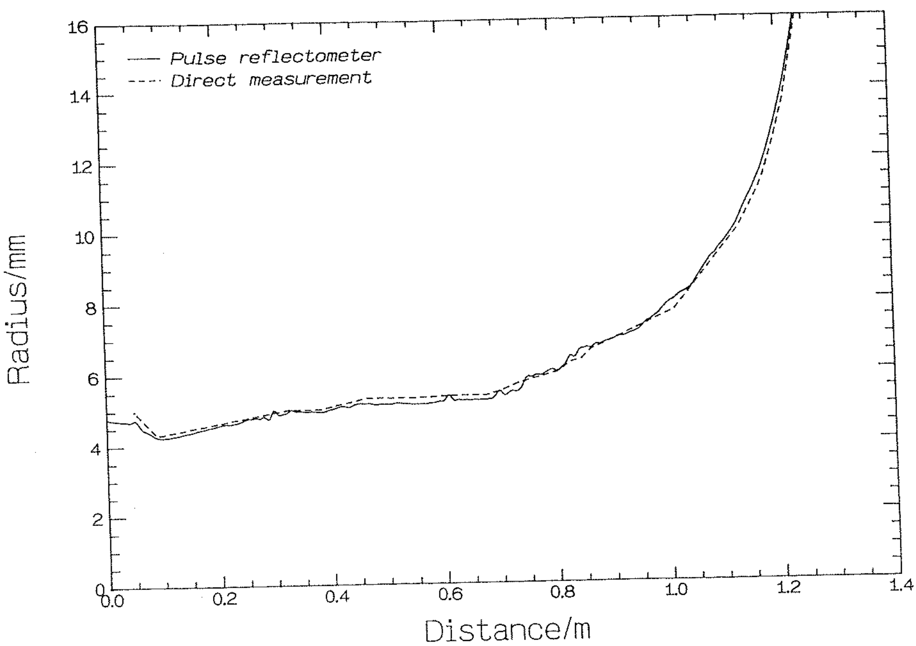


Figure 8.1: *Comparison of directly-measured bore profile with reconstruction obtained by pulse reflectometry.*

The bore (y axis) is exaggerated here: drawn with the same scale for both axes it would appear as Figure 8.2. The final flare of the bell (bore radius greater than 16mm) has been omitted: bore reconstruction by pulse reflectometry is not reliable in highly flared tubing and the techniques discussed in Chapter 6 are more appropriate for plotting the final section of the bore.

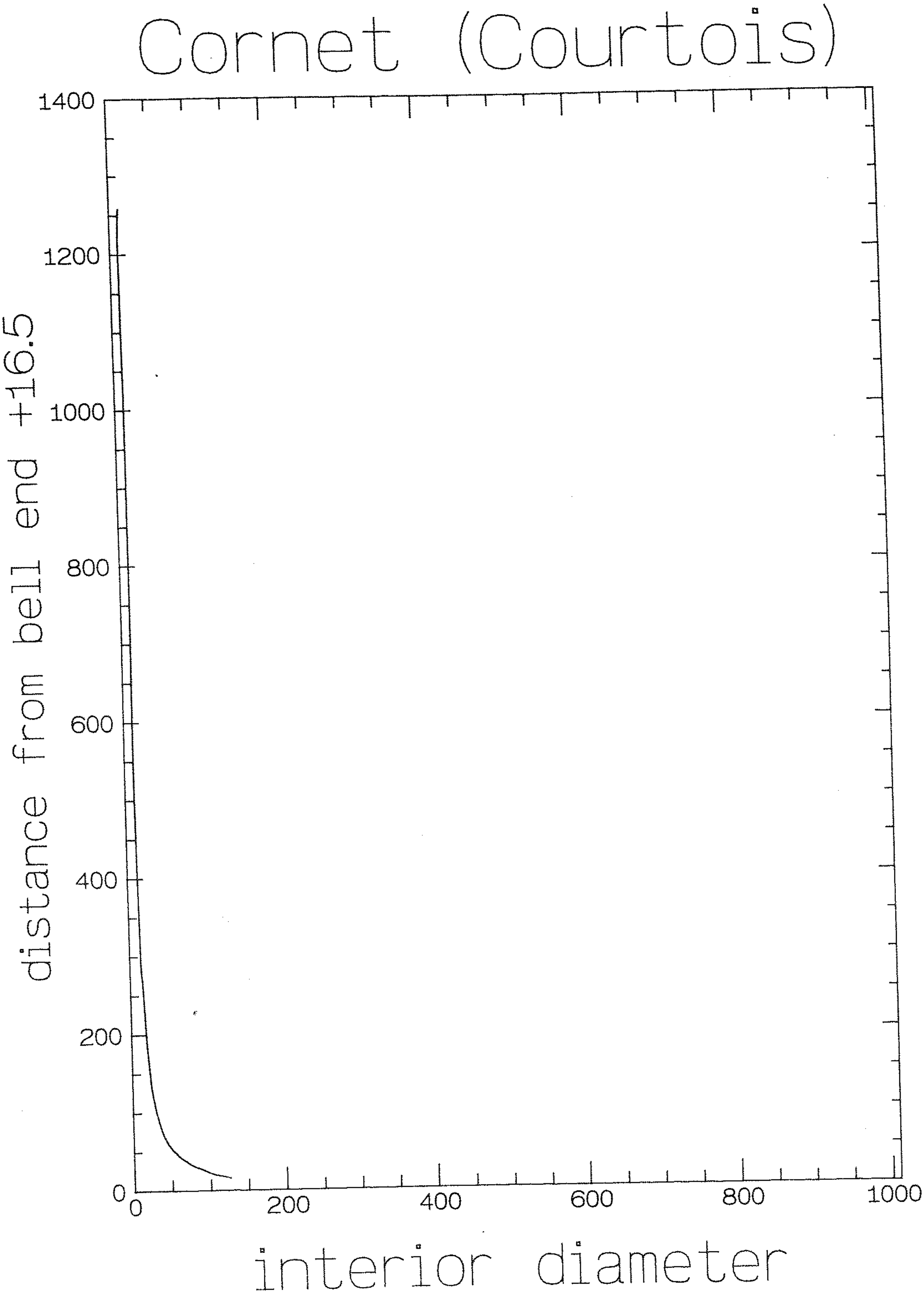


Figure 8.2: *Plot of Courtois cornet (EUCHMI 2560) to scale, axial distance and bore both in millimetres.*

Inspection of the central part of the bore in Figure 8.1 indicates that the bore through the valves is not cylindrical, but expands gradually. This is indeed the case: the Rudall Carte cornet is the 'Patent Conical Bore' model (Tomes and Myers 1995) with incremental bore cross-section in the windways through the pistons and in the tuning-slide bows.

Figure 8.3 shows a comparison of the Rudall Carte 'Conical Bore' cornet (EUCHMI 2988) with a standard cornet by Boosey (EUCHMI 2704), all three valves of both instruments operated. The Boosey cornet has at some time had its playing pitch lowered by extension of each leg of its tuning-slide; this accounts both for the greater overall length and for the two peaks around 0.5 metres from the mouthpipe.

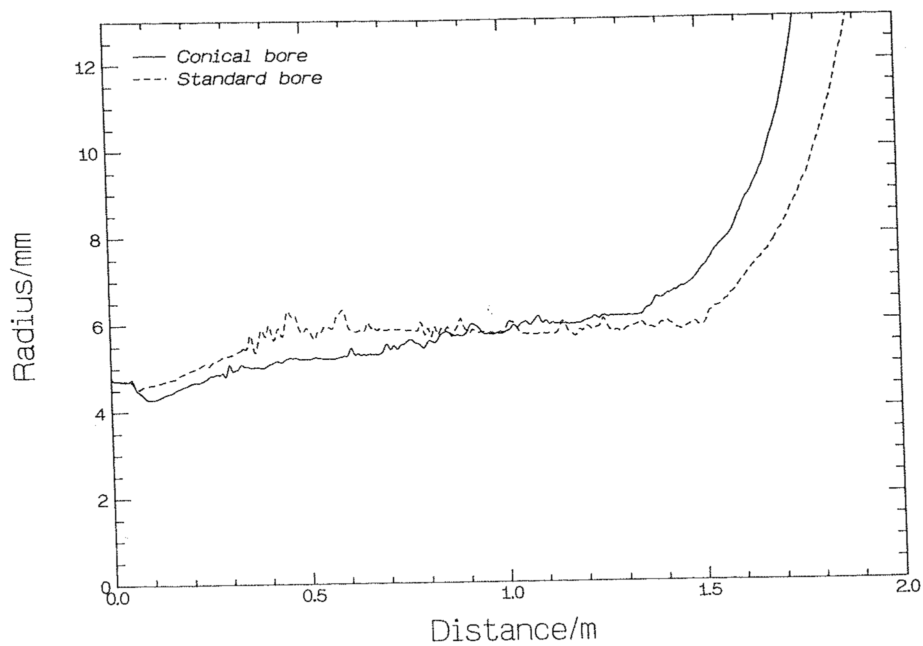


Figure 8.3: *Reconstructions of Rudall Carte 'Patent Conical Bore' cornet [solid line] and standard cornet by Boosey & Co [broken line], both with all three valves operated.*

The method of pulse reflectance is of potential value for coiled tubes with bores inaccessible to direct measurement. Figure 8.4 shows the successful reconstruction of a coiled posthorn (EUCHMI 561). Only the mouthpipe (sliding for tuning purposes) and the bell flare could be reached for direct measurement.

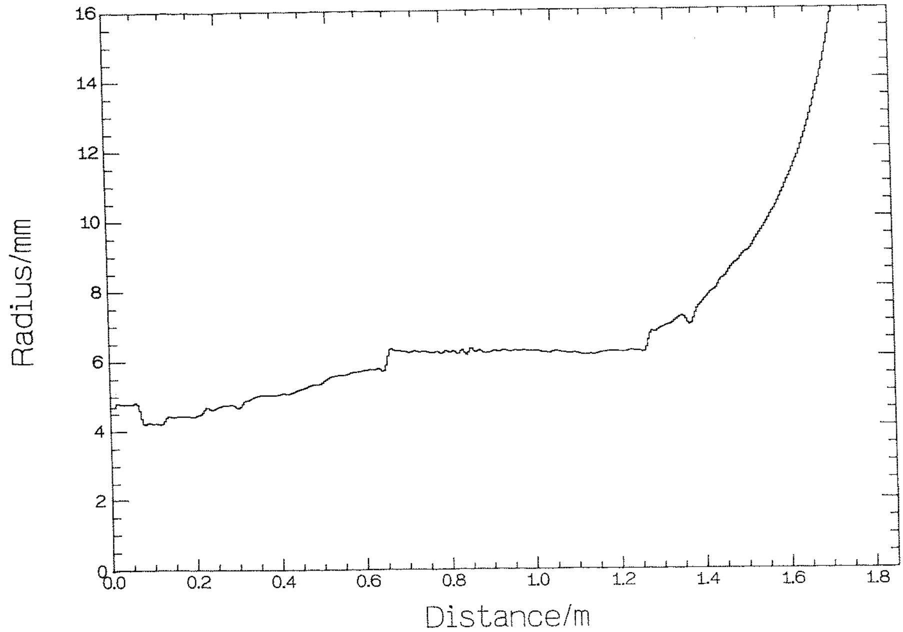


Figure 8.4: *Reconstruction of coiled posthorn or cornet simple in B♭ by Morhange, c 1895.*

For purposes of comparison of bore profile between instruments, bore reconstructions of the accuracy now possible (see Appendix H) with corrections for attenuation offer a useful tool for taxonomy. The problems of measuring the mid-line in coils are avoided, since the use of sound waves in measurement ensures that the acoustically defined path is what is measured.

8.3 Comparison of cornets and trumpets

It is commonly stated in the literature of musical instruments (Baines 1976 and elsewhere) that the cornet was a development of the post-horn - it was virtually a post-horn with valves added. It is also stated (for example in Bate 1978) that since the development of the cornet in the mid 1820s, the cornet and the trumpet have evolved to become virtually indistinguishable. This has practical application in the performance of original cornet parts by Berlioz, Elgar and others: if it is desired to approach the originally intended sound, it is necessary to know if they should be performed on modern cornets, modern trumpets, or if antique cornets are necessary.

Figure 8.5 shows the bore profile of a coiled posthorn or 'cornet simple' by Kretzschmann, Strasbourg (EUCHMI 3052), the supposed natural predecessor of the cornet. It has tapered crooks.

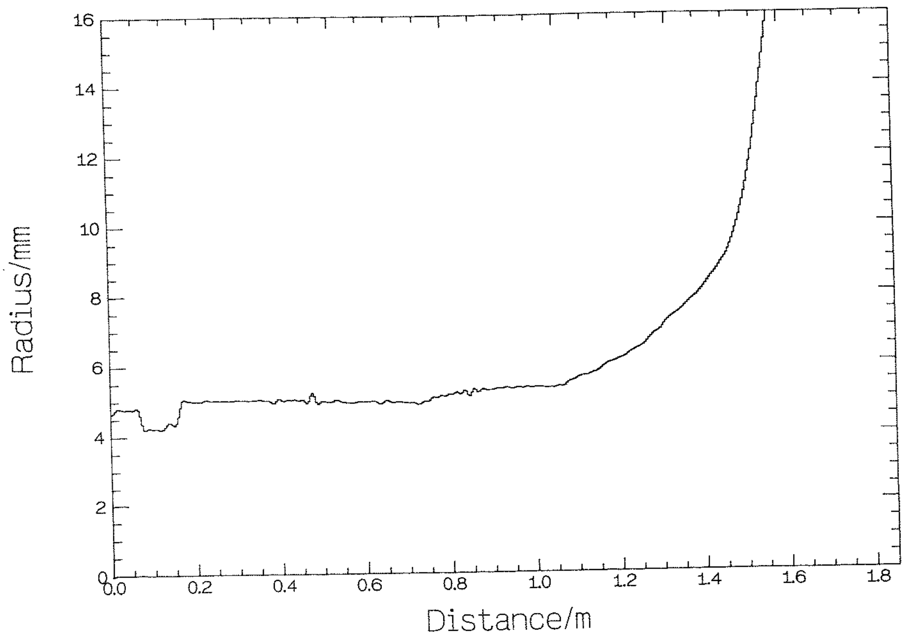


Figure 8.5: *Reconstruction of posthorn by Kretzschmann, c 1830.*

Figure 8.6 shows the bore profile of a cornopean - an English cornet made c 1845. The crooks are virtually cylindrical in this model. The Stölzel valves have acute bends in the windway, with irregularities in the bore radius of ± 1mm.

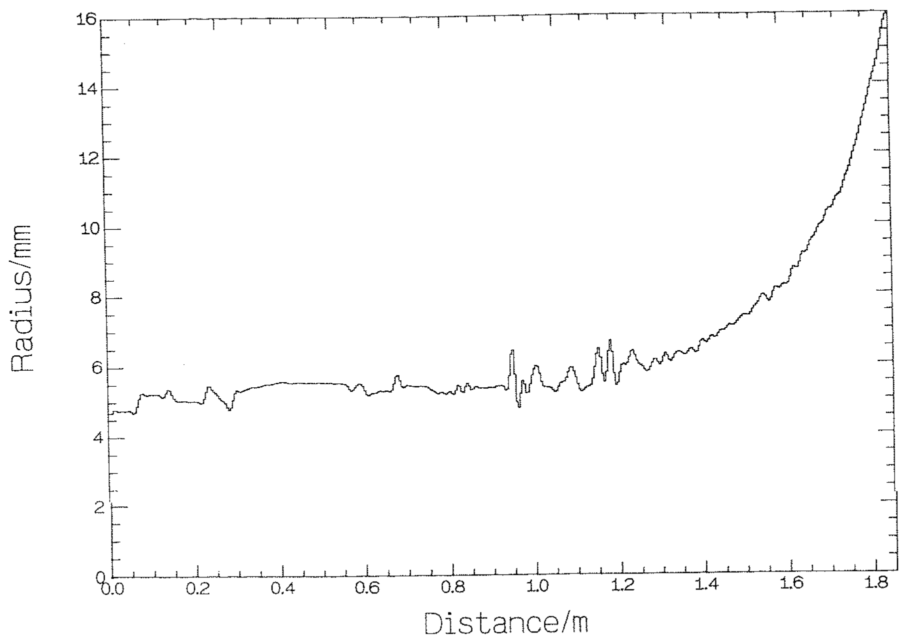


Figure 8.6: *Reconstruction of cornopean by Pace (EUCHMI 2485).*

These early cornets can be compared with more modern cornets, which have a fixed mouthpipe (i.e., without crooks): Figure 8.7 shows an American cornet of the 1930s (EUCHMI 3275). The windway is much smoother, but there are inevitable ripples at the tuning-slides and valves.

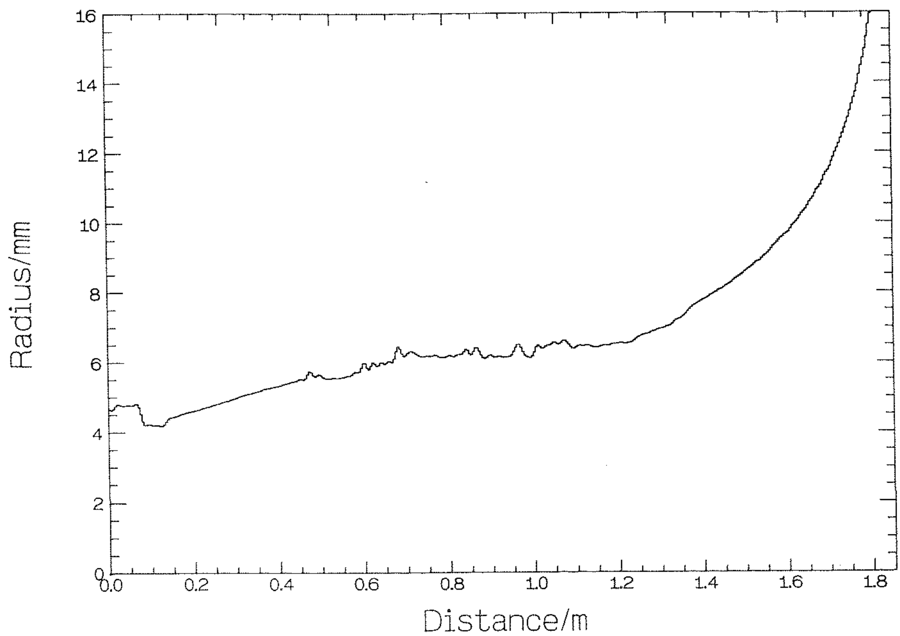


Figure 8.7 : *Reconstruction of cornet by York, c 1935.*

A further comparison can be made with trumpets of the same 4 to 4½ ft tube length. A modern trumpet by Amati (belonging to the Department of Physics and Astronomy, University of Edinburgh) is shown in Figure 8.8.

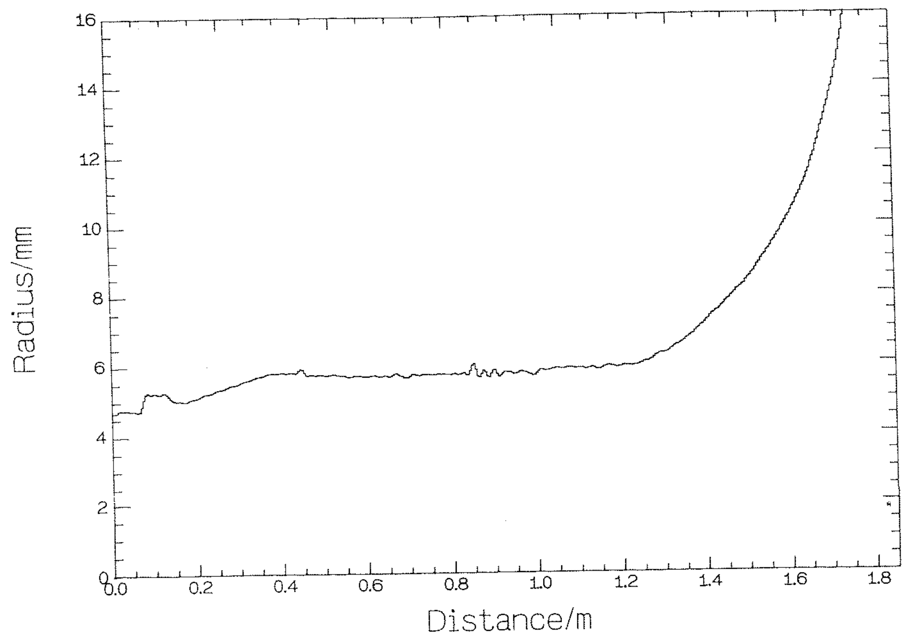


Figure 8.8: *Reconstruction of trumpet by Amati, c 1992.*

We can immediately discount any simple attempt to distinguish between trumpets and cornets by comparing the ratio of lengths of 'conical' tubing (meaning the bell section) to 'cylindrical' tubing. The only distinction between the York cornet and the Amati trumpet is in the steepness of the taper at the proximal end of the windway, the so-called 'leadpipe'. This is reflected in the different external design of the mouthpieces for trumpets and cornets, discussed in Chapter 7.

The distinction in leadpipe taper is not always as clear as between Figures 8.7 and 8.8; some instruments seem to come half-way between the modern trumpet and the modern cornet in bore profile, as in Figure 8.9.

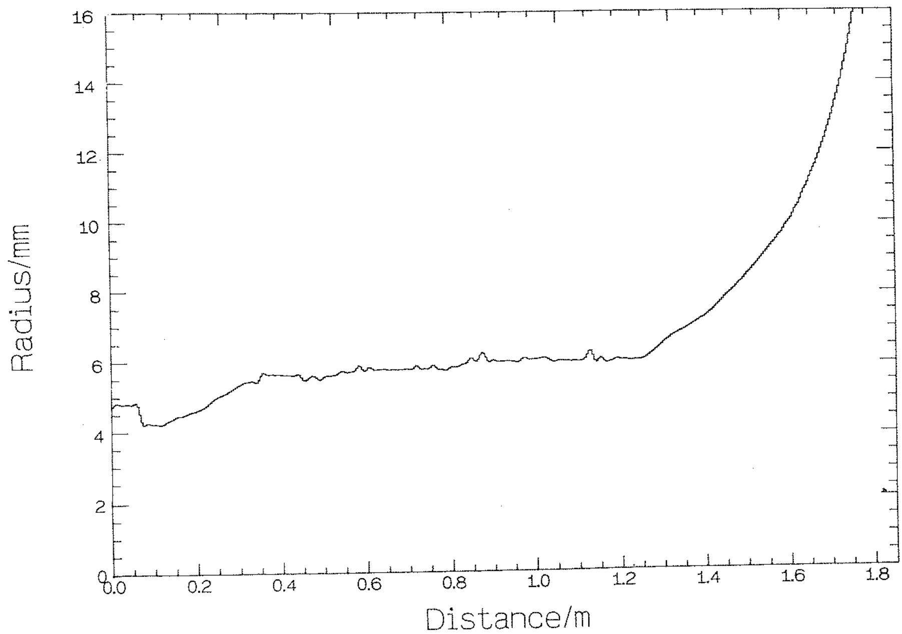


Figure 8.9: *Reconstruction of cornet by Conn, 1924 (EUCHMI 3273).*

Figure 8.1 showed a 'conical-bore' cornet by Rudall Carte, based on a patent of 1903 (Klussman et al, 1903). Another patent for conical bore cornets was taken out by E.A. Couturier in 1913 (Couturier, 1913) in which the concept of a smoothly tapered leadpipe and expansion of the bore through the valve section passages was taken to the greatest extent found in the course of this study [Figure 8.10]. (Couturier subsequently took out patents for other conical bore instruments, including one for a slide trombone.)

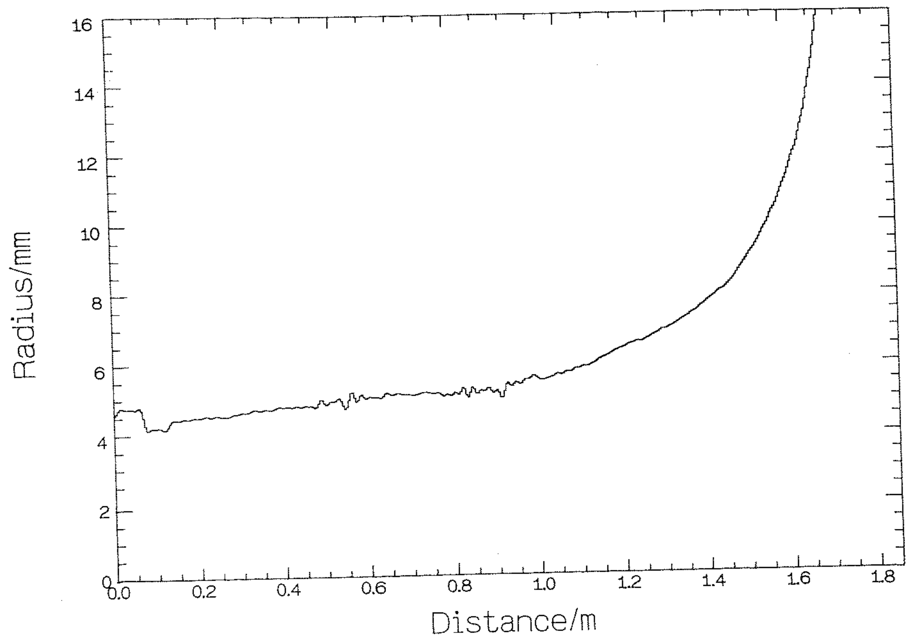


Figure 8.10a: *Reconstruction of cornet by Couturier, 1913 or soon after (EUCHMI 3274).*

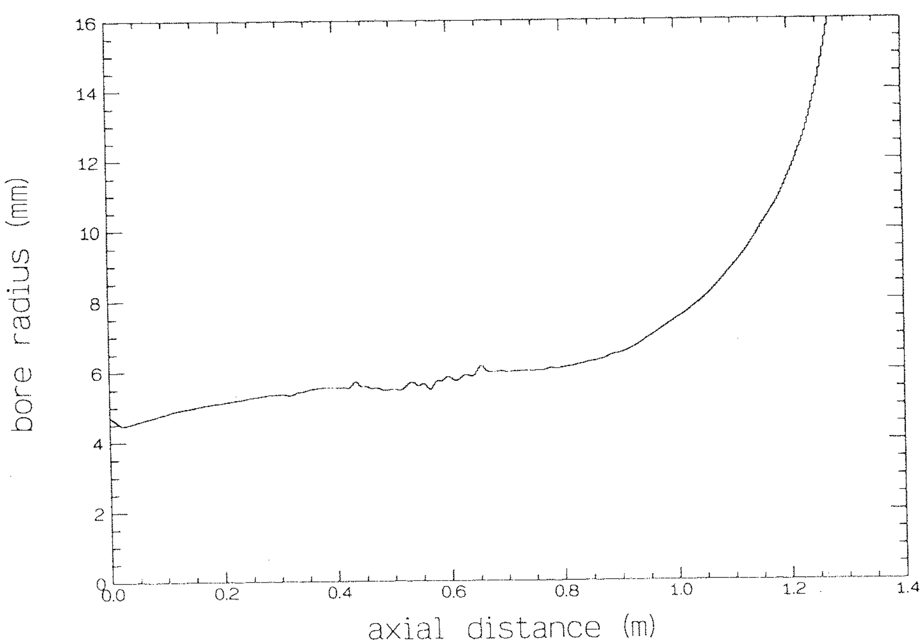


Figure 8.10b: *Reconstruction of cornet by Couturier, 1913 or soon after (EUCHMI 3694).*

There have also been models of valve trumpet employing the 'Patent Conical Bore' concept. One of these was introduced earlier this century by Rudall Carte, the 'Webster Trumpet'. The subjective appraisal of this instrument by players endorses its design as being acceptable as a trumpet (Tomes and Myers 1995). The unusual design includes a leadpipe so tapered that the instrument accepts a cornet mouthpiece [Figure 8.11] with the valves placed closer to the proximal end of the air column than usual. The profile of the bell, however, is so acutely flared that it has the highest peak horn function value (1062 m^{-2} for EUCHMI 3460) and cut-off frequency (1789 Hz for EUCHMI 3460) of all the instruments in 4½-ft B♭ studied.

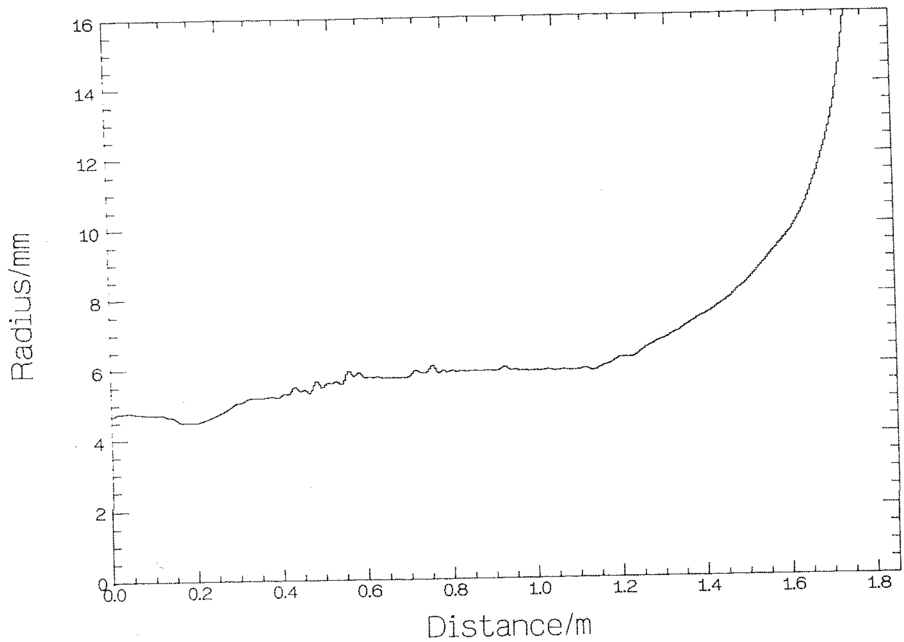


Figure 8.11: *Reconstruction of a Webster trumpet by Rudall Carte, 1926.*

Figure 8.12 shows the bore profile of a trumpet in B♭ by Boosey and Hawkes (EUCHMI 3212), not significantly different from the standard modern B♭ trumpet. The relative similarity between a modern trumpet and a cornet is made more apparent by comparison of their bore profiles with that of a flugelhorn [Figure 8.13].

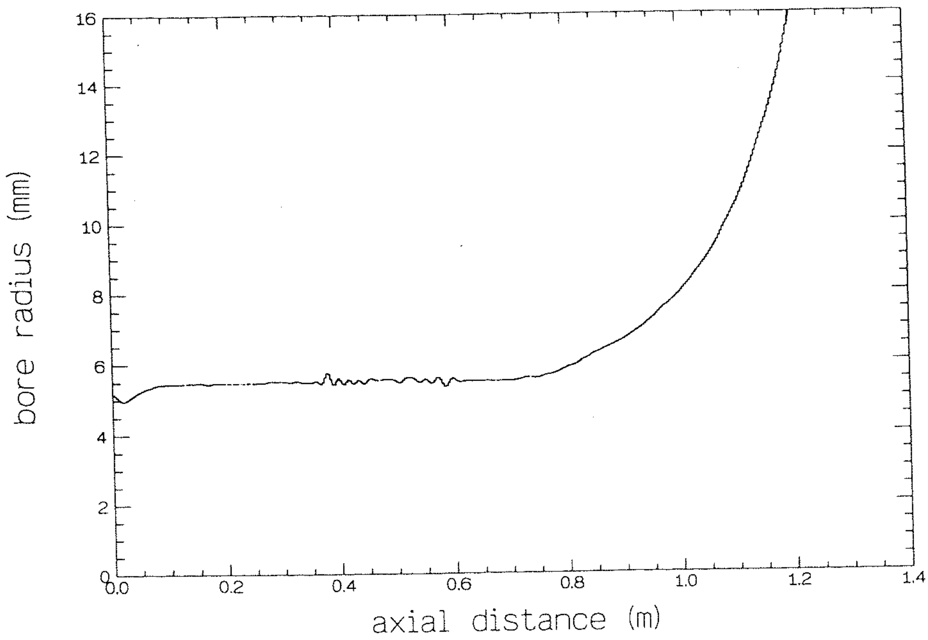


Figure 8.12: *Reconstruction of B♭ trumpet by Boosey & Hawkes, c 1931.*

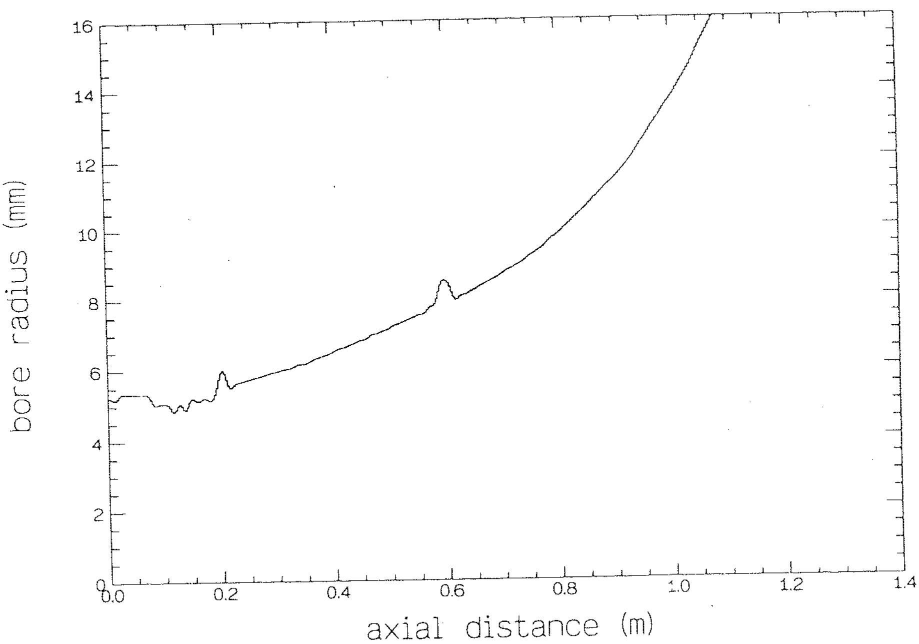


Figure 8.13: *Reconstruction of flugelhorn by Besson, c 1900 (EUCHMI 3592).*

The cornet widely used over a long period was the French model, developed by Paris makers such as Besson and Courtois circa 1850 and still in use quite recently. This model had detachable shanks or crooks of different length which were inserted between the mouthpiece and the body of the instrument to put the instrument into different keys. Figure 8.14 shows a cornet by Courtois (EUCHMI 3710) with a shank for B♭. The shank is not significantly tapered and there is a rather abrupt increase in bore where the shank is inserted into the body of the instrument, in turn followed by a tapering section.

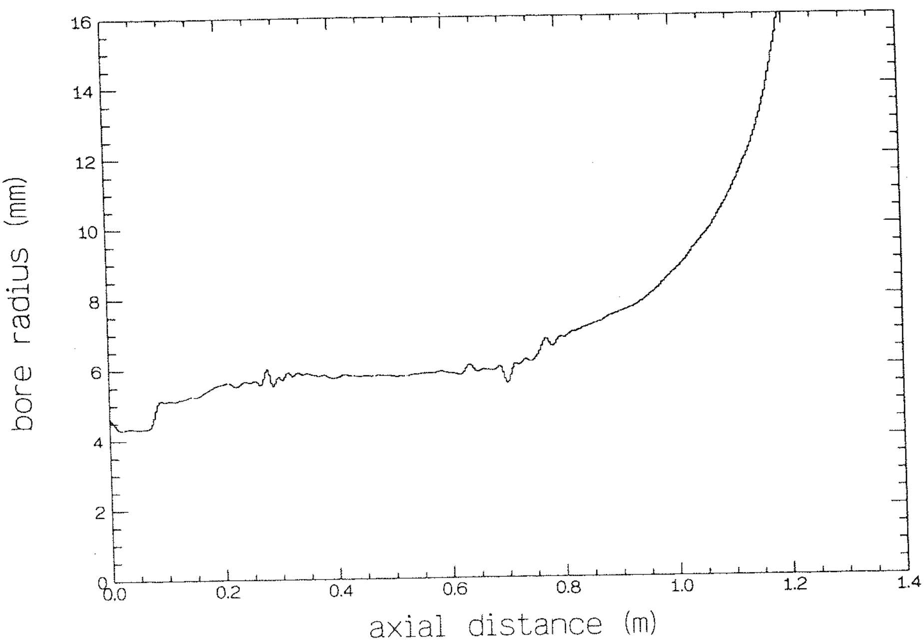


Figure 8.14: *Reconstruction of cornet with B♭ shank (Courtois, 1862-71).*

Figure 8.15 shows the bore profile of an early British cornet of the model sometimes known as a "cornopean" (EUCHMI 215) by Glen, Edinburgh, c 1840. This employed an earlier form of valve (the Stölzel valve) which has noticeably more irregularities in the windway due to the abrupt bends in the valve passages. The significant feature is the lack of any tapered leadpipe. The tubing of the crooks is of approximately the same radius as the tubing of the body of the instrument. The overall topography is thus very similar to that of the modern trumpet.

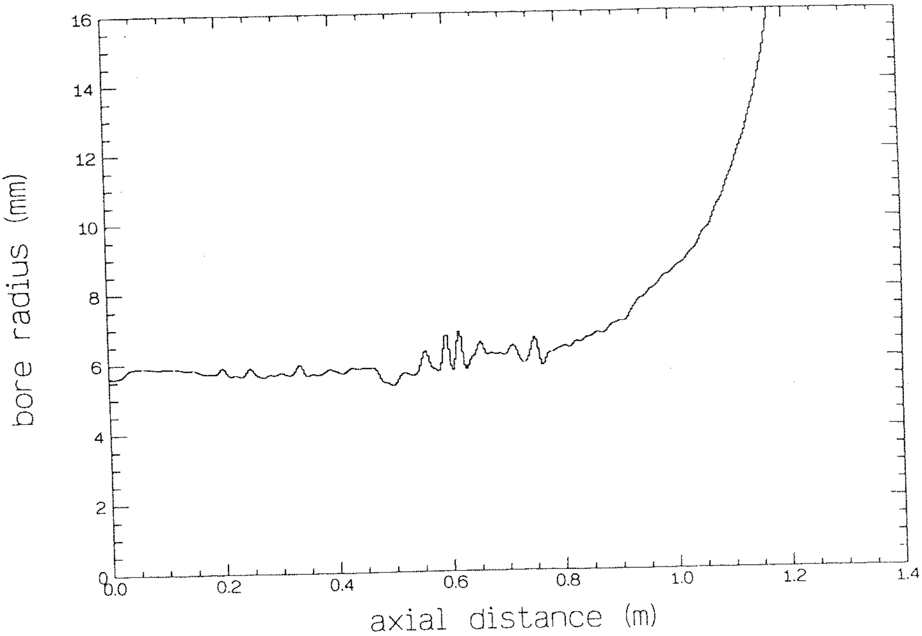


Figure 8.15: *Reconstruction of a cornopean in B♭.*

It should be pointed out that in the mid-nineteenth century the trumpet was of a longer basic tube length, and thus is not comparable with the instruments discussed above, and that the mouthpieces for cornet and trumpet were of markedly different designs, so the similarity between trumpet and cornet now observed would not have been apparent at that time.

Pulse reflectometry can thus quickly and accurately provide 'inside information' about brass instruments and reveal the hidden differences and similarities. It is a non-invasive technique and hence is very useful in the measurement of instruments with a degree of inaccessibility, and can be safely used on museum instruments.

8.4 Taxonomy of the proximal half of the air column

A variety of instruments of approximately 1.25 metre tube length (4-ft C and 4½-ft B♭) have been regularly used: bugles, cornets, flugelhorns, trumpets and others. Of the common types, bugles and flugelhorns are readily distinguished from the others by their bell flare shapes, but modern B♭ trumpets and cornets are not: apart from the Webster Trumpet, the examples shown in Figures 8.1 to 8.10 do not differ markedly in the profile of the distal half of the air column, and the cut-off frequencies for modern B♭ trumpets and cornets [Chapter 6] do not provide a clear distinction. Mouthpiece cup shapes for cornet and trumpet were distinct in the nineteenth century [Chapter 7], but present-day mouthpieces are made with exactly the same cup shapes for cornet and trumpet. It is therefore useful to examine the bore profile of these instruments considering the overall topography of the tube.

The longitudinal wave behaviour of a column of air in a tube with circular symmetry about the z axis is given by the "Webster" equation (8.1):

$$\frac{1}{S}\frac{d}{dz}\left(S\frac{dp}{dz}\right) + k^2 p = 0 \qquad (8.1)$$

where S is the area of a wavefront, k is the wave number and p is the acoustic pressure (Fletcher and Rossing 1991). For a gently expanding bore profile, S may be taken as the cross sectional area of the tube. The solution of this equation for the air column contained by the actual instruments described above is beyond the scope of this study. It is clear, however, that the variation of S with z is of critical importance to the acoustical behaviour of a brass instrument, and an appropriate parameter dependent on these quantities can be defined to facilitate quantitative comparisons corresponding to the qualitative comparisons of the instruments in the above discussions.

If S_{min} is the cross-sectional area of the bore at its minimum (which occurs at or near the mouthpiece receiver) and S_{mid} is the cross-sectional area of the bore at the point mid-way between the two ends (ignoring local irregularities), then a dimensionless parameter K can be defined such that

$$K = \frac{S_{mid}}{S_{\min}} \qquad (8.2)$$

For instruments conventionally regarded as cylindrical, K is unity or little more. For instruments conventionally regarded as conical, K is significantly greater. Clearly for a full consideration of an instrument design, a detailed description of the whole bore profile is needed; this parameter is a candidate for a simple, widely applicable and readily determinable measure which can be useful in the classification of instrument models.

The mid-point of the air column occurs in cornets and trumpets towards the end of the approximately cylindrical part of the tube, before the marked expansion of the bell flare. Figure 8.16 gives for some instruments of comparable basic tube length and comparable normal tessitura the values of K derived from pulse reflectometry and physical measurements. (The parameter C is discussed in Section 8.5 below.)

		Instrument	Nom Pitch	Maker	Place	Date	*K*	*C*
EU	215	Cornopean	4½-ft Bb	Glen	Edinburgh	c 1840	1.13	0.78
EU	2438	Trumpet	4½-ft Bb	Micol-Montagna	Trieste	m.20	1.14	0.80
EU	599	Trumpet	4½-ft Bb	Schediwy	Ludwigsburg	c 1921	1.20	0.72
EU	218	Cornopean	4½-ft Bb		England	c 1845	1.23	0.76
EU	2502	Orchestral cornet	4½-ft Bb	Hall & Quinby	Boston	c 1870	1.24	0.68
EU	3269	Cornet à pistons, wide mouthpipe	4½-ft Bb		France	c 1840	1.26	0.79
EU	3212	Trumpet	4½-ft Bb	Boosey & Hawkes	London	c 1931	1.26	0.77
EU	1553	Cornopean, narrow mouthpipe	4½-ft Bb	Metzler	London	c 1842	1.27	0.74
EU	1701	Trumpet	4½-ft Bb	Vega	Boston	c 1955	1.31	0.77
PH	1	Trumpet	4½-ft Bb	Amati	Czech Republic	c 1992	1.32	0.79
CRB	326	Valve trumpet, `Handelian' model	4½-ft Bb	Kohler	London	c 1895	1.37	0.81
EU	3052	Post horn	4-ft C	Kretzschmann	Strasbourg	c 1830	1.52	0.80
EU	2704	Cornet	4½-ft Bb	Boosey & Co	London	c 1922	1.60	0.80
EU	3460	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1927	1.73	0.81
EU	3694	Cornet, conical-bore	4½-ft Bb	Couturier	USA	c 1920	1.75	0.79
EU	3275	Cornet	4½-ft Bb	York	Michigan	c 1935	1.80	0.77
FT	183	Slide cornet	4½-ft Bb	Conn	Elkhart	e.20	1.85	0.81
JW	CLK	Cornet	4½-ft Bb	Kohler	London	c 1865	1.88	0.80
NSB	1	Cornet	4½-ft Bb	Besson	UK	1997	1.97	0.78
EU	3710	Cornet	4½-ft Bb	Courtois	Paris	1862-71	1.98	0.78
BK	211	Cornet	4-ft C	Ch. Sax	Brussels	c 1840	2.00	0.71
OB	711	Trumpet, PCB model	4½-ft Bb	Rudall Carte	London	c 1925	2.00	0.83
EU	3273	Cornet	4½-ft Bb	Conn	Elkhart	1924	2.01	0.80
RD	6488	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1928	2.01	0.79
EU	3737	Bayley's acoustic cornet	4½-ft Bb	Kohler	London	c 1865	2.09	0.80
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	2.29	0.67
EU	3344	Aïda trumpet	4½-ft B natural	Ad. Sax	Paris	c 1870	2.58	0.70
EU	3664	Flugelhorn	4½-ft Bb	Cerveny	Königgrätz	c 1900	2.62	0.67
EU	3592	Flugelhorn	4½-ft Bb	Besson & Co	London	c 1900	2.70	0.70
EU	907	Keyed bugle	4-ft C	Halari	Paris	c 1830	4.30	0.68

Figure 8.16: *Specimen instruments with a nominal pitch of 4-ft C or 4½-ft B♭ ranked by parameter* K.

Some of these (such as those by Rudall Carte) are rarer models of instrument which it is interesting to compare with common models. Considering only typical models, the values of K are as follows:

Cornopean	K = 1.13 - 1.23
Valve trumpet	K = 1.14 - 1.32
Cornet	K = 1.98 - 2.00
Flugelhorn	K = 2.62 - 2.70

This demonstrates the value of parameter K in distinguishing instrument types. Further use of the parameter is made in Chapter 9. Appendix H gives a further listing of instruments ranked by K.

8.5 Taxonomy of the distal half of the air column

The capacity to distinguish between cornets and trumpets which have similar bell profiles has been used in this study as a test of the usefulness of the parameter K. The capacity to distinguish between different trombone models which have similar (i.e. cylindrical) bore profiles for the proximal half of the air column has similarly been used in this study as a test of the usefulness of a parameter C used to characterize the distal half of the air column.

For early instruments there is often a clear division between the cylindrical part of the tubing and the expanding part, with one section of tube being made on a cylindrical mandrel and the adjoining section made on a tapered mandrel. However this is not the case for nineteenth- and twentieth-century instruments. To compare trombones of the nineteenth century with earlier models, it is not possible to use an *Anteilverhältnis* [Chapter 2 Section 2.2] since this ratio is no longer clearly defined. There are many instruments for which the transition from cylindrical bore to expanding is not well-defined, including all valve trombones. Gai (1984) attempted to distinguish between upright model valve trombones and 'flicorni tenore' (a brasswind type similar to a baritone saxhorn) by comparing the proportions of cylindrical tube, conical tube expanding at a rate of approximately 0.5%, conical tube expanding at a rate of approximately 1.0%, and bell section ("forma geometrica non facilmente determinabile"). Gai's approach succeeded in its immediate aim, but for wider use would be hampered by (a) use of external diameters rather than internal and (b) imprecision in determining where the division between the sections of the windway occur.

One of the most striking differences between early and modern trombones is that the tubing of the early trombone is cylindrical until the ferrule at the start of the bell-pipe, whereas the modern trombone tubing expands from the top of the main slide ascending bore. This expansion through the main tuning-slide at the bell bow is considered by makers to be important for the response and intonation of the instrument. In the modern trombone, there is also a wider bore, but even in the narrow-bore French model trombone of the nineteenth century and early twentieth century this earlier expansion is pronounced.

A parameter *C* can be defined with a view to characterizing the bore profile in this area of the instrument. The region of the bell has its own properties and has already been investigated, so it would seem to be worth while investigating the part of the bore just beyond the mid-point (which is near the top of the ascending bore of the main slide of the trombone). *C* is defined as the proportion of the overall length of the air column up to the point in the air column where the cross-sectional area is double that at the mid-point. This proportion is necessarily between 0.5 and 1.0.

For instruments measured by pulse reflectometry, this point in the windway can be directly located from the reconstruction. Otherwise, for portions of the tubing beyond the reach of, or outwith the range of, the rod gauges, measurements of the exterior diameter are made. At a point near the deepest insertion of the gauges, an estimate of the bell wall thickness is made. A further estimate can often be made at a tuning-slide or valve passage, and interpolated tube wall thicknesses are used to estimate the interior diameters at intermediate points.

Figure 8.17 gives for some instruments of comparable basic tube length and comparable normal tessitura the values of *C* (and also of *K*, discussed in Section 8.4 above):

		Instrument	Nom Pitch	Maker	Place	Date	*K*	*C*
EU	3753	Tenor trombone	9-ft Bb	Mitsching Alschausky	Germany	c 1935	1.00	0.76
JW	PQP	Tenorbass trombone	9-ft Bb	Penzel Nachfolger	Leipzig	c 1900	1.00	0.77
EU	3207	Tenor trombone	9-ft Bb	R. Schopper	Leipzig	c 1910	1.13	0.79
AM	171	Tenor trombone, 8H model	9-ft Bb	Conn	Elkhart	1978	1.28	0.78
EU	2695	Tenor trombone	9-ft Bb	Schnitzer	Nürnberg	1594	1.00	0.81
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	1.40	0.81
CRB	408	Tenor/bass trombone	9-ft Bb	Courtois	Paris	c 1903	1.18	0.81
BG	2011	O.T.S. tenor trombone	8-ft C	Van Engelen	Belgium	c 1840	1.00	0.81
BK	201	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1867	1.29	0.81
LG	1897	Tenor trombone	9-ft Bb	Ehe	Nürnberg	c 1720	1.02	0.82
EU	1770	Tenor trombone	9-ft Bb	G.H. Pace	London	c 1895	1.42	0.83
LG	4139	Tenorbass trombone	9-ft Bb	Sattler	Leipzig	1841	1.06	0.83
LG	1899	Tenor trombone	9-ft Bb	Eschenbach	Markneukirchen	1796	1.06	0.83
PC	711	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1850	1.21	0.83
LG	1896	Tenor trombone	9-ft Bb	Ehe	Nürnberg	1668	1.00	0.83
FT	94	Tenor valve trombone	8-ft C	Higham	Manchester	c 1865	1.01	0.84
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	1.08	0.84
EU	2991	Tenor trombone	9-ft Bb	Besson	London	c 1900	1.09	0.84
EU	3534	Tenor trombone	9-ft Bb	Riedlocker	Paris	c 1810	1.07	0.84
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	1.16	0.85
PC	2224	Tenor trombone	9-ft Bb	Halary	Paris	1837	1.06	0.85
EU	3738	O.T.S. tenor trombone, bell to front	9-ft Bb		France or Belgium (?)	e.19	1.00	0.85
EU	3747	Tenor trombone	9-ft Bb	Courtois	Paris	1865	1.02	0.85
EU	3738	O.T.S. tenor trombone, bell to rear	9-ft Bb		France or Belgium (?)	e.19	1.00	0.85
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	1.05	0.85
EU	3205	Tenor trombone	9-ft Bb	Huschauer	Vienna	1794	1.00	0.85
PC	1252	Tenor trombone	9-ft Bb	Courtois frères	Paris	pre 1845	1.06	0.85
LG	4138	Tenor trombone	9-ft Bb	Sattler	Leipzig	1841	1.25	0.86
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	1.04	0.86
FT	155	Tenor valve trombone	9-ft Bb	Higham	Manchester	c 1880	1.81	0.89

Figure 8.17: *Specimen instruments with a nominal pitch of 8-ft C or 9-ft B♭ ranked by parameter* C.

Some of these are rarer models of instrument which it is interesting to compare with common models. Considering only typical models, the values of C are as follows:

German model trombones	$C = 0.76 - 0.79$
American trombones	$C = 0.78$
French trombones	$C = 0.84 - 0.85$
Early trombones	$C = 0.81 - 0.88$

This demonstrates the value of parameter C in distinguishing instrument models. Further use of the parameter is made in Chapter 9. Appendix I gives a further listing of instruments ranked by C.

8.6 Taxonomy of the overall air column

The parameters defined above are derived from the minimum cross-sectional area, the cross-sectional area at the mid-point of the air column, and the position of the point in the air column where the cross-sectional area is double the latter.

The final (and maximum) cross-sectional area of the bore is the area of the bell mouth. This, however, has to be discounted as a taxonomically significant parameter on two grounds: firstly, the final portion of the bell of instruments with substantial flares has little acoustical significance (the exact diameter of a sousaphone bell is not critically important); secondly, the wavefronts in flared bells are not plane surfaces but are intermediate between plane and spherical surfaces (Benade and Jansson 1974). In the portions of the tube which are locally close to cylindrical, such as those used in defining K and C, the area of a wavefront is effectively the cross-sectional area of the tube. Determining a cross-sectional area near the distal end of the tube which can be of value in comparisons with the minimum and mid-point cross-sectional areas is not easy. For this reason in this study more attention has been given to the horn function (using a spherical wavefront approximation) in characterizing the final portion of the windway. It is shown in Appendix B that the position of the maximum value of the horn function is a well defined point near the distal end of the tube, and that the cross-sectional area at that point can be computed to an acceptable accuracy: nevertheless this area cannot necessarily be usefully compared with the areas in the portions of the tube with little flare.

Chapter 9

Synthesis of criteria

This chapter gives some case studies on instruments in museums and collections in which the capabilities and limitations of the methods of characterization previously developed are tested. Some conclusions can be drawn as to the possibility of making a detailed history of brasswind design presented in terms of the parameters discussed in Chapters 6, 7 and 8, and the evolution of instrument design since 1750 in terms of these characterization criteria is outlined.

9.1 Scaling of designs

When it is desired to make instruments in a range of sizes, such as alto, tenor and bass trombones or soprano, alto, tenor and baritone saxhorns, the maker needs to decide how to scale the dimensions. The pitch centres of the playable notes need to be scaled to give the correct pitch, so the effective cone length L_{EC} needs to be scaled so that

$$L_{EC} = \frac{c}{2f_1} \tag{9.1}$$

where f_1 is the frequency of the pedal note in the series of playable notes. For example, an alto trombone in E♭ with slide closed will have three-quarters of the effective tube length of a tenor trombone in B♭ with slide closed (the exact proportion may differ slightly from 0.75 depending on considerations of temperament). This applies in comparable settings of slide or valves.

To a first approximation, the overall tube length is scaled similarly, but effects of factors such as bore diameter, mouthpiece cup volume and bell flare properties on effective tube length will mean that the tube length is not necessarily scaled by such a simple formula. In practice makers will have had to adjust the tube length of a prototype empirically. The other factors such as cross-sectional area of minimum bore and mid-length bore and the mouthpiece and bell flare parameters may also need to be scaled, but it is not necessarily to be expected that they will vary in simple proportion to effective tube length. The factors discussed in Chapter 4 that are dependent on the player (lip and vocal tract) can only be changed within limits. The range of frequencies used by the human ear for pitch recognition do not change at all.

Extensive measurements of matched sets would be needed to establish scaling rules; examples of sets of museum instruments intended to be a family by the maker are rare or conjectural. Psychoacoustic assessment of the performance of different instruments, even if sounded by artificial lips to remove variations due to human players, is beyond the scope of this study, but would be of great value.

There is no reason why one type of instrument in (say) 9-ft B♭ should not sound indistinguishably like a different type of instrument in 6-ft E♭ with valves 1 and 3 operated or slide extended. For simplicity and consistency in making comparisons, the measurements for this study involving tube length (those for calculating *K* and *C*) have unless otherwise stated been made without any slides extended, keys opened or valves operated.

9.2 Case study: the saxhorn families

Adolphe Sax did a great service to taxonomy by marking many of his instruments with their model name, and requiring other makers who produced saxhorns in the period between the imposition of licensing in 1855 and the expiry of his patent in 1865 to do likewise. Thus included in this study are a number of instruments marked "SAXHORN BARYTON" or comparable name. Figure 9.1 gives values for the principal parameters for such saxhorns, and other instruments which are indubitably saxhorns.

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*	*C*	*Dpeak*	*Cutoff*
OB	x616	Soprano saxhorn	3¼-ft Eb	Ad. Sax	Paris	c 1870	13.70	1.84	0.66	90.3	1197
BK	115	Contralto saxhorn	4-ft C	Gautrot	Paris	1855-1860				90.8	1083
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	16.50	2.29	0.67	99.1	1168
BK	283	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870				95.5	1200
EU	887	Tenor saxhorn	6-ft F	Ad. Sax (?)	Paris (?)	c 1850	12.00	1.11	0.56	104.1	902
PC	1695	Tenor saxhorn	6½-ft Eb	Ad. Sax	Paris	c 1850				98.4	1137
EU	3352	Baryton	8-ft C	Aug. Courtois	Paris	c 1855	15.80	1.86	0.53		
OB	662	Baritone saxhorn	9-ft Bb	Ad. Sax	Paris	c 1865	16.80	1.99	0.73		
EU	3697	Baritone saxhorn	9-ft Bb	Besançon	Paris	c 1860	18.00	2.94	0.66		
EU	2711	Baritone	9-ft Bb	Higham	Manchester	c 1890	19.80	3.30	0.68		
EU	3812	Saxhorn basse	8-ft C	Fischer	Paris	c 1860	22.40	4.00	0.62		
EU	3115	Saxhorn nouveau basse	8-ft C	Ad. Sax	Paris	1867	24.60	4.35	0.64		
EU	2776	Euphonium	9-ft Bb	Higham	Manchester	c 1880	26.00	5.59	0.64	171.8	694
EU	2131	Tuba	12-ft F	Higham	Manchester	c 1910	38.00	9.86	0.63	200.7	668
EU	2109	Saxhorn contrebasse	13-ft Eb	A.C.	Paris	c 1860	32.70	6.33	0.62		
EU	3229	Saxhorn contrebasse	18-ft Bb	Ad. Sax	Paris	1867	45.00	10.33	0.65		

Figure 9.1: *Mid-length bore (millimetres), parameters* C *and* K, *bore at position of maximum horn function (millimetres), and cut-off frequency (Hz) for various saxhorns. Not all measurements were made for each instrument.*

This table includes data on several early saxhorns of Adolphe Sax's own manufacture, some made under licence from Sax (Gautrot, Besançon, Fischer and A.C.) and, for comparison, some typical English instruments by Higham. The fact that there are two distinct saxhorn families is immediately obvious from the values of *K*: from soprano down to baritone the proximal half of the bore is of moderate conicity, for the bass and contrabass it is markedly expanding. The parameter *C* remains low for all saxhorns, an indication that the bore expands rapidly from the mid-length point. The mid-length bore is wider and the parameter *K* is larger for the later instruments, indeed the proportions of the Higham baritone approach those of the Fischer instrument (which is inscribed "SAXHORN BASSE").

Given that there is considerable variety even in this small sample, it appears that parameters *C* and *K* are reasonably consistent for the two families of saxhorn. A considerably larger sample and a statistical analysis would be required to draw confident conclusions about the scaling of mid-length bore diameter and peak value of the horn function (or cut-off frequency) with tube length (or nominal pitch).

9.3 Case study: the trombone in different sizes

One matched set of trombones has been studied, the set dated 1814 of alto, tenor and bass formerly belonging to Reginald Morley-Pegge now in the Bate Collection, University of Oxford. In addition, a number of late nineteenth-century and early twentieth-century narrow-bore trombones, all either French or on the French model, have been measured. Figure 9.2 gives the parameter values for these two groups.

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*	*C*	*Dpeak*	*Cutoff*
OB	730	Alto trombone	6½-ft Eb		Germany	1814	9.50			68.3	1539
OB	731	Tenor trombone	9-ft Bb		Germany	1814	11.10		0.88	88.4	1264
OB	732	Bass trombone	12-ft F		Germany	1814	11.40		0.84	118.9	791
JW	PAC	Alto trombone	6½-ft Eb	Courtois / Mille	Paris	c 1880	10.60	1.19	0.83	73.0	1250
EU	521	Alto trombone	6½-ft Eb	Hawkes & Son	London	c 1900	10.90				
EU	1556	Alto trombone	6½-ft Eb	Boosey & Co	London	1885-6	11.50	1.13	0.82		
EU	2782	Alto trombone	6½-ft Eb	Besson & Co	London	c 1940	11.50			90.9	1043
LHC	85	Alto trombone	6½-ft Eb	F. Besson	London	1.19	11.60			69.6	1430
LHC	171	Alto trombone	7½-ft Db	Courtois	Paris	c 1850	11.50			90.8	990
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	11.40	1.16	0.85	89.6	916
EU	3747	Tenor trombone	9-ft Bb	Courtois	Paris	1865	11.40	1.02	0.85		
CRB	408	Tenor/bass trombone	9-ft Bb	Courtois	Paris	c 1903	11.40	1.18	0.81		
EU	1770	Tenor trombone	9-ft Bb	G.H. Pace	London	c 1895	11.45	1.42	0.83		
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	11.50	1.05	0.85	89.9	1086
EU	2991	Tenor trombone	9-ft Bb	Besson	London	c 1900	11.60	1.09	0.84		
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	11.68	1.04	0.86	90.1	988
EU	581	Bass trombone	11-ft G	Courtois	Paris	c 1869	11.80			107.7	854
JW	PLR	Bass trombone, double slide	11-ft G	Rudall Carte	London	c 1880	12.34	1.01	0.80	108.1	972
EU	519	Bass trombone	11-ft G	Besson	London	c 1890	12.35	1.08	0.75		
PC	630	Bass trombone	11-ft G	Courtois	Paris	post 1872	12.35	1.16	0.80		
EU	2702	Bass trombone	11-ft G	Hawkes & Son	London	c 1900	12.40			102.5	1000
CRB	410	Contrabass trombone	16-ft C	Thibouville-Lamy	Paris	c 1900	12.90	1.79	0.86		
BK	234	Contrabass trombone	18-ft Bb	Courtois	Paris	c 1895	11.90	1.13	0.79	133.5	814

Figure 9.2: *Mid-length bore (millimetres), parameters* C *and* K*, bore at position of maximum horn function (millimetres), and cut-off frequency (Hz) for various trombones.*

Regrettably the 1814 alto no longer has all its original slide tubing, so parameters *C* and *K* cannot be obtained.

The average mid-length bore is for E♭ altos 11.22mm, for B♭ tenors 11.49mm, for G basses 12.24mm, for contrabasses 12.40mm. This suggests that there is no simple rule for scaling bore diameter for different sizes of instrument. Again, a larger sample might give a clearer picture.

9.4 Case study: the early history of the modern trombone

The period from 1750 to 1850 when the old form of trombone gave way to the standard late-nineteenth century German and French models is not presented clearly in the literature of the instrument. The values of the parameters discussed in Chapters 6 and 8 and bore size can be plotted against time in an attempt to chart the development of the trombone in the period of transition (Figures 9.3, 9.4, and 9.5)

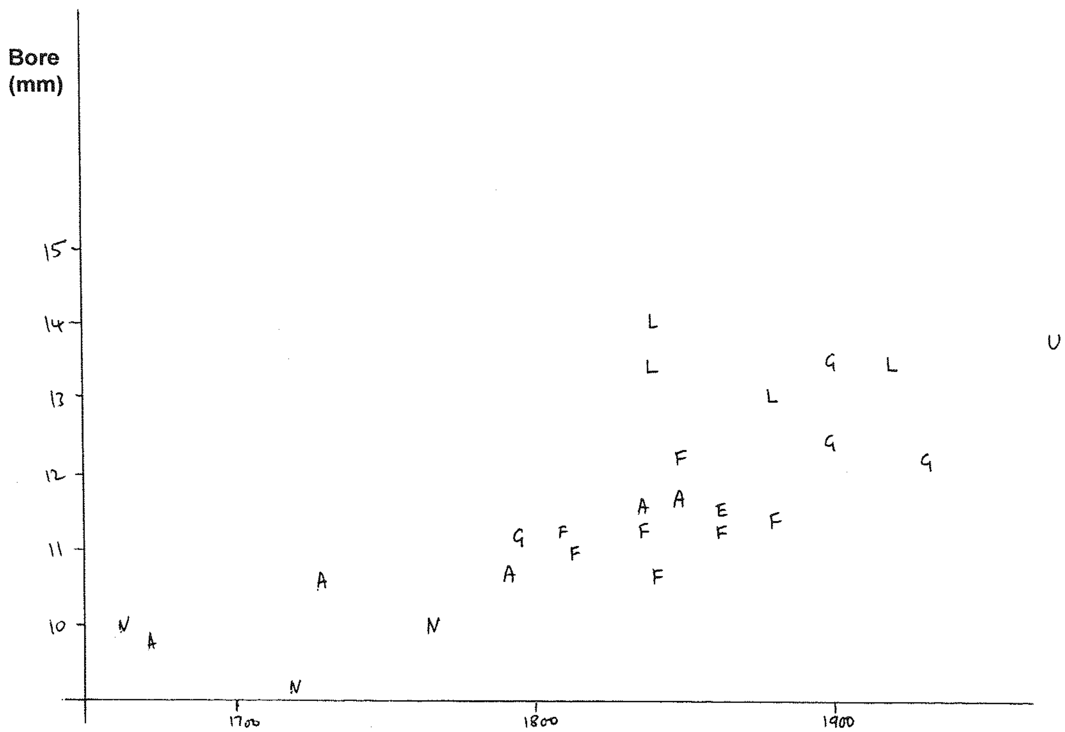


Figure 9.3: *Mid-length bore diameter (millimetres) plotted against date for various trombones. Places of manufacture are coded A = Austria, B = Belgium, E = England, G = Germany (L = Leipzig, N = Nuremberg), U = U.S.A.).*

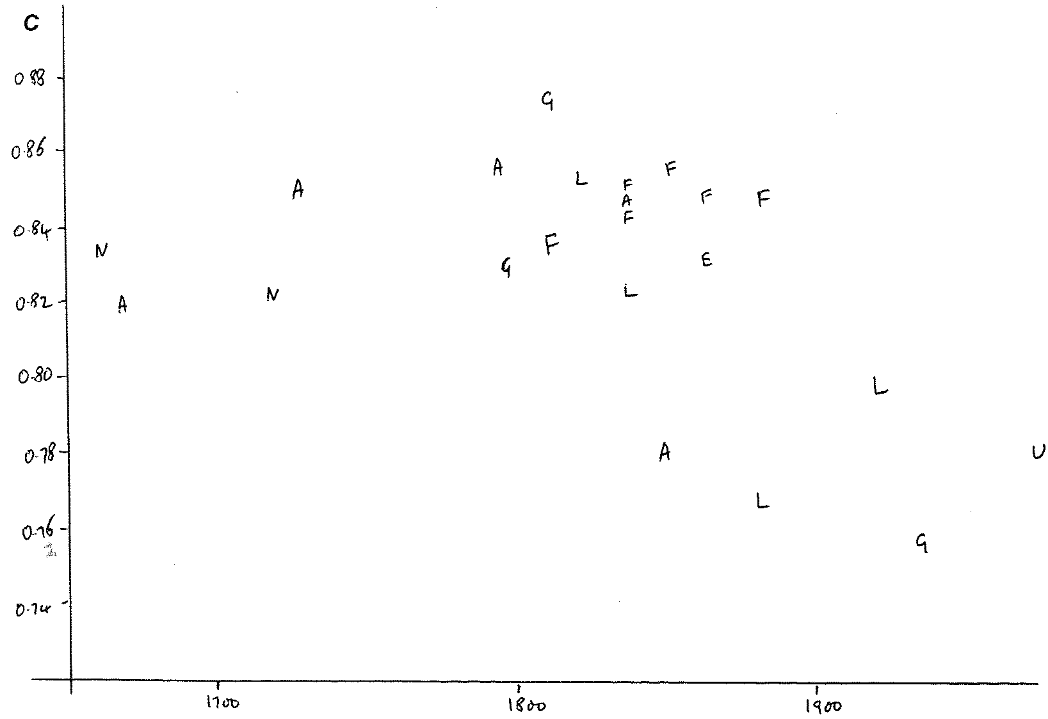


Figure 9.4: *Parameter* C *plotted against date for various trombones. Places of manufacture are coded A = Austria, B = Belgium, E = England, G = Germany (L = Leipzig, N = Nuremberg), U = U.S.A.).*

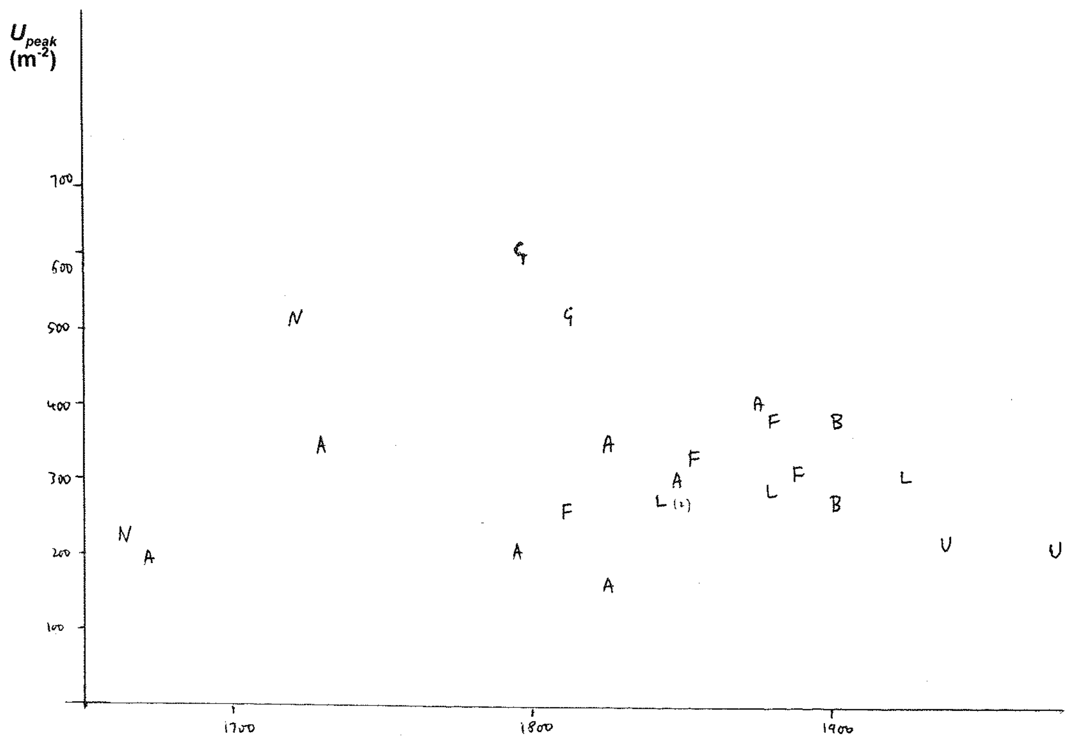


Figure 9.5: *Maximum horn function value (m^{-2}) plotted against date for various trombones. Places of manufacture are coded A = Austria, B = Belgium, E = England, G = Germany (L = Leipzig, N = Nuremberg), U = U.S.A.).*

Early and modern trombones are based on fairly well-established models. The period of transition, however, appears to be characterized by wide variation in design rather than an orderly process of evolution from old to new. The bore diameter (the parameter most familiar to players) increases slightly from the early trombone to the French model discussed in Section 9.3 above, and more markedly to the German and American models. Parameter *C* and the cut-off frequency show wide variations before settling into recognisable ranges for French and German model instruments. A larger sample would allow conclusions to be drawn with more confidence; however, the use of parameter *C* and the cut-off frequency in addition to bore size already allows some interesting views to be given of this pilot sample.

9.5 Case study: valve trombone and bass trumpet

One of the least obvious distinctions between recognised instrument classes is that between tenor valve trombone and bass valve trumpet, both being conventionally regarded as 'cylindrical-bore' and both standing in 8-ft C or 9-ft B♭. The continuing existence of both types and subjective experience attest to a perceptible difference in response between tenor valve trombone and bass valve trumpet, though both have been made in a variety of models. Baines (1976) recognises two models of bass trumpet, those of the makers Moritz and Alexander, the latter now being the normal orchestral model. The mid-length bore, parameters *C* and *K*, the bore at position of maximum horn function, and the cut-off frequency for several specimens have been assembled in Figure 9.6.

Figure 9.6 ***[overleaf]***: *Mid-length bore (millimetres), parameters* C *and* K, *bore at position of maximum horn function (millimetres), and cut-off frequency (Hz) for various bass trumpets and tenor valve trombones.*

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*	*C*	*Dpeak*	*Cutoff*
WAG	1	Bass trumpet	8-ft C	Alexander	Mainz	c 1985	12.00	1.31	0.82	88.8	1029
EU	229	Bass trumpet	9-ft Bb		Germany (?)	c 1900	14.40	1.60	0.72		
EU	2858	Bass trumpet	9-ft Bb	Cerveny	Königgrätz	c 1900	14.90	1.65	0.72	110.7	1158
EU	3257	Bass trumpet	9-ft Bb	Conn	Elkhart	1929-30	12.20	1.90	0.83	95.5	906
FT	94	Tenor valve trombone	8-ft C	Higham	Manchester	c 1865	11.50	1.01	0.84		
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	12.00	1.08	0.84	92.8	1003
PC	711	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1850	12.42	1.21	0.83		
BK	201	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1867	12.70	1.29	0.81		
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	14.20	1.40	0.81	106.0	1108
FT	155	Tenor valve trombone	9-ft Bb	Higham	Manchester	c 1880	15.13	1.81	0.89		
EU	2931	Tenor trombone, 6-valve model	9-ft Bb	Persy	Brussels	c 1910				88.7	1002
BG	2010	Tenor trombone, valve-slide model	9-ft Bb	Besson		l.19				92.4	1013
OB	x702	Valve trombone	8-ft C	Halary	Paris	m.19				107.1	1034
TRM	715	Valve trombone	9-ft Bb	Buescher	Paris	c 1900				92.3	925
FT	191	Valve trombone	9-ft Bb	Le Brun	Brussels	c 1919				91.8	1089
LHC	313	Valve trombone, upright model	9-ft Bb	Besson	Paris	m.19				97.6	1060

Of these, the Alexander bass trumpet is distinguished by a higher value of parameter *C* than for typical German trombones; it is also normally used with a mouthpiece of smaller cup volume than average for a trombone. The Conn bass trumpet is built to receive a mouthpiece with a trumpet shank, hence the higher value of *K*. EUCHMI 229 and the Cerveny bass trumpets appear to be Moritz model instruments, with both higher values of *K* than most valve trombones and lower values of *C*. The valve trombones themselves show considerable variety in bore profile, some having low values of *K* like slide trombones, others being noticeably conical in the proximal half of the windway.

It is not possible to make a universal distinction between tenor valve trombones and bass valve trumpets, the differences between the various models of each being of the same order of magnitude as the differences between the two types.

9.6 Case study: Wagner tuba and cornophone

Given the historic use of cornophones to play Wagner tuba parts, it is interesting to compare examples of the two instruments to see how they differ. The following table gives a comparison of a Wagner tuba in B♭ by Alexander, Mainz, c 1930 with a cornophone basse in C by Besson, Paris, c 1890.

Instrument	**Wagner tuba**	**Cornophone basse**
Diameter of mouthpiece receiver	8.3mm	8.5mm
Minimum bore diameter	7.7mm	7.3mm
Mid-length bore diameter	21.7mm	20.0mm
Bore at position of maximum horn function	167mm	149mm
Bell diameter	236mm	200mm
Tube length	2758mm	2471mm
K	7.94	7.51
C	0.65	0.63
Maximum horn function value	161 m^{-2}	233 m^{-2}
Cut-off frequency	697 Hz	838 Hz

Figure 9.7: *Comparison of a Wagner tuba in 9-ft B♭ (EUCHMI 2515) with a cornophone basse in 8-ft C (EUCHMI 3758).*

Thus the bore profiles of the two instruments are remarkably similar for the proximal 65% of the air column length. The bell flare of the cornophone is more acute than that of the Wagner tuba: the maximum value of the horn function is higher and as a result the cut-off frequency is 320 cents higher. Simple playing tests of the two instruments (the comparison is facilitated by operating the 1st valve of the cornophone so that it sounds the B♭ series) confirm that the overall tone quality and response to the player is very similar, but the cornophone is perceptibly brighter. In situations where French-model instruments were being used orchestrally, the slightly brighter sound of the cornophone might well have balanced better with the other wind instruments than the German-model Wagner tuba would have done.

9.7 The evolution of instrument design since 1750

Given the complexity shown in Section 9.4 by the evolution of a single instrument, the trombone, it is not to be expected that a simple picture can emerge for the evolution of brasswind in general. Nevertheless an overview can be given, drawing data from Appendices C, H, and I, which could be developed into a treatment comparable to that of Benade (1994) for woodwinds. As we saw in Section 1.3, not only did the invention of valves revolutionise horn and trumpet technique, but it also permitted the development of new kinds of brass instrument.

The natural trumpet and the trombone before 1750 have no significant leadpipe taper and with their considerable lengths of cylindrical tubing have values of *K* very little over 1 and high values of *C*, over 0.8. Trumpets may have tended to have a higher cut-off frequency than trombones of the same nominal pitch, but the difference was probably mostly in mouthpiece design. French horns with their approximately conical bore profile for much of their length had values of *K* between 2 and 4.5, values of *C* between 0.7 and 0.8, and very low cut-off frequencies. The cornett and serpent had almost purely conical bore profiles and no bell flare at all.

The use of keys for the keyed bugle and ophicleide allowed a 'conical' bore profile with higher values of *K* and lower values of *C*. With valves, instrument makers had complete freedom to introduce instruments with any bore profile that resulted in an instrument that was acceptably in tune with itself. In the course of the nineteenth century the adoption of the valve led to a proliferation of viable bore profiles for acceptable brass instruments. This variety was also exhibited in the trombone. A new instrument, the cornet, had fairly low values of both K and C; other new instruments such as the smaller saxhorns were characterized by very low values of K and C, a bore profile with a marked expansion around the mid-length point which was not known in any pre-nineteenth century brasswind. The larger saxhorns and the tuba were also radical developments, with lower values of K than the ophicleide.

The established repertoire for existing instrument types such as the horn and trumpet required instrument designs capable of performing this repertoire, with sufficient performance characteristics remaining intact through each design development. Thus these instruments have changed gradually to meet the requirements for higher dynamic levels and performance safety. However, the largely new repertoire for the trombone and the necessarily innovative repertoire for newly invented instruments gave rise to an apparent chaos in brasswind design in the nineteenth century from which the present-day instruments have emerged by a process of 'survival of the fittest'.

The parameters developed in this study would enable classification schemes to be created to meet museum and other needs which could use well-defined categories based on practicable (though labour-intensive) measurements. Figure 9.8 shows one possible classification. However, the inventiveness of instrument makers has been such that no taxonomic system is likely to present in a simple structure the full diversity of brasswind design.

- $1 \leq K \leq 1.5$
  - $1 \geq C \geq 0.8$
    - $V \leq 2500$ — *natural, slide and early valve trumpets*
    - $2500 \leq V$ — *German model and modern trombones*
  - $0.8 \geq C \geq 0.5$
    - $V \leq 2500$ — *cornopeans, modern valve trumpets*
    - $2500 \leq V$ — *early and French model trombones*

- $1.5 \leq K \leq 2.2$
  - $0.8 \geq C \geq 0.5$
    - $D_{mid} \leq 12.5$ — *cornets*
    - $12.5 \leq D_{mid}$ — *higher saxhorns*

- $2.2 \leq K \leq 4$
  - $0.8 \geq C \geq 0.7$
    - $L \leq 1500$ — *flugelhorns*
    - $1500 \leq L$ — *french horns*

- $2.5 \leq K$
  - $1 \geq C \geq 0.6$
    - $V \leq 4500$
      - $L \leq 1500$
        - $D_{mid} \leq 20$ — *cornetts*
        - $20 \leq D_{mid}$ — *keyed bugles*
      - $1500 \leq L$ — *wagner tubas*
    - $4500 \leq V$ — *lower saxhorns, tubas*
  - $0.6 \geq C \geq 0.5$
    - $U_{peak} \leq 100$ — *serpents*
    - $100 \leq U_{peak}$ — *ophicleides*

Figure 9.8: *A classification scheme based on measurable parameters.* K *and* C *are as defined in Chapter 8,* V *is the mouthpiece cup volume as defined in Equation 7.2,* D_{mid} *is the bore diameter in millimetres at the point mid-way between the two ends of the overall air column,* L *is the overall air column length in millimetres (without extending a slide, operating valves or opening tone-holes), and* U_{peak} *is the maximum horn function value in* m^{-2} *calculated as described in Chapter 6. This scheme is not suggested for use in any situation - it is given to demonstrate feasibility.*

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Appendix A

Brass Instruments sold by Henry Distin, 1857

This table lists the varieties of brass instrument offered by Henry Distin, maker of and dealer in military and brass band instruments in London, in 1857. The information is extracted from an illustrated trade catalogue in the National Library of Scotland.

Alto chromatic horn in B♭
Alto flügel horn in C, 3 valves
Alto flügel horn in C, 4 valves
Alto flügel horn in B♭, 3 valves
Alto flügel horn in B♭, 4 valves
Alto slide trombone in F
Alto slide trombone in E♭
Alto trombone in F, 3 valves
Alto trombone in E♭, 3 valves
Alto tuba in B♭
Appello trumpet in F, 3 valves
Baritone chromatic horn in B♭
Baritone tuba in C, 3 valves
Baritone tuba in C, 4 valves
Baritone tuba in B♭, 3 valves
Bass euphonion in C, 4 valves
Bass euphonion in B♭, 4 valves
Bass piston trombone in G, 3 valves
Bass slide trombone in G
Bass slide trombone in F
Bass trombone tuba in G, 3 valves
Bass trombone tuba in F, 3 valves
Bass tuba in C, 3 valves
Bass tuba in C, 4 valves
Bass tuba in B , 3 valves
Bass tuba in B♭, 4 valves
Brussels model cornet in B♭, 4 crooks
Cavalry appello trumpet
Cavalry trumpet
Cologne model rotary cornet in B♭, 4 crooks
Contrabass in F, 4 valves
Contrabass in E♭, 3 valves
Contrabass in E♭, 4 valves
Cornet, bell reversed, in B♭, 4 crooks
Distin's amateur cornet in B♭, 4 crooks
Distin's improved portable field bugle in C
Distin's military cornet in B♭, 4 crooks
Distin's new cornet in B♭, 4 crooks
Distin's new model regulation bugle in C
Distin's patent 6 keyed cylinder ophicleide in C

Distin's piccolo cornet in C, 5 crooks
Double-turned portable post horn in A
French horn, 0 valves and 10 crooks
French horn, 2 valves and 10 crooks
French horn, 3 valves and 10 crooks
Hunting horn (short) for the saddle
Hunting horn (single turn)
Mail horn in A
Military french horn in G, 3 valves and 5 crooks
Ophicleide in C, 13 keys
Ophicleide in B♭, 13 keys
Ordinary valved cornet in B♭, 4 crooks
Perinet model cornet in B♭, 4 crooks
Perpendicular rotary cornet in B♭, 4 crooks
Piccolino soprano in A♭, 4 valves
Piccolo soprano in E♭
Piccolo soprano cornet in E♭
Portable alto chromatic horn in B♭
Post horn in A
Soprano chromatic horn in E♭
Soprano chromatic tuba in E♭
Soprano flügel horn in E♭
Tenor chromatic horn in F
Tenor chromatic horn in E♭
Tenor cylinder trombone in B♭, 3 valves
Tenor flügel horn in F, 3 valves
Tenor flügel horn in F, 4 valves
Tenor slide trombone in C
Tenor slide trombone in B♭
Tenor trombone tuba in C, 3 valves
Tenor trombone tuba in B♭, 3 valves
Tenor piston tuba in B♭, 3 valves
Tenor tuba in F
Tenor tuba in E♭
Trumpet in F, 3 valves
Trumpet in E♭, 3 valves

Appendix B

Instruments ranked by peak horn function value

This table lists the peak horn function values of selected instruments in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Nominal pitch**, **Maker**, **Place** and **Date**

Specimens have been sought which are recognized types, typical of their place and period and which have survived without significant modification. Further information on these instruments is in many cases given in the catalogues of the respective museums and in other appendices to this study.

$z_{peak} - z_0$, D_{peak}

These respectively are the position of the maximum horn function value relative to the distal end of the instrument, and the diameter of the bell at the point of maximum horn function value, both given in millimetres.

U_{peak}

This is the maximum horn function value calculated as described in Chapter 6, given in m^{-2}.

The principal sources of inaccuracy in arriving at these values are:

1. Errors in measurement of objects which can be deformed and damaged
2. Errors introduced by the selection of the portion of the bell flare to be modelled
3. Errors introduced by the selection of the distance z_0 between the end of the bell and the origin of co-ordinates
4. Errors arising from imperfect fit of a Bessel horn to the selected portion of the bore profile

The measurements of bell flares used as the basis for computations of horn function parameters are subject to some spread, especially when dealing with bells which have the deformations which are frequently found in historic instruments. The process of making a least-squares fit reduces the effect of these on the calculated values; however, it is necessary to state the expected accuracy of the resulting quantities. A further source of error is introduced by the process of selecting the portion of the flare to be modelled as a Bessel horn, so it is also necessary to calculate the variation which occurs if a different portion of the bell flare is selected (but one which also includes the peak of the horn function value). If the bore profile of the bell of an instrument were an *exact* Bessel horn, then selecting any portion of the flare would give the same results: the further a bell departs from a Bessel horn the more critical it becomes to model the portion of highest horn function value. For some instruments studied the value of chi-square (χ^2) for the best fit of Bessel horn to eleven points exceeded a 10; no further attempt was made to compute the horn function for these instruments.

As an example of an instrument with a low maximum value of horn function, the bell flare of a Wagner tuba in 9-ft B♭ (EUCHMI 2515) can be modelled by a Bessel horn with characteristic radius R_F = 66.15mm and dimensionless 'flare parameter' α = 0.436; this Bessel horn has a maximum horn function value of 161 m^{-2}, equivalent to a cut-off frequency of 697 Hz (assuming c = 345 ms^{-1}). The maximum horn function occurs at 39mm from the asymptotic plane, 21mm from the actual end of the instrument. This is derived from a least-squares fit to eleven measured points, the depths of insertion z of eleven rods measuring diameters ranging from 221.4mm down to 81.45mm with the depths and diameters logarithmically transformed; the distance of the asymptotic plane from the actual end of the instrument z_0 is chosen to give a minimum value of χ^2, in this case 2.515.

The depths of insertion are measured to the nearest 1mm: if the depth of insertion of the first rod (221.4mm) is taken as 3mm instead of the actual 2mm, it is found that the bell flare can be modelled by a Bessel horn with characteristic radius R_F = 65.81mm and dimensionless 'flare parameter' α = 0.431; this Bessel horn has a maximum horn function value of 164 m^{-2}, equivalent to a cut-off frequency of 703 Hz. The maximum horn function occurs at 38mm from the asymptotic plane, 21mm from the actual end of the instrument. The minimum value of χ^2 is now 2.521. Thus an error in the measurement of one point of 1mm here increases the computed peak value of the horn function by 1.55% and increases the computed cut-off frequency by 0.75% or 14 cents. The position of the peak relative to the end of the instrument is changed less than 1mm.

If a different portion of the bell flare is modelled, using eleven rods measuring diameters ranging from 200.3mm down to 73.70mm, it is found that the bell flare can be modelled by a Bessel horn with characteristic radius R_F = 68.25mm and dimensionless 'flare parameter' α = 0.478; this Bessel horn has a maximum horn function value of 147 m^{-2}, equivalent to a cut-off frequency of 665 Hz. The maximum horn function occurs at 44mm from the asymptotic plane, 20mm from the actual end of the instrument. The minimum value of χ^2 is now 5.072. The portion of the bell flare modelled still includes the location of peak value of the horn function, but less of the flare immediately beyond. This change lowers the computed peak value of the horn function by 9.1% and lowers the computed cut-off frequency by 4.65% or 83 cents. The position of the peak relative to the end of the instrument is changed by very nearly 1mm. For the purposes of this study, fits of Bessel horns to bell flares have been based on eleven measured points, with the greatest rod length (tube diameter) *e* (2.718) times the smallest length (diameter). The portion of the flare modelled has been chosen so that the horn function value and the two ends is as far as possible equal; in cases where the peak falls near the end of the bell this is not possible, and the set of eleven measurements closest to the end of the bell has had to be used.

As an example of an instrument with a high maximum value of horn function, the bell flare of "Handelian" trumpet in 4½-ft B♭ (CRB 326) can be modelled by a Bessel horn with characteristic radius R_F = 31.09mm and dimensionless 'flare parameter' α = 0.5809; this Bessel horn has a maximum horn function value of 680 m^{-2}, equivalent to a cut-off frequency of 1432 Hz. The maximum horn function occurs at 24mm from the asymptotic plane, 12.5mm from the actual end of the instrument. This is derived from a least-squares fit to eleven measured points, the depths of insertion z of eleven rods measuring diameters ranging from 90.17mm down to 33.12mm with the depths and diameters logarithmically transformed; The distance of the asymptotic plane from the actual end of the instrument z_0 is chosen to give a minimum value of χ^2, in this case 0.654.

If the depth of insertion of the third rod (73.70mm) is taken as 12.5mm instead of the actual 11.5mm, it is found that the bell flare can be modelled by a Bessel horn with characteristic radius R_F = 31.13mm and dimensionless 'flare parameter' α = 0.5840; this Bessel horn has a maximum horn function value of 678 m^{-2}, equivalent to a cut-off frequency of 1430 Hz. The maximum horn function occurs at 24.5mm from the asymptotic plane, 12.5mm from the actual end of the instrument. The minimum value of χ^2 is now 1.346. Thus an error in the measurement of one point of 1mm here lowers the computed peak value of the horn function by 0.29% and lowers the computed cut-off frequency by 0.15% or 2 cents. The position of the peak relative to the end of the instrument is hardly changed.

If a different portion of the bell flare is modelled, using eleven rods measuring diameters ranging from 99.48mm down to 81.45mm, it is found that the bell flare can be modelled by a Bessel horn with characteristic radius R_F = 31.87mm and dimensionless 'flare parameter' α = 0.6112; this Bessel horn has a maximum horn function value of 646 m^{-2}, equivalent to a cut-off frequency of 1395 Hz. The maximum horn function occurs at 26mm from the asymptotic plane, 12mm from the actual end of the instrument. The minimum value of χ^2 is now 1.046. The portion of the bell flare modelled still includes the location of peak value of the horn function, but less of the flare immediately before. This change lowers the computed peak value of the horn function by 5.02% and lowers the computed cut-off frequency by 2.58% or 45 cents. The position of the peak relative to the end of the instrument is changed by less than 0.5mm.

The presence of small imprecisions in measurement thus limits the accuracy of the resulting horn function values; however the cumulative effect of random imprecisions in measurements will tend to be mitigated by the process of least-squares curve fitting. If (as an extreme example) the depths of insertion of **all** the rods were over-estimated by 1mm, then the best fit (lowest χ^2) would be given by a Bessel horn with a distance of the asymptotic plane from the actual end of the instrument z_0 exactly 1mm greater and there would be zero error in the horn function values resulting from these over-estimates.

Without more detailed statistical analysis, it appears to be the case that the peak value of the horn function can be computed to an accuracy of better than $\pm$ 10% and the cut-off frequency can be given to an accuracy $\pm$ 5% (in terms of pitch, better than one semitone).

The position of the peak horn function value relative to the end of the instrument (z_{PEAK} - z_0) shows very little variation with error, and the diameter (or cross sectional area) of the bell at this point could be considered as a candidate taxonomic parameter. In the example of the Wagner tuba considered above, the maximum horn function occurs 21mm from the actual end of the instrument. At this point, the cross-sectional area (computed from the best-fit Bessel horn) is 21650 mm^2; since (z_{PEAK} - z_0) can be given to an accuracy better than $\pm$ 1mm, the cross-sectional area of this gentle flare at this point can be given to an accuracy of better than $\pm$ 2.3%.

In the example of the valved trumpet considered above, the maximum horn function occurs 12.5mm from the actual end of the instrument. At this point, the cross-sectional area (computed from the best-fit Bessel horn) is 4000 mm^2; again, since (z_{PEAK} - z_0) can be given to an accuracy better than $\pm$ 1mm, the cross-sectional area of this more acute flare at this point can be given to an accuracy of better than $\pm$ 5%.

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
EU	2589	Piccolo trumpet	2¼-ft Bb	J. Monke	Köln	c 1960	10.1	54.8	1601
RD	6488	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1928	17.2	59.9	1370
WGDM	183	Trompete	7-ft D	Ehe	Nürnberg	1747	22.7	59.4	1349
EU	598	Field trumpet	5½-ft G	Rexcraft	USA	c 1950	13.2	63.0	1186
WSAM	252	Trompete	7-ft D	Geyer	Wien		10.1	67.6	1115
LG	1867	Buchsentrompete	7-ft D	Buchschwender	Ellwangen	c 1730	19.9	64.9	1105
EU	3460	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1927	15.1	61.2	1062
WSAM	251	Trompete	7-ft D	Hainlein	Nürnberg	1689	13.5	66.5	995
BK	327	Piccolo cornet	2-ft C		France (?)	c 1900	9.8	55.1	958
WSAM	599	Trompete	7-ft D	Leichamschneider	Wien		13.4	65.1	948
JW	TMW	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1925	16.7	62.2	888
LG	1884	Alto trombone	6½-ft Eb	Stark	Nürnberg	1690	12.5	62.7	857
PC	728	Valve trumpet	6-ft F	Alphonse Sax	Paris	c 1865	13.8	69.5	855
WGDM	198	Alt Posaune	6½-ft Eb	Schmidt	Nürnberg	1675	16.0	60.8	835
EU	3284	Natural trumpet	6½-ft Eb		England (?)	e.18	10.2	72.4	830
LHC	74	Post horn	3½-ft D			19	17.4	53.5	808
OB	730	Alto trombone	6½-ft Eb		Germany	1814	17.6	68.3	786
LHC	95	Keyed trumpet	5½-ft G			e.19	13.2	82.7	755
EU	2321	Valve and slide trumpet	6-ft F	Mahillon	Brussels	c 1885	15.3	67.3	750
JW	CLK	Cornet	4½-ft Bb	Kohler	London	c 1865	12.4	71.9	717
LG	4070	Inventionstrompete	6-ft F	Heckel	Dresden	1836-1837	19.3	69.4	692
LG	4137	Alto trombone	6½-ft Eb	Sattler	Leipzig	1841	16.8	71.6	692
EU	1671	Post horn	4½-ft Bb			c 1900	9.2	71.1	691
LHC	187	Bayley's acoustic cornet	4½-ft Bb	Kohler	London	c 1865	11.2	73.1	684
LHC	290	Valve trumpet	6-ft F	Pace	London	c 1840	11.9	72.3	680
LHC	85	Alto trombone	6½-ft Eb	F. Besson	London	l.19	16.4	69.6	679
OB	712	Valve trumpet	7-ft D	Pace	London	c 1835	10.7	88.8	675
AM	1095	Trompette de cavalerie	6½-ft Eb	Couesnon	Paris	m.20	22.2	60.9	668
EU	3233	Trumpet	3½-ft D	Besson	London	c 1944	17.1	64.7	666
EU	1860	Cornet	4½-ft Bb	Kohler	London	c 1860	20.3	67.8	665
EU	3246	Soprano flugelhorn	3¼-ft Eb	Besson	London	c 1870	14.4	71.9	660

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
BK	270	Trompette demilune	6-ft F			e.19	12.0	77.9	659
LC	TR59	Soprano cornet	3¼-ft Eb	Courtois	Paris	c 1890	16.8	60.4	657
FT	205	Albion cornopean	4½-ft Bb	Pace	London	c 1850	11.4	75.4	652
CRB	326	Valve trumpet, `Handelian' model	4½-ft Bb	Kohler	London	c 1895	12.2	71.9	646
OB	711	Trumpet, PCB model	4½-ft Bb	Rudall Carte	London	c 1925	15.2	69.0	635
LHC	150	Valve trumpet	4½-ft Bb	Sandbach & Wyatt	London	c 1835	14.6	75.9	634
EU	2704	Cornet	4½-ft Bb	Boosey & Co	London	c 1922	15.3	69.0	633
JW	CMT	Pocket cornet	4½-ft Bb	Thibouville-Lamy	Paris	e.20	0.3	68.5	627
LHC	244	Natural trumpet	7-ft D	Hass	Nürnberg	l.17	11.0	80.2	625
OB	x70	Slide trumpet	6-ft F	Harris	London	18	14.7	69.8	620
BK	107	Sudrophone cornet	4½-ft Bb	F. Sudre	Paris	l.19	11.1	68.5	617
EU	3247	Trumpet	7-ft D	Huschauer	Wien	1794	16.2	69.5	615
LC	TR56	Piccolo trumept	2¼-ft Bb	Couesnon	Paris	c 1935	18.7	55.6	615
LG	1899	Tenor trombone	9-ft Bb	Eschenbach	Markneukirchen	1796	17.6	82.6	610
EU	3280	Natural trumpet	6½-ft Eb	Hofmaster	London	c 1760	11.4	73.6	608
GS	2	Natural trumpet	7-ft D	Huschauer	Wien	1806	14.5	72.4	605
EU	2337	Trumpet	4½-ft Bb		Czechoslovakia	c 1935	13.8	72.3	603
LHC	100	Coiled trumpet	6½-ft Eb			19	15.1	72.2	599
EU	3282	Natural trumpet	6½-ft Eb	Winkings	London	m.18	18.3	66.8	588
EU	1299	Straight trumpet	3¼-ft Eb	Hawkes & Son	London	c 1916	20.2	64.0	583
EU	220	Cornet	4½-ft Bb	Rudall, Rose & Carte	London	c 1865	18.1	70.2	573
FT	108	Valve trumpet	5½-ft G	Besson		c 1865	17.8	68.8	570
FT	52	Cornophone cornettito	4½-ft Bb	Besson	London	c 1900	15.6	65.7	567
DB	7	Marching trumpet	5½-ft G	Dynasty	USA	c 1980	18.2	69.0	564
BG	1987	Soprano cornet	3¼-ft Eb	Uhlmann	Vienna	c 1870	12.0	79.8	564
LHC	76	Valve trumpet	6-ft F	Pace	London	c 1840	15.7	70.3	555
OB	71	Trompette demilune	5½-ft G	Guichard	Paris	e.19	19.3	76.2	554
EU	2460	Cornet	4½-ft Bb	Courtois	Paris	1856-1858	20.6	68.2	553
JW	BFG	Flugelhorn	4½-ft Bb	Gisborne	Birmingham	1845	16.9	83.0	544
BG	2007	Alto trombone	6-ft F		England (?)	m.19	16.5	79.9	543
EU	2975	Slide trumpet	6-ft F	Kohler	London	c 1850	15.6	69.3	537

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
BK	1	Soprano cornet	3-ft F	Ad. Sax	Paris	c 1850	19.1	59.6	536
OB	731	Tenor trombone	9-ft Bb		Germany	1814	16.2	88.4	530
EU	2779	Flugelhorn	4½-ft Bb	Kohlert	Winneneden	m.20	12.0	102.0	522
JW	PAC	Alto trombone	6½-ft Eb	Courtois / Mille	Paris	c 1880	20.5	73.0	519
LHC	239	Bugle horn	6-ft F	Fürst	Ellwang	1770	21.2	79.7	517
LG	1897	Tenor trombone	9-ft Bb	Ehe	Nürnberg	c 1720	19.4	80.9	516
MB	5169	PCB cornet	4½-ft Bb	Rudall Carte	London	c 1905	19.7	66.7	514
EU	619	Cornet, PCB model	4½-ft Bb	Rudall Carte	London	1905	18.9	68.5	513
BG	1984	Post horn, 2-valve	6½-ft Eb		Germany (?)	m.19	14.6	74.8	511
JW	CEC	Cornet	4½-ft Bb	Courtois	Paris	c 1855	25.4	64.4	505
LHC	34	Cornet, circular model	4½-ft Bb	Distin	London	c 1855	14.4	67.8	505
FT	178	Valve trumpet	6-ft F	Courtois	Paris	c 1885	20.1	73.3	502
OB	647	Soprano cornet	3¼-ft Eb	H. Distin	London	c 1860	22.4	64.1	495
BK	385	Trompette demilune	5½-ft G	Kretzschmann	Strasbourg	e.19	13.9	78.4	495
LG	1829	Inventionstrompete	6-ft F	Krause	Berlin	1793	19.1	79.9	491
EU	2464	Cavalry trumpet	6½-ft Eb	Hohner	London	c 1955	17.9	71.4	489
OB	x607	Kornett	4½-ft Bb	Müller	Mainz	m.19	22.1	70.4	482
EU	602	Fanfare	6½-ft Eb		Germany (?)	m.20	19.7	80.3	481
BK	283	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	13.8	95.5	477
OB	x616	Soprano saxhorn	3¼-ft Eb	Ad. Sax	Paris	c 1870	10.2	90.3	476
EU	599	Trumpet	4½-ft Bb	Schediwy	Ludwigsburg	c 1921	19.2	74.3	475
BG	1988	Valved post horn	4½-ft Bb		Germany (?)	l.19	16.6	76.8	459
G	17665	Natural trumpet	7-ft D	Kerner	Wien	1790	18.7	75.8	459
BK	192	Natural trumpet	8-ft C	Scholler	München	e.19	27.9	62.6	459
PC	1252	Tenor trombone	9-ft Bb	Courtois frères	Paris	pre 1845	10.8	90.2	458
EU	2343	Marching bugle	4-ft C	Honsuy	Spain	c 1980	18.6	77.0	457
PH	1	Trumpet	4½-ft Bb	Amati	Czech Republic	c 1992	17.5	72.8	457
NSB	1	Cornet	4½-ft Bb	Besson	UK	1997	24.5	64.5	456
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	16.5	99.1	453
EU	2858	Bass trumpet	9-ft Bb	Cerveny	Königgrätz	c 1900	12.5	110.7	445
GBC		Trumpet	7-ft D	Dudley	London	1665	12.7	82.8	444

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
FT	140	Tenor flugelhorn	6½-ft Eb	Cerveny	Königgrätz	l.19/e.20	13.7	106.5	441
PC	1695	Tenor saxhorn	6½-ft Eb	Ad. Sax	Paris	c 1850	17.2	98.4	429
FT	225	Flugelhorn	4-ft C	Distin	London	c 1850	13.5	101.6	426
LHC	198	Cornet, upturned bell model	4½-ft Bb	Distin	London	c 1855	26.3	68.4	422
EU	3194	Kuhlo horn	4½-ft Bb	David	Bielefeld	c 1920	14.5	100.6	419
JW	CEM	Cornet à pistons, 2-valve	4½-ft Bb	Meriel fils	Caen	c 1840	29.0	66.1	417
OB	623	Cornet simple	4-ft C	Florent	Valenciennes	e.19	25.3	66.5	416
AS	884	Omnitonic trumpet	6-ft F	Labbaye	Paris	m.19	22.2	72.5	409
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	18.0	106.0	407
LHC	75	Lied horn	4-ft C	Boosey & Co	London	c 1890	17.1	96.3	407
EU	3018	Post horn	6-ft F	Schürrlein	Nürnberg	l.19	19.2	72.5	405
LHC	91	Tenor flügel horn	6½-ft Eb	Ad. Sax / T. Distin		c 1850	15.0	112.6	399
EU	3267	Cornet à pistons, 2-valve	4½-ft Bb	David	Paris	c 1840	22.7	72.7	396
FT	191	Valve trombone	9-ft Bb	Le Brun	Brussels	c 1919	19.7	91.8	394
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	24.6	89.9	391
BK	115	Contralto saxhorn	4-ft C	Gautrot	Paris	1855-1860	22.6	90.8	389
LHC	286	Keyed trumpet	5½-ft G	Beni	Citta di Castello	1836	25.4	76.1	387
BK	211	Cornet	4-ft C	Ch. Sax	Brussels	c 1840	21.2	77.9	386
AS	2172	Solo alto	6½-ft Eb	Boston M.I. Mfr.	Boston	c 1890	20.1	98.7	386
LHC	161	Tenor cor	6-ft F	Distin	London	c 1860	22.7	107.8	386
BG	1994	Trompette demilune	6-ft F (?)	Lintner	Augsburg	c 1790	23.3	68.6	383
EU	1081	Koenighorn	6-ft F	Courtois	Paris	c 1858	29.6	102.1	381
G	2902	Halbmond	3½-ft D	Cretien	Vernon	c 1650	18.3	115.0	374
LHC	313	Valve trombone, upright model	9-ft Bb	Besson	Paris	m.19	22.4	97.6	373
LH	9250	Clavicor or althorn	8-ft C	Kohler	London	c 1850	21.9	94.1	366
EU	3745	Trumpet	3½-ft D	Hüttl	Germany	c 1970	19.0	67.1	365
LG	1885	Alto trombone	6½-ft Eb	Ehe	Nürnberg	c 1720	22.3	66.3	364
EU	2782	Alto trombone	6½-ft Eb	Besson & Co	London	c 1940	23.3	90.9	361
EU	3484	Bugle alto	6-ft F	Hawkes & Son	London	c 1910	25.5	101.7	359
LHC	314	Helicon trombone	9-ft Bb	Roth	Milan	l.19	16.8	108.4	358
EU	3486	Vocal horn	8-ft C	Rudall, Rose & Carte	London	c 1870	22.1	101.1	357

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
OB	x702	Valve trombone	8-ft C	Halary	Paris	m.19	16.9	107.1	355
DB	8	American bugle	5½-ft G	Olds	California	c 1980	24.1	76.2	354
OB	x78	Natural trumpet	6½-ft Eb	Beale	London	1667	7.6	87.1	353
WAG	1	Bass trumpet	8-ft C	Alexander	Mainz	c 1985	24.2	88.8	351
LHC	298	Bugle horn	4½-ft Bb	Couesnon	Paris	l.19 / e.20	21.7	97.2	351
WSAM	255	Tenor Posaune	9-ft Bb	Leichamschneider	Wien	1732	9.0	91.1	350
PC	261	Trompette circulaire	5½-ft G	Raoux	Paris	1820	25.0	73.7	348
EU	223	Flugelhorn	4½-ft Bb	Hawkes & Son	London	c 1925	20.6	98.8	344
BG	2010	Tenor trombone, valve-slide model	9-ft Bb	Besson		l.19	11.7	92.4	340
OB	75	Coiled trumpet	5½-ft G	Jahn	Paris	e.19	33.3	69.7	340
OB	72	Trompette demilune	5½-ft G	Dubois	Lyon	e.19	18.5	68.7	335
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	23.5	92.8	334
EU	2931	Tenor trombone, 6-valve model	9-ft Bb	Persy	Brussels	c 1910	23.9	88.7	333
EU	2702	Bass trombone	11-ft G	Hawkes & Son	London	c 1900	28.0	102.5	332
BK	36	Cor d'harmonie, tuba form	13-ft Eb		France ?	m.19	17.4	117.3	326
LHC	171	Alto trombone	7½-ft Db	Courtois	Paris	c 1850	22.4	90.8	325
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	25.4	90.1	324
JW	PLR	Bass trombone, double slide	11-ft G	Rudall Carte	London	c 1880	26.7	108.1	313
EU	3207	Tenor trombone	9-ft Bb	R. Schopper	Leipzig	c 1910	36.2	109.2	312
WGDM	199	Tenor Posaune	9-ft Bb	Uhlmann	Wien	e.19	29.7	91.3	309
LSA		Bass trombone, two-slided	13-ft Eb	Salvation Army	London	c 1900	25.4	108.2	306
JW	PQP	Tenorbass trombone	9-ft Bb	Penzel Nachfolger	Leipzig	c 1900	40.0	109.2	304
EU	3050	Cornophone alto	6-ft F	Besson	Paris	c 1895	14.2	109.4	297
JW	TBB	Tenor fanfare trumpet	9-ft Bb	Boosey & Hawkes	London	c 1938	16.6	106.5	290
EU	3219	Bass valve trombone	9-ft Bb	Le Brun	Brussels	c 1919	24.3	102.7	288
TRM	715	Valve trombone	9-ft Bb	Buescher	Paris	c 1900	30.2	92.3	284
LHC	130	Baritone, circular model	9-ft Bb	Aggio (?)		l.19	21.7	124.4	282
G	8482	Tenor trombone	9-ft Bb	Kinzel	Graz	c 1825	47.5	90.9	280
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	26.9	89.6	278
EU	3534	Tenor trombone	9-ft Bb	Riedlocker	Paris	c 1810	12.1	95.0	277
FT	120	Contrabass trombone	18-ft Bb	Salvation Army	London	c 1900	29.1	108.1	273

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
EU	3257	Bass trumpet	9-ft Bb	Conn	Elkhart	1929-30	22.8	95.5	273
RC	3265	Flugelhorn	4-ft C	Ebblewhite	London	l.19	23.0	93.5	271
PC	620	O.T.S. alto trombone	6½-ft Eb	Riedloker	Paris	c 1810	21.5	76.9	270
EU	887	Tenor saxhorn	6-ft F	Ad. Sax (?)	Paris (?)	c 1850	25.5	104.1	270
LHC	307	Natural horn	12-ft F	Bull	London	1699	18.7	89.9	269
JW	PVM	Contrabass trombone	12-ft F	Mahillon	Brussels	c 1900	24.3	127.7	266
EU	3738	O.T.S. tenor trombone	9-ft Bb		France or Belgium (?)	e.19	20.3	92.4	266
EU	3480	Baritone bugle	11-ft G	Ludwig	USA	c 1980	23.4	99.9	264
JW	BBT	Bersag horn	4½-ft Bb	Boosey & Co	London		19.8	115.8	263
LG	4138	Tenor trombone	9-ft Bb	Sattler	Leipzig	1841	35.6	101.0	263
EU	3217	Trompette basse	13-ft Eb	F.G.S.F.P.	Paris	c 1900	23.0	111.2	256
EU	3348	Ballad horn	8-ft C	Boosey & Co	London	c 1895	20.5	115.8	256
LG	1909	Bass trombone	12-ft F	Goltbeck	Cottbus	1635	3.5	117.6	255
G	14921	Jagdhorn	4-ft C	Nagel (Droschel)	Nuremberg	1647	25.9	63.1	248
EU	3350	Néocor	6-ft F	Schneider	Strasbourg	c 1840	32.3	91.7	244
OB	x740	Bass trombone	12-ft F	Boosey & Co	London	c 1910	21.8	117.0	243
EU	581	Bass trombone	11-ft G	Courtois	Paris	c 1869	29.3	107.7	242
LHC	315	Bimbomifono	6-ft F	Bimboni	Florence	l.19	14.8	110.0	239
LG	4139	Tenorbass trombone	9-ft Bb	Sattler	Leipzig	1841	39.4	114.5	239
LG	1896	Tenor trombone	9-ft Bb	Ehe	Nürnberg	1668	7.7	93.2	236
EU	3758	Cornophone basse	8-ft C	Besson	Paris	c 1890	15.1	149.1	234
OB	625	Bugle horn	4-ft C	Shaw	London	e.19	26.1	112.2	229
EU	2802	Tenor trombone, 5H model	9-ft Bb	Conn	USA	c 1925	30.3	100.6	227
EU	3596	Superbone	9-ft Bb	Holton	USA	c 1980	38.8	103.0	226
WSAM	248	Trompete	7-ft D	Schnitzer	Nürnberg	1581	1.7	96.6	224
BK	234	Contrabass trombone	18-ft Bb	Courtois	Paris	c 1895	26.1	133.5	220
WSAM	721	Naturhorn	7-ft D		Dresden	18	31.3	84.7	219
JW	HWM	Wagner tuba	12-ft F	Mahillon	Brussels	c 1900	20.6	146.1	217
EU	2532	Contrabass trombone	18-ft Bb	Stowasser	Graslitz	m.20	30.3	141.6	214
AM	171	Tenor trombone, 8H model	9-ft Bb	Conn	Elkhart	1978	38.7	103.0	213
OB	603	Horn	12-ft F	Bennet	London	m.18	49.8	96.4	212

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
EU	3205	Tenor trombone	9-ft Bb	Huschauer	Vienna	1794	13.0	94.2	212
EU	613	Tenor cor	6-ft F	Higham	Manchester	c 1895	33.3	109.9	210
OB	732	Bass trombone	12-ft F		Germany	1814	17.7	118.9	208
OB	605	Horn	12-ft F	Haas	Nürnberg	c 1700	46.1	114.1	204
LG	1753	Tenorhorn	8-ft C	Schneider	Augsburg	1846-1850	28.0	123.5	202
WGDM	433	Tenor Posaune	9-ft Bb	Geyer	Wien	1671	3.5	98.0	201
EU	3208	Contrabass trombone	12-ft F		Germany (?)	c 1930	32.1	128.7	193
EU	3045	Clavicor	6½-ft Eb	Jean	France	c 1840	34.0	112.5	185
LG	3579	Stellahorn	6-ft F	Wunderlich	Markneukirchen (?)	c 1935	54.1	111.2	180
EU	3519	Trompe de chasse basse	14-ft D	Couesnon	Paris	1923	48.8	130.0	173
WSAM	656	Tenor Posaune	9-ft Bb	Riedl		e.19	20.6	122.0	169
JW	BBB	Bersag horn	4½-ft Bb	Boosey & Co	London		19.8	133.5	167
EU	2515	Wagner tuba	9-ft Bb	Alexander	Mainz	c 1930	21.3	166.2	164
EU	2627	Natural horn	14-ft D	Winkings	London	c 1740	33.7	120.1	162
EU	2776	Euphonium	9-ft Bb	Higham	Manchester	c 1880	20.3	171.8	160
SR		Tenor cor, bell-up model	6½-ft Eb	Boosey & Co	London	c 1910	44.4	112.7	157
EU	2493	Natural horn	14-ft D	Winkings	London	c 1740	42.8	117.7	156
EU	204	Orchestral horn	12-ft F	Kersten	Dresden	c 1830	53.3	124.4	151
LHC	206	Clavicor	8-ft C	Guichard	Paris	c 1840	29.5	135.3	150
EU	2131	Tuba	12-ft F	Higham	Manchester	c 1910	23.1	200.7	148
EU	2155	Ventilwaldhorn	12-ft F	Rott	Prague	c 1900	58.9	124.2	144
AM	1074	Tenor cor	6-ft F	Boosey & Co	London	c 1928	48.4	107.8	142
BK	28	Clavicor	8-ft C	Guichard	Paris	c 1850	33.1	134.4	138
EU	3494	Trompe de chasse	14-ft D	Lecomte	Paris	1906 (?)	71.3	100.1	134
BG	2011	O.T.S. tenor trombone	8-ft C	Van Engelen	Belgium	c 1840	43.0	94.5	134
EU	1874	Orchestral horn	12-ft F	Mahillon	Brussels or London	c 1890	83.9	89.7	133
EU	3297	Orchestral hand horn	12-ft F	Hofmaster	London	c 1760	44.1	120.6	132
EU	3441	Double horn	12-ft F	Couesnon	Paris	c 1914	67.8	118.2	125
EU	1804	Double horn	12-ft F	Alexander	Mainz	c 1950	74.4	113.9	124
EU	203	Orchestral hand horn	12-ft F	Sandbach	London	1810-1830	52.9	124.0	122
LG	1910	Bass trombone	11-ft G	Birckholtz	Nürnberg	1650	15.8	109.4	122

		Instrument	Nom Pitch	Maker	Place	Date	*Zpeak - Zo*	*Dpeak*	*Upeak*
EU	2161	Trompe dauphine	14-ft D	Le Brun	Paris	1721	68.1	117.8	120
TRM	804	Trompe de chasse	14-ft D		France (?)	l.19 (?)	84.3	94.1	117
OB	64	Trompe de chasse	14-ft D	Carlin	Paris	m.18	75.8	85.5	114
AS	937	Cor d'harmonie, tuba form	13-ft Eb	Ad. Sax	Paris	m.19	73.0	102.7	113
EU	3363	Omnitonic horn	12-ft F	Ch. Sax	Brussels	c 1835	67.4	120.1	106
EU	2888	Orchestral hand horn	12-ft F		Britain (?)	l.18	55.7	123.1	104
EU	3048	Cor d'harmonie	12-ft F	Besson	Paris	1864-1869	98.2	87.7	98
EU	1714	Valved horn	12-ft F	Ellard	Dublin	1835-1840	63.7	136.8	98
EU	531	Orchestral hand horn	12-ft F	Kretzschmann	Strasbourg	c 1830	84.7	101.8	97
BK	101	Trompe de chasse contrebasse	28-ft D	Millereau	Paris	l.19 / e.20	72.6	145.5	82
LG	1767	Ventilophikleide	16-ft C	Saurle	München	c 1840	37.3	212.7	66
WSAM	706	Tenor Posaune	9-ft Bb	Neuschel	Nürnberg	1557	7.3	96.9	58
EU	3097	Alphorn	11-ft G	Oberli	Zwischenflüh	c 1935	-201.4	272.9	7

Appendix C

Instruments grouped by nominal pitch and ranked by cut-off frequency

This table lists the cut-off frequencies of selected instruments in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Nominal pitch**, **Maker**, **Place** and **Date**

These are the same specimens as those in Appendix B. The nominal pitches for early instruments may not be those that would have been used in the period of manufacture: they are ascribed to specimens here solely to facilitate comparison with later instruments of similar tube length. Similarly, french horns with crooks have been considered to be in 12-ft F purely for purposes of comparison.

Cut-off frequency

This is derived directly from the peak horn function value assuming a speed of sound in free air of 345 ms^{-1} and is given in hertz. The accuracy of these results is treated in Appendix B.

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
BK	327	Piccolo cornet	2-ft C		France (?)	c 1900	1699
EU	2589	Piccolo trumpet	2¼-ft Bb	J. Monke	Köln	c 1960	2197
LC	TR56	Piccolo trumept	2¼-ft Bb	Couesnon	Paris	c 1935	1361
BK	1	Soprano cornet	3-ft F	Ad. Sax	Paris	c 1850	1271
EU	3246	Soprano flugelhorn	3¼-ft Eb	Besson	London	c 1870	1410
LC	TR59	Soprano cornet	3¼-ft Eb	Courtois	Paris	c 1890	1407
EU	1299	Straight trumpet	3¼-ft Eb	Hawkes & Son	London	c 1916	1325
BG	1987	Soprano cornet	3¼-ft Eb	Uhlmann	Vienna	c 1870	1304
OB	647	Soprano cornet	3¼-ft Eb	H. Distin	London	c 1860	1222
OB	x616	Soprano saxhorn	3¼-ft Eb	Ad. Sax	Paris	c 1870	1197
LHC	74	Post horn	3½-ft D			19	1561
EU	3233	Trumpet	3½-ft D	Besson	London	c 1944	1417
G	2902	Halbmond	3½-ft D	Cretien	Vernon	c 1650	1061
EU	3745	Trumpet	3½-ft D	Hüttl	Germany	c 1970	1049
EU	2343	Marching bugle	4-ft C	Honsuy	Spain	c 1980	1174
FT	225	Flugelhorn	4-ft C	Distin	London	c 1850	1133
OB	623	Cornet simple	4-ft C	Florent	Valenciennes	e.19	1120
LHC	75	Lied horn	4-ft C	Boosey & Co	London	c 1890	1108
BK	115	Contralto saxhorn	4-ft C	Gautrot	Paris	1855-1860	1083
BK	211	Cornet	4-ft C	Ch. Sax	Brussels	c 1840	1078
RC	3265	Flugelhorn	4-ft C	Ebblewhite	London	l.19	904
G	14921	Jagdhorn	4-ft C	Nagel (Droschel)	Nuremberg	1647	864
OB	625	Bugle horn	4-ft C	Shaw	London	e.19	832

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
RD	6488	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1928	2032
EU	3460	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1927	1789
JW	TMW	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1925	1636
JW	CLK	Cornet	4½-ft Bb	Kohler	London	c 1865	1470
EU	1671	Post horn	4½-ft Bb			c 1900	1443
LHC	187	Bayley's acoustic cornet	4½-ft Bb	Kohler	London	c 1865	1436
EU	1860	Cornet	4½-ft Bb	Kohler	London	c 1860	1416
FT	205	Albion cornopean	4½-ft Bb	Pace	London	c 1850	1402
CRB	326	Valve trumpet, 'Handelian' model	4½-ft Bb	Kohler	London	c 1895	1395
OB	711	Trumpet, PCB model	4½-ft Bb	Rudall Carte	London	c 1925	1384
LHC	150	Valve trumpet	4½-ft Bb	Sandbach & Wyatt	London	c 1835	1382
EU	2704	Cornet	4½-ft Bb	Boosey & Co	London	c 1922	1382
JW	CMT	Pocket cornet	4½-ft Bb	Thibouville-Lamy	Paris	e.20	1375
BK	107	Sudrophone cornet	4½-ft Bb	F. Sudre	Paris	l.19	1363
EU	2337	Trumpet	4½-ft Bb		Czechoslovakia	c 1935	1348
EU	220	Cornet	4½-ft Bb	Rudall, Rose & Carte	London	c 1865	1315
FT	52	Cornophone cornettito	4½-ft Bb	Besson	London	c 1900	1307
EU	2460	Cornet	4½-ft Bb	Courtois	Paris	1856-1858	1291
JW	BFG	Flugelhorn	4½-ft Bb	Gisborne	Birmingham	1845	1280
EU	2779	Flugelhorn	4½-ft Bb	Kohlert	Winneneden	m.20	1254
MB	5169	PCB cornet	4½-ft Bb	Rudall Carte	London	c 1905	1244
EU	619	Cornet, PCB model	4½-ft Bb	Rudall Carte	London	1905	1243
JW	CEC	Cornet	4½-ft Bb	Courtois	Paris	c 1855	1234
LHC	34	Cornet, circular model	4½-ft Bb	Distin	London	c 1855	1234
OB	x607	Kornett	4½-ft Bb	Müller	Mainz	m.19	1205
BK	283	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	1200
EU	599	Trumpet	4½-ft Bb	Schediwy	Ludwigsburg	c 1921	1196
BG	1988	Valved post horn	4½-ft Bb		Germany (?)	l.19	1176
PH	1	Trumpet	4½-ft Bb	Amati	Czech Republic	c 1992	1173
NSB	1	Cornet	4½-ft Bb	Besson	UK	1997	1173

		Instrument	**Nom Pitch**	**Maker**	**Place**	**Date**	***Cutoff***
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	1168
LHC	198	Cornet, upturned bell model	4½-ft Bb	Distin	London	c 1855	1128
EU	3194	Kuhlo horn	4½-ft Bb	David	Bielefeld	c 1920	1124
JW	CEM	Cornet à pistons, 2-valve	4½-ft Bb	Meriel fils	Caen	c 1840	1121
EU	3267	Cornet à pistons, 2-valve	4½-ft Bb	David	Paris	c 1840	1093
LHC	298	Bugle horn	4½-ft Bb	Couesnon	Paris	l.19 / e.20	1029
EU	223	Flugelhorn	4½-ft Bb	Hawkes & Son	London	c 1925	1019
JW	BBT	Bersag horn	4½-ft Bb	Boosey & Co	London		890
JW	BBB	Bersag horn	4½-ft Bb	Boosey & Co	London		710
EU	598	Field trumpet	5½-ft G	Rexcraft	USA	c 1950	1891
LHC	95	Keyed trumpet	5½-ft G			e.19	1509
FT	108	Valve trumpet	5½-ft G	Besson		c 1865	1311
DB	7	Marching trumpet	5½-ft G	Dynasty	USA	c 1980	1304
OB	71	Trompette demilune	5½-ft G	Guichard	Paris	e.19	1292
BK	385	Trompette demilune	5½-ft G	Kretzschmann	Strasbourg	e.19	1222
LHC	286	Keyed trumpet	5½-ft G	Beni	Citta di Castello	1836	1080
DB	8	American bugle	5½-ft G	Olds	California	c 1980	1033
PC	261	Trompette circulaire	5½-ft G	Raoux	Paris	1820	1024
OB	75	Coiled trumpet	5½-ft G	Jahn	Paris	e.19	1012
OB	72	Trompette demilune	5½-ft G	Dubois	Lyon	e.19	1005
PC	728	Valve trumpet	6-ft F	Alphonse Sax	Paris	c 1865	1605
EU	2321	Valve and slide trumpet	6-ft F	Mahillon	Brussels	c 1885	1504
LG	4070	Inventionstrompete	6-ft F	Heckel	Dresden	1836-1837	1444
LHC	290	Valve trumpet	6-ft F	Pace	London	c 1840	1432
BK	270	Trompette demilune	6-ft F			e.19	1410
OB	x70	Slide trumpet	6-ft F	Harris	London	18	1367
LHC	76	Valve trumpet	6-ft F	Pace	London	c 1840	1293
BG	2007	Alto trombone	6-ft F		England (?)	m.19	1279
EU	2975	Slide trumpet	6-ft F	Kohler	London	c 1850	1272

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
LHC	239	Bugle horn	6-ft F	Fürst	Ellwang	1770	1249
FT	178	Valve trumpet	6-ft F	Courtois	Paris	c 1885	1230
LG	1829	Inventionstrompete	6-ft F	Krause	Berlin	1793	1216
AS	884	Omnitonic trumpet	6-ft F	Labbaye	Paris	m.19	1110
EU	3018	Post horn	6-ft F	Schürrlein	Nürnberg	l.19	1104
LHC	161	Tenor cor	6-ft F	Distin	London	c 1860	1078
EU	1081	Koenighorn	6-ft F	Courtois	Paris	c 1858	1072
EU	3484	Bugle alto	6-ft F	Hawkes & Son	London	c 1910	1040
EU	3050	Cornophone alto	6-ft F	Besson	Paris	c 1895	946
EU	887	Tenor saxhorn	6-ft F	Ad. Sax (?)	Paris (?)	c 1850	902
EU	3350	Néocor	6-ft F	Schneider	Strasbourg	c 1840	857
LHC	315	Bimbomifono	6-ft F	Bimboni	Florence	l.19	849
EU	613	Tenor cor	6-ft F	Higham	Manchester	c 1895	795
LG	3579	Stellahorn	6-ft F	Wunderlich	Markneukirchen (?)	c 1935	736
AM	1074	Tenor cor	6-ft F	Boosey & Co	London	c 1928	653
BG	1994	Trompette demilune	6-ft F (?)	Lintner	Augsburg	c 1790	1074
LG	1884	Alto trombone	6½-ft Eb	Stark	Nürnberg	1690	1608
WGDM	198	Alt Posaune	6½-ft Eb	Schmidt	Nürnberg	1675	1586
EU	3284	Natural trumpet	6½-ft Eb		England (?)	e.18	1581
OB	730	Alto trombone	6½-ft Eb		Germany	1814	1539
LG	4137	Alto trombone	6½-ft Eb	Sattler	Leipzig	1841	1444
LHC	85	Alto trombone	6½-ft Eb	F. Besson	London	l.19	1430
AM	1095	Trompette de cavalerie	6½-ft Eb	Couesnon	Paris	m.20	1418
EU	3280	Natural trumpet	6½-ft Eb	Hofmaster	London	c 1760	1354
LHC	100	Coiled trumpet	6½-ft Eb			19	1344
EU	3282	Natural trumpet	6½-ft Eb	Winkings	London	m.18	1332
JW	PAC	Alto trombone	6½-ft Eb	Courtois / Mille	Paris	c 1880	1250
BG	1984	Post horn, 2-valve	6½-ft Eb		Germany (?)	m.19	1241
EU	2464	Cavalry trumpet	6½-ft Eb	Hohner	London	c 1955	1214
EU	602	Fanfare	6½-ft Eb		Germany (?)	m.20	1204

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
FT	140	Tenor flugelhorn	6½-ft Eb	Cerveny	Königgrätz	l.19/e.20	1153
PC	1695	Tenor saxhorn	6½-ft Eb	Ad. Sax	Paris	c 1850	1137
LHC	91	Tenor flügel horn	6½-ft Eb	Ad. Sax / T. Distin		c 1850	1097
AS	2172	Solo alto	6½-ft Eb	Boston M.I. Mfr.	Boston	c 1890	1078
LG	1885	Alto trombone	6½-ft Eb	Ehe	Nürnberg	c 1720	1048
EU	2782	Alto trombone	6½-ft Eb	Besson & Co	London	c 1940	1043
OB	x78	Natural trumpet	6½-ft Eb	Beale	London	1667	1031
PC	620	O.T.S. alto trombone	6½-ft Eb	Riedloker	Paris	c 1810	903
EU	3045	Clavicor	6½-ft Eb	Jean	France	c 1840	747
SR		Tenor cor, bell-up model	6½-ft Eb	Boosey & Co	London	c 1910	688
LHC	171	Alto trombone	7½-ft Db	Courtois	Paris	c 1850	990
WGDM	183	Trompete	7-ft D	Ehe	Nürnberg	1747	2016
WSAM	252	Trompete	7-ft D	Geyer	Wien		1833
LG	1867	Buchsentrompete	7-ft D	Buchschwender	Ellwangen	c 1730	1825
WSAM	251	Trompete	7-ft D	Hainlein	Nürnberg	1689	1732
WSAM	599	Trompete	7-ft D	Leichamschneider	Wien		1691
OB	712	Valve trumpet	7-ft D	Pace	London	c 1835	1427
LHC	244	Natural trumpet	7-ft D	Hass	Nürnberg	l.17	1373
EU	3247	Trumpet	7-ft D	Huschauer	Wien	1794	1362
GS	2	Natural trumpet	7-ft D	Huschauer	Wien	1806	1350
G	17665	Natural trumpet	7-ft D	Kerner	Wien	1790	1176
GBC		Trumpet	7-ft D	Dudley	London	1665	1157
WSAM	248	Trompete	7-ft D	Schnitzer	Nürnberg	1581	822
WSAM	721	Naturhorn	7-ft D		Dresden	18	812

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
BK	192	Natural trumpet	8-ft C	Scholler	München	e.19	1176
LH	9250	Clavicor or althorn	8-ft C	Kohler	London	c 1850	1050
EU	3486	Vocal horn	8-ft C	Rudall, Rose & Carte	London	c 1870	1038
OB	x702	Valve trombone	8-ft C	Halary	Paris	m.19	1034
WAG	1	Bass trumpet	8-ft C	Alexander	Mainz	c 1985	1029
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	1003
EU	3348	Ballad horn	8-ft C	Boosey & Co	London	c 1895	878
EU	3758	Cornophone basse	8-ft C	Besson	Paris	c 1890	839
LG	1753	Tenorhorn	8-ft C	Schneider	Augsburg	1846-1850	780
LHC	206	Clavicor	8-ft C	Guichard	Paris	c 1840	673
BK	28	Clavicor	8-ft C	Guichard	Paris	c 1850	644
BG	2011	O.T.S. tenor trombone	8-ft C	Van Engelen	Belgium	c 1840	634
LG	1899	Tenor trombone	9-ft Bb	Eschenbach	Markneukirchen	1796	1356
OB	731	Tenor trombone	9-ft Bb		Germany	1814	1264
LG	1897	Tenor trombone	9-ft Bb	Ehe	Nürnberg	c 1720	1247
PC	1252	Tenor trombone	9-ft Bb	Courtois frères	Paris	pre 1845	1175
EU	2858	Bass trumpet	9-ft Bb	Cerveny	Königgrätz	c 1900	1158
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	1108
FT	191	Valve trombone	9-ft Bb	Le Brun	Brussels	c 1919	1089
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	1086
LHC	313	Valve trombone, upright model	9-ft Bb	Besson	Paris	m.19	1060
LHC	314	Helicon trombone	9-ft Bb	Roth	Milan	l.19	1039
WSAM	255	Tenor Posaune	9-ft Bb	Leichamschneider	Wien	1732	1028
BG	2010	Tenor trombone, valve-slide model	9-ft Bb	Besson		l.19	1013
EU	2931	Tenor trombone, 6-valve model	9-ft Bb	Persy	Brussels	c 1910	1002
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	988
EU	3207	Tenor trombone	9-ft Bb	R. Schopper	Leipzig	c 1910	970
WGDM	199	Tenor Posaune	9-ft Bb	Uhlmann	Wien	e.19	965
JW	PQP	Tenorbass trombone	9-ft Bb	Penzel Nachfolger	Leipzig	c 1900	958

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
JW	TBB	Tenor fanfare trumpet	9-ft Bb	Boosey & Hawkes	London	c 1938	935
EU	3219	Bass valve trombone	9-ft Bb	Le Brun	Brussels	c 1919	931
TRM	715	Valve trombone	9-ft Bb	Buescher	Paris	c 1900	925
LHC	130	Baritone, circular model	9-ft Bb	Aggio (?)		l.19	922
G	8482	Tenor trombone	9-ft Bb	Kinzel	Graz	c 1825	918
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	916
EU	3534	Tenor trombone	9-ft Bb	Riedlocker	Paris	c 1810	913
EU	3257	Bass trumpet	9-ft Bb	Conn	Elkhart	1929-30	906
EU	3738	O.T.S. tenor trombone	9-ft Bb		France or Belgium (?)	e.19	895
LG	4138	Tenor trombone	9-ft Bb	Sattler	Leipzig	1841	890
LG	4139	Tenorbass trombone	9-ft Bb	Sattler	Leipzig	1841	849
LG	1896	Tenor trombone	9-ft Bb	Ehe	Nürnberg	1668	843
EU	2802	Tenor trombone, 5H model	9-ft Bb	Conn	USA	c 1925	827
EU	3596	Superbone	9-ft Bb	Holton	USA	c 1980	825
AM	171	Tenor trombone, 8H model	9-ft Bb	Conn	Elkhart	1978	801
EU	3205	Tenor trombone	9-ft Bb	Huschauer	Vienna	1794	799
WGDM	433	Tenor Posaune	9-ft Bb	Geyer	Wien	1671	779
WSAM	656	Tenor Posaune	9-ft Bb	Riedl		e.19	714
EU	2515	Wagner tuba	9-ft Bb	Alexander	Mainz	c 1930	703
EU	2776	Euphonium	9-ft Bb	Higham	Manchester	c 1880	694
WSAM	706	Tenor Posaune	9-ft Bb	Neuschel	Nürnberg	1557	418
EU	2702	Bass trombone	11-ft G	Hawkes & Son	London	c 1900	1000
JW	PLR	Bass trombone, double slide	11-ft G	Rudall Carte	London	c 1880	972
EU	3480	Baritone bugle	11-ft G	Ludwig	USA	c 1980	892
EU	581	Bass trombone	11-ft G	Courtois	Paris	c 1869	854
LG	1910	Bass trombone	11-ft G	Birckholtz	Nürnberg	1650	606
EU	3097	Alphorn	11-ft G	Oberli	Zwischenflüh	c 1935	146

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
LHC	307	Natural horn	12-ft F	Bull	London	1699	900
JW	PVM	Contrabass trombone	12-ft F	Mahillon	Brussels	c 1900	896
LG	1909	Bass trombone	12-ft F	Goltbeck	Cottbus	1635	876
OB	x740	Bass trombone	12-ft F	Boosey & Co	London	c 1910	856
JW	HWM	Wagner tuba	12-ft F	Mahillon	Brussels	c 1900	808
OB	603	Horn	12-ft F	Bennet	London	m.18	800
OB	732	Bass trombone	12-ft F		Germany	1814	791
OB	605	Horn	12-ft F	Haas	Nürnberg	c 1700	784
EU	3208	Contrabass trombone	12-ft F		Germany (?)	c 1930	763
EU	204	Orchestral horn	12-ft F	Kersten	Dresden	c 1830	676
EU	2131	Tuba	12-ft F	Higham	Manchester	c 1910	668
EU	2155	Ventilwaldhorn	12-ft F	Rott	Prague	c 1900	660
EU	1874	Orchestral horn	12-ft F	Mahillon	Brussels or London	c 1890	634
EU	3297	Orchestral hand horn	12-ft F	Hofmaster	London	c 1760	630
EU	3441	Double horn	12-ft F	Couesnon	Paris	c 1914	615
EU	1804	Double horn	12-ft F	Alexander	Mainz	c 1950	612
EU	203	Orchestral hand horn	12-ft F	Sandbach	London	1810-1830	606
EU	3363	Omnitonic horn	12-ft F	Ch. Sax	Brussels	c 1835	566
EU	2888	Orchestral hand horn	12-ft F		Britain (?)	l.18	559
EU	3048	Cor d'harmonie	12-ft F	Besson	Paris	1864-1869	545
EU	1714	Valved horn	12-ft F	Ellard	Dublin	1835-1840	542
EU	531	Orchestral hand horn	12-ft F	Kretzschmann	Strasbourg	c 1830	540
BK	36	Cor d'harmonie, tuba form	13-ft Eb		France ?	m.19	991
LSA		Bass trombone, two-slided	13-ft Eb	Salvation Army	London	c 1900	960
EU	3217	Trompette basse	13-ft Eb	F.G.S.F.P.	Paris	c 1900	878
AS	937	Cor d'harmonie, tuba form	13-ft Eb	Ad. Sax	Paris	m.19	584

		Instrument	Nom Pitch	Maker	Place	Date	*Cutoff*
EU	3519	Trompe de chasse basse	14-ft D	Couesnon	Paris	1923	723
EU	2627	Natural horn	14-ft D	Winkings	London	c 1740	700
EU	2493	Natural horn	14-ft D	Winkings	London	c 1740	687
EU	3494	Trompe de chasse	14-ft D	Lecomte	Paris	1906 (?)	636
EU	2161	Trompe dauphine	14-ft D	Le Brun	Paris	1721	601
TRM	804	Trompe de chasse	14-ft D		France (?)	l.19 (?)	595
OB	64	Trompe de chasse	14-ft D	Carlin	Paris	m.18	586
LG	1767	Ventilophikleide	16-ft C	Saurle	München	c 1840	446
FT	120	Contrabass trombone	18-ft Bb	Salvation Army	London	c 1900	908
BK	234	Contrabass trombone	18-ft Bb	Courtois	Paris	c 1895	814
EU	2532	Contrabass trombone	18-ft Bb	Stowasser	Graslitz	m.20	803
BK	101	Trompe de chasse contrebasse	28-ft D	Millereau	Paris	l.19 / e.20	497

Appendix D

Minimum shank diameter of mouthpieces in EUCHMI

This table lists the minimum shank diameters of all the mouthpieces for brasswind instruments in EUCHMI on 1st January 1996, accession numbers in the range (1) to (3599).
The information has been extracted from the catalogue of the Collection (Myers and Parks 1996a and Myers and Parks 1996b).

Within each type, entries have been ranked by minimum shank diameter.

7.5 Mouthpiece for cornettino (1283)

7.5 Mouthpiece for cornett (1878)
8.2 Mouthpiece for cornett (3589)
8.4 Mouthpiece for cornett (3492)
8.5 Mouthpiece for cornett (3192)
8.6 Mouthpiece for cornett (626)
8.7 Mouthpiece for cornett (1147)
8.7 Mouthpiece for cornett (863)
8.8 Mouthpiece for cornett (1877)
9.9 Mouthpiece for cornett (3302)

9.2 Mouthpiece for soprano bugle (2342)

9.8 Mouthpiece for Kornett (?) (3248)
10.3 Mouthpiece for Swedish kornett (3500)
10.8 Mouthpiece for Kornett (2451)

9.7 Mouthpiece for clarion (1133)
9.9 Mouthpiece for bugle (2344)
10.2 Mouthpiece for bugle (2469)
10.2 Mouthpiece for bugle (3224)
10.3 Mouthpiece for bugle (2646)
10.6 Mouthpiece for bugle (628)
10.6 Mouthpiece for bugle (1137)
10.7 Mouthpiece for bugle (914)
10.8 Mouthpiece for bugle (904)
10.8 Mouthpiece for bugle (1730)
10.9 Mouthpiece for bugle (697)
10.9 Mouthpiece for bugle (644)
10.9 Mouthpiece for bugle (3285)
11.0 Mouthpiece for bugle (?) (3228)
11.0 Mouthpiece for bugle (3265)
11.0 Mouthpiece for bugle (993)
12.2 Mouthpiece for bugle (1086)

10.0 Mouthpiece for cornopean (1861)
10.2 Mouthpiece for cornopean (1298)
10.5 Mouthpiece for cornopean (1871)
10.5 Mouthpiece for keyed bugle with trumpet cup (?) (1288)
10.8 Mouthpiece for cornopean (845)
10.8 Mouthpiece for cornopean (?) (642)
10.8 Mouthpiece for keyed bugle (3238)
11.0 Mouthpiece for keyed bugle (991)
11.0 Mouthpiece for keyed bugle (1285)
11.0 Mouthpiece for keyed bugle (908)
11.1 Mouthpiece for keyed bugle (633)
11.2 Mouthpiece for keyed bugle (1284)
11.6 Mouthpiece for cornopean (3294)
11.8 Mouthpiece for keyed bugle (956)
12.0 Mouthpiece for keyed bugle (1286)
12.0 Mouthpiece for keyed bugle (3025)

8.9 Mouthpiece for flugelhorn (874)
9.1 Mouthpiece for flugelhorn (647)
9.1 Mouthpiece for flugelhorn (2817)
9.2 Mouthpiece for flugelhorn (2928)
9.3 Mouthpiece for flugelhorn (3514)
9.3 Mouthpiece for flugelhorn (3482)
9.3 Mouthpiece for flugelhorn (3513)
9.4 Mouthpiece for flugelhorn (2320)
9.5 Mouthpiece for flugelhorn (1892)
9.5 Mouthpiece for flugelhorn (1574)
9.8 Mouthpiece for flugelhorn (1672)
9.9 Mouthpiece for flugelhorn (1151)
10.0 Mouthpiece for flugelhorn (2958)
10.0 Mouthpiece for flugelhorn (2996)
10.1 Mouthpiece for flugelhorn (3088)
10.2 Mouthpiece for valved bugle (3300)

7.9 Mouthpiece for soprano cornet (2810)
8.0 Mouthpiece for cornet (3364)
8.1 Mouthpiece for cornet (1886)
8.1 Mouthpiece for cornet or soprano cornet (3503)
8.2 Mouthpiece for cornet (2994)
8.3 Mouthpiece for cornet (2815)
8.3 Mouthpiece for cornet (3506)
8.3 Mouthpiece for cornet (3268)
8.3 Mouthpiece for cornet (1554)
8.3 Mouthpiece for cornet (2461)
8.3 Mouthpiece for cornet (2813)
8.3 Mouthpiece for cornet (643)
8.3 Mouthpiece for cornet (2811)
8.3 Mouthpiece for cornet (2937)
8.3 Mouthpiece for cornet (2933)
8.4 Mouthpiece for soprano cornet (1880)
8.4 Mouthpiece for cornet or soprano cornet (1300)
8.4 Mouthpiece for cornet (2816)
8.4 Mouthpiece for cornet (1588)

8.4 Mouthpiece for cornet (1883)
8.4 Mouthpiece for cornet (1295)
8.4 Mouthpiece for cornet (3409)
8.4 Mouthpiece for cornet (651)
8.4 Mouthpiece for cornet (1879)
8.4 Mouthpiece for cornet (2812)
8.4 Mouthpiece for cornet (2936)
8.4 Mouthpiece for cornet (3504)
8.4 Mouthpiece for cornet (2372)
8.5 Mouthpiece for cornet with trumpet cup (3593)
8.5 Mouthpiece for cornet (2938)
8.5 Mouthpiece for cornet (3428)
8.5 Mouthpiece for cornet (688)
8.5 Mouthpiece for cornet (1888)
8.5 Mouthpiece for cornet (1084)
8.5 Mouthpiece for cornet (1452)
8.5 Mouthpiece for cornet (870)
8.6 Mouthpiece for soprano cornet (3501)
8.6 Mouthpiece for soprano cornet (3502)
8.6 Mouthpiece for cornet with trumpet cup (3512)
8.6 Mouthpiece for soprano cornet (2814)
8.6 Mouthpiece for cornet (1885)
8.6 Mouthpiece for soprano cornet (2809)
8.6 Mouthpiece for cornet (2956)
8.6 Mouthpiece for cornet (3505)
8.6 Mouthpiece for cornet (680)
8.6 Mouthpiece for cornet (2995)
8.6 Mouthpiece for cornet (2955)
8.6 Mouthpiece for cornet (645)
8.6 Mouthpiece for cornet (2318)
8.6 Mouthpiece for cornet (1153)
8.6 Mouthpiece for cornet de poste (669)
8.6 Mouthpiece for cornet (1590)
8.6 Mouthpiece for cornet (2470)
8.7 Mouthpiece for cornet (2982)
8.7 Mouthpiece for cornet (1884)
8.7 Mouthpiece for cornet (2875)
8.7 Mouthpiece for cornet with trumpet cup (3028)
8.7 Mouthpiece for cornet (2437)
8.7 Mouthpiece for cornet (3347)
8.7 Mouthpiece for cornet (681)
8.7 Mouthpiece for cornet (1887)
8.7 Mouthpiece for cornet (2781)
8.7 Mouthpiece for cornet (3511)
8.7 Mouthpiece for cornet (3478)
8.7 Mouthpiece for posthorn (3019)
8.8 Mouthpiece for soprano cornet (2954)
8.8 Mouthpiece for soprano cornet (3508)
8.8 Mouthpiece for cornet or soprano cornet (3055)
8.8 Mouthpiece for soprano saxhorn (3430)
8.8 Mouthpiece for cornet (3276)
8.8 Mouthpiece for cornet (695)
8.8 Mouthpiece (3359)

8.8 Mouthpiece for cornet (2957)
8.8 Mouthpiece for cornet (880)
8.8 Mouthpiece for cornet (1882)
8.8 Mouthpiece for cornet (1881)
8.8 Mouthpiece for cornet (1164)
8.8 Mouthpiece for cornet (906)
8.8 Mouthpiece for cornet (641)
8.8 Mouthpiece for cornet (3507)
8.9 Mouthpiece for soprano cornet (2808)
8.9 Mouthpiece for soprano cornet (2302)
8.9 Mouthpiece for cornet (3509)
8.9 Mouthpiece for cornet (3053)
8.9 Mouthpiece for cornet (3226)
8.9 Mouthpiece for cornet (830)
8.9 Mouthpiece for cornet (3476)
8.9 Mouthpiece for cornet (3510)
8.9 Mouthpiece for cornet (1141)
8.9 Mouthpiece for cornet (3479)
9.0 Mouthpiece for cornet (1611)
9.0 Mouthpiece for cornet (3316)
9.0 Mouthpiece for cornet (640)

9.3 Mouthpiece for trumpet (2338)
9.3 Mouthpiece for trumpet (2820)
9.3 Mouthpiece for trumpet (1890)
9.4 Mouthpiece for trumpet (2997)
9.4 Mouthpiece for trumpet (3234)
9.5 Mouthpiece for trumpet (652)
9.5 Mouthpiece for trumpet (2322)
9.6 Mouthpiece for trumpet (878)
9.6 Mouthpiece for trumpet (3002)
9.6 Mouthpiece for trumpet (1889)
9.6 Mouthpiece for trumpet (886)
9.7 Mouthpiece for trumpet (3000)
9.7 Mouthpiece for trumpet (882)
9.7 Mouthpiece for trumpet (3516)
9.7 Mouthpiece for trumpet (2999)
9.7 Mouthpiece for trumpet (658)
9.7 Mouthpiece for trumpet (1702)
9.7 Mouthpiece for trumpet (2455)
9.8 Mouthpiece for trumpet (2819)
9.8 Mouthpiece for trumpet (3001)
9.8 Mouthpiece for trumpet (2481)
9.8 Mouthpiece for trumpet (1614)
9.8 Mouthpiece for trumpet (2998)
9.8 Mouthpiece for trumpet (2503)
9.8 Mouthpiece for trumpet (3345)
9.9 Mouthpiece for trumpet (2818)
9.9 Mouthpiece for trumpet (916)
10.0 Mouthpiece for trumpet (3211)
10.0 Mouthpiece for trumpet (3515)
10.0 Mouthpiece for trumpet (2528)
10.0 Mouthpiece for trumpet (3235)

10.0 Mouthpiece for trumpet (672)
10.0 Mouthpiece for trumpet (844)
10.0 Mouthpiece for trumpet or bass trumpet (653)
10.1 Mouthpiece for trumpet (2514)
10.2 Mouthpiece for trumpet (3281)
10.3 Mouthpiece for trumpet (997)
10.3 Mouthpiece for trumpet (2872)
10.3 Mouthpiece for trumpet (842)
10.3 Mouthpiece for trumpet (2495)
10.4 Mouthpiece for trumpet (3195)
10.4 Mouthpiece for trumpet (2465)
10.4 Mouthpiece for trumpet (2644)
10.4 Mouthpiece for trumpet (3159)
10.5 Mouthpiece for trumpet, formerly cornet (2978)
10.5 Mouthpiece for cavalry trumpet (1863)
10.6 Mouthpiece for trumpet (649)
10.6 Mouthpiece for trumpet (2526)
10.6 Mouthpiece for trumpet (648)
10.6 Mouthpiece for trumpet (3283)
10.6 Mouthpiece for trumpet (1720)
10.6 Mouthpiece for alto trumpet (2374)
10.7 Mouthpiece for trumpet (3291)
10.7 Mouthpiece for trumpet (650)
10.8 Mouthpiece for trumpet (3216)
10.8 Mouthpiece for trumpet (622)
11.0 Mouthpiece for trumpet (3204)
11.0 Mouthpiece for trumpet (3287)
11.0 Mouthpiece for trumpet (3289)
11.0 Mouthpiece for trumpet (679)
11.5 Mouthpiece for trumpet (995)

9.6 Mouthpiece for soprano trombone (3029)
9.9 Mouthpiece for soprano trombone (1287)
10.2 Mouthpiece for soprano trombone (639)

5.8 Mouthpiece for french horn (2628)
5.9 Mouthpiece for trompe de chasse (3493)
6.2 Mouthpiece for trompe de chasse (2162)
6.3 Mouthpiece for french horn (1891)
6.5 Mouthpiece for trompe de chasse (3495)
6.6 Mouthpiece for french horn (635)
6.7 Mouthpiece for french horn (2156)
6.7 Mouthpiece for french horn (656)
6.8 Mouthpiece for french horn (2993)
6.9 Mouthpiece for french horn (663)
6.9 Mouthpiece for french horn (3496)
6.9 Mouthpiece for french horn (1125)
7.0 Mouthpiece for french horn (848)
7.0 Mouthpiece for french horn (1868)
7.0 Mouthpiece for french horn (3161)
7.1 Mouthpiece for french horn (3118)
7.1 Mouthpiece for french horn (846)
7.2 Mouthpiece for french horn (837)

7.3 Mouthpiece for french horn (1875)
7.3 Mouthpiece for french horn (866)
7.3 Mouthpiece for french horn (664)
7.4 Mouthpiece for french horn (3099)
7.5 Mouthpiece for french horn (1805)
7.6 Mouthpiece for french horn (636)
7.6 Mouthpiece for french horn (3497)
7.6 Mouthpiece for Wagner tuba (1678)
7.7 Mouthpiece for French horn (3498)

8.7 Mouthpiece for néocor (3351)
8.8 Mouthpiece for tenor cor (3425)
8.8 Mouthpiece for tenor cor (3427)
8.9 Mouthpiece for ballad horn (3349)
9.2 Mouthpiece for tenor horn (3047)
9.2 Mouthpiece for tenor horn (1893)
9.4 Mouthpiece for tenor horn (876)
9.4 Mouthpiece for tenor horn (668)
9.5 Mouthpiece for tenor horn (2960)
9.5 Mouthpiece for tenor horn (693)
9.8 Mouthpiece for mellohorn (?) (3517)
9.7 Mouthpiece for tenor horn (2303)
9.7 Mouthpiece for tenor horn (2821)
9.8 Mouthpiece for tenor horn (2976)
9.9 Mouthpiece for tenor tuba (3546)
10.0 Mouthpiece for tenor horn (1557)
10.0 Mouthpiece for tenor horn (674)
10.1 Mouthpiece for tenor horn (2959)
10.1 Mouthpiece for tenor horn (673)
10.1 Mouthpiece for tenor horn (629)
10.1 Mouthpiece for tenor horn (2737)
10.2 Mouthpiece for tenor horn (3518)
10.2 Mouthpiece for alto trumpet (3258)
10.2 Mouthpiece for tenor horn (2775)
10.3 Mouthpiece for tenor horn (3046)
10.3 Mouthpiece for tenor horn (2972)
10.3 Mouthpiece for tenor horn (683)
10.4 Mouthpiece for vocal horn (890)
10.5 Mouthpiece for tenor horn (3485)
11.3 Mouthpiece for tenor saxhorn (2657)

11.8 Mouthpiece for alphorn (3098)
12.2 Mouthpiece for alphorn (1828)

10.2 Mouthpiece for quinticlave (3240)

9.5 Mouthpiece for tenor trombone, suitable for alto trombone (661)
9.9 Mouthpiece for tenor trombone (3523)
9.7 Mouthpiece for tenor trombone (1895)
9.9 Mouthpiece for tenor trombone (1896)
10.0 Mouthpiece for trompette basse or tenor trombone (3218)
10.2 Mouthpiece for tenor trombone (3100)
10.3 Mouthpiece for tenor trombone (675)

10.3 Mouthpiece for tenor trombone (3006)
10.3 Mouthpiece for tenor trombone (827)
10.4 Mouthpiece for tenor trombone (1131)
10.4 Mouthpiece for tenor trombone (685)
10.4 Mouthpiece for baritone (3003)
10.5 Mouthpiece for tenor trombone (3008)
10.5 Mouthpiece for tenor trombone (3007)
10.6 Mouthpiece for tenor trombone or baritone (3594)
10.6 Mouthpiece for tenor tuba (3547)
10.6 Mouthpiece for tenor trombone (2828)
10.6 Mouthpiece for tenor trombone (2963)
10.6 Mouthpiece for tenor trombone or baritone saxhorn (2826)
10.6 Mouthpiece for tenor trombone (840)
10.6 Mouthpiece for tenor trombone (2983)
10.6 Mouthpiece for tenor trombone (2656)
10.6 Mouthpiece for baritone (805)
10.6 Mouthpiece for baritone (2304)
10.6 Mouthpiece for tenor trombone (2729)
10.6 Mouthpiece for tenor trombone (838)
10.7 Mouthpiece for alto trombone (2825)
10.7 Mouthpiece for tenor trombone (2962)
10.7 Mouthpiece for tenor trombone (1771)
10.7 Mouthpiece for tenor trombone (3005)
10.7 Mouthpiece for baritone (2961)
10.7 Mouthpiece for tenor trombone (637)
10.7 Mouthpiece for tenor trombone (2803)
10.7 Mouthpiece for tenor trombone (3009)
10.7 Mouthpiece for clairon basse (bass bugle) (3163)
10.7 Mouthpiece for tenor trombone (1289)
10.7 Mouthpiece for tenor trombone (701)
10.8 Mouthpiece for tenor trombone (665)
10.8 Mouthpiece for tenor trombone (2829)
10.9 Mouthpiece for tenor trombone (2696)
10.9 Mouthpiece for baritone (2822)
10.9 Mouthpiece for tenor trombone (2497)
10.9 Mouthpiece for tenor trombone (657)
10.9 Mouthpiece for baritone (2824)
10.9 Mouthpiece for baritone (2823)
10.9 Mouthpiece for tenor trombone (3526)
10.9 Mouthpiece for tenor trombone (2501)
10.9 Mouthpiece for baritone (1894)
11.0 Mouthpiece for tenor trombone (1123)
11.0 Mouthpiece for tenor trombone (2498)
11.0 Mouthpiece for tenor trombone (?) (3591)
11.0 Mouthpiece for tenor trombone (3597)
11.0 Mouthpiece for tenor trombone (1696)
11.0 Mouthpiece for tenor trombone (2964)
11.0 Mouthpiece for tenor trombone (666)
11.1 Mouthpiece for tenor trombone (3206)
11.1 Mouthpiece for baritone (2482)
11.1 Mouthpiece for tenor trombone (3595)
11.1 Mouthpiece for baritone (2827)
11.1 Mouthpiece for tenor trombone (2984)

11.1 Mouthpiece for baritone saxhorn (3353)
11.2 Mouthpiece for trompette basse (3522)
11.2 Mouthpiece for tenor trombone (2305)
11.2 Mouthpiece for tenor trombone (3413)
11.2 Mouthpiece for tenor trombone (2830)
11.3 Mouthpiece for baritone (3004)
11.3 Mouthpiece for tenor trombone (3525)
11.3 Mouthpiece for tenor trombone (3524)
11.3 Mouthpiece for tenor trombone (654)
11.3 Mouthpiece for bass trumpet (1290)
11.4 Mouthpiece for tenor trombone or Tenorhorn (1586)

10.6 Mouthpiece for euphonium (3014)
10.6 Mouthpiece for bass trombone (3011)
10.7 Mouthpiece for euphonium (3012)
10.8 Mouthpiece for ophicleide (3244)
10.8 Mouthpiece for euphonium (2832)
10.8 Mouthpiece for bass trombone (2985)
10.9 Mouthpiece for euphonium (3488)
10.9 Mouthpiece for bass trombone (2831)
10.9 Mouthpiece for euphonium (3490)
10.9 Mouthpiece for euphonium (3013)
10.9 Mouthpiece for bass trombone (677)
11.0 Mouthpiece for ophicleide (3314)
11.2 Mouthpiece for euphonium (2109)
11.2 Mouthpiece for ophicleide or bass trombone (1296)
11.1 Mouthpiece for trompe de chasse basse (3520)
11.1 Mouthpiece for ophicleide (3368)
11.3 Mouthpiece for bass trombone (824)
11.3 Mouthpiece for bass trombone (676)
11.4 Mouthpiece for bass trombone (2788)
11.5 Mouthpiece for euphonium (2326)
11.5 Mouthpiece for euphonium (3527)
11.5 Mouthpiece for ophicleide (2158)
11.6 Mouthpiece for bass saxhorn or trompe de chasse basse (?) (3473)
11.7 Mouthpiece (623)
11.7 Mouthpiece for bass trombone (3340)
11.7 Mouthpiece for bass trombone (2966)
11.7 Mouthpiece for bass trombone (638)
11.8 Mouthpiece for euphonium (2306)
11.8 Mouthpiece for bass trombone (3010)
11.8 Mouthpiece for bass trombone (2965)
11.8 Mouthpiece for bass trombone (3256)
11.8 Mouthpiece for euphonium (1899)
11.8 Mouthpiece for bass trombone (3095)
11.9 Mouthpiece for bass saxhorn (3529)
12.0 Mouthpiece for bass trombone (1291)
12.1 Mouthpiece for bass trombone (1577)
12.2 Mouthpiece for euphonium (3528)
12.5 Mouthpiece for bass trombone (3027)
13.2 Mouthpiece for bass trombone (2707)

11.1 Mouthpiece for bass horn (3306)

11.2 Mouthpiece for Russian bassoon (2981)
11.2 Mouthpiece for serpent or bass horn (3311)
11.4 Mouthpiece for serpent or ophicleide (1897)
11.8 Mouthpiece for Russian bassoon (3308)
11.9 Mouthpiece for serpent (3373)
12.0 Mouthpiece for serpent (999)
12.2 Mouthpiece for serpent (1007)
12.4 Mouthpiece for serpent (1726)
12.6 Mouthpiece for bass horn (627)
12.7 Mouthpiece for serpent (1898)
12.3 Mouthpiece for serpent (884)
13.2 Mouthpiece for serpent (624)
13.5 Mouthpiece for serpent (3304)

12.9 Mouthpiece for contrabass serpent (2930)

11.0 Mouthpiece for E♭ bass (872)
11.3 Mouthpiece for E♭ bass (655)
11.7 Mouthpiece for E♭ bass (1159)
11.8 Mouthpiece for E♭ bass (2836)
11.8 Mouthpiece for tuba (686)
11.9 Mouthpiece for bombardon (2967)
12.1 Mouthpiece for tuba (2132)
12.3 Mouthpiece for contrabass (3531)
12.5 Mouthpiece for E♭ bass (2834)
12.4 Mouthpiece for bombardon or E♭ bass (2588)
12.4 Mouthpiece for bombardon (1161)
12.5 Mouthpiece for bombardon or E♭ bass (631)
12.5 Mouthpiece for B♭ tuba (825)
12.5 Mouthpiece for B♭ tuba (801)
12.5 Mouthpiece for B♭ tuba (634)
12.6 Mouthpiece for B♭ tuba (1794)
12.6 Mouthpiece for B♭ tuba (2710)
12.6 Mouthpiece for E♭ bass (1873)
12.6 Mouthpiece for B♭ tuba (632)
12.7 Mouthpiece for E♭ bass (2835)
12.8 Mouthpiece for E♭ bass (3530)
12.8 Mouthpiece for B♭ tuba (2837)
13.1 Mouthpiece for contrabass saxhorn (3230)
13.2 Mouthpiece for contrabass (2483)
13.4 Mouthpiece for contrabass (3532)
14.0 Mouthpiece for contrabass (2499)
14.3 Mouthpiece for contrabass (2340)

Appendix E

Mouthpieces ranked by cup volume

This table lists the cup volumes of selected mouthpieces in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Maker**, **Place** and **Date**

Specimens have been sought which are closely associated with particular instruments typical of their place and period. There is nearly always a considerable degree of uncertainty as to whethèr a historic mouthpiece was supplied with an instrument when new, used by a former player with an instrument, or 'thrown in with' an instrument when it was last sold. In many cases curators and collectors do not know the nature of the association. Consequently, there will be some degree of scatter in the instrument names given to these specimens, especially where mouthpieces have in the past been numerous and readily interchangeable as with keyed bugles and cornopeans, bass trombones and ophicleides respectively.

Volume

This is the cup volume calculated as defined in Equation 7.2, given in cubic millimetres.

The calculation of mouthpiece cup volumes depends on measurements of depth and diameter using plug gauges. Since most mouthpieces are lathe turned to close tolerances, the gauges give measurements to a high degree of accuracy. An error in a single gauge depth of 1mm leads to an error in the volume of an average mouthpiece of only 1.5%; the plug gauges can in fact be confidently used to an accuracy of better than 0.1mm and a mistaken depth measurement of much less than 1mm would be noticed in the drawing of the profile. The least precise measurement is that of the bite radius of curvature, which is given to the nearest 0.25mm but is necessarily an approximation since in general the curvature of between the cup and the rim is not a quadrant of a circle. Calculations on data for typical small, medium and large mouthpieces, a cornett

(EUCHMI 3492), a trompe (EUCHMI 3493) and a trombone (EUCHMI 665) respectively, show that an error of 0.25mm in the bite radius of curvature leads to an error in the computed volume of between 1% and 3%.

Thus for comparative purposes, these mouthpiece volumes can be considered accurate to ± 3%. There must be a higher degree of uncertainty in the degree to which volumes calculated in this way correspond to the acoustically effective volumes. There is necessarily a degree of uncertainty as to where the cup ends and the grain or backbore begins, though the contribution to total volume of a short distance of narrow diameter tubing is small. There is an even greater degree of uncertainty as to how much of the cup volume is occupied by the lips of the player since this is dynamically changing as a tone is produced and statically varied by the player as part of performance technique.

		Instrument	Maker	Place	Date	Volume
HW	E	Cornett	Monk	UK	l.20	498
HW	C	Cornett	Monk	UK	l.20	531
EU	3492	Cornett	Monk	UK	l.20	569
HW	16	Cornett	Monk	UK	l.20	615
HW	DE	Cornett	Delmas	France	l.20	631
EU	2344	Bugle	Honsuy	Spain	1984	793
EU	2469	Bugle	Honsuy	Spain	1985	839
EU	3515	Trumpet	Bach	New York	m.20	905
HW	DW3E	Trumpet	Wick 3E	UK	l.20	910
EU	3593	Cornet with trumpet cup			e.20	937
FT	242	Trumpet	Rudall Carte	London	c 1930	956
RP	MC	Mute cornett	Monk	UK	l.20	1062
LHC	74	Posthorn				1080
OB	621	Post horn in 3½-ft Eflat	Rudall Carte	London	l.19	1096
EU	997	Trumpet	Haas (?)	Nürnberg	c 1700	1109
EU	3268	Cornet	Courtois	Paris	m.19	1135
BK	385	Trumpet	Kretzschmann (?)	France (?)	e.19	1139
EU	3500	Swedish kornett	Ahlberg & Ohlsson	Sweden	l.19 /e.20	1176
EU	3516	Trumpet	Zottola	USA	l.20	1176
HW	VB7C	Trumpet	Bach 7C	USA	l.20	1211
EU	3502	Soprano cornet	Higham	Manchester	l.19	1281
EU	1287	Soprano trombone	Couesnon (?)	Paris	c 1925	1281
HW	VB1C	Trumpet	Bach 1C	USA	l.20	1319
EU	904	Bugle		Germany	c 1914	1410
EU	3019	Post-horn		Germany	l.19/e.20	1421
EU	3430	Soprano saxhorn	Gautrot (?)	Paris	l.19	1469
LHC	201	Cornet simple	Kretschmann (?)	France	e.19	1472
JW	TSB	Slide trumpet	Besson	London	m.19	1515
EU	672	Trumpet			l.19/e.20	1544
EU	648	Trumpet	Glen (?)	Edinburgh	1855 (?)	1573
EU	3294	Cornopean			m.19	1620
LHC	75	Lied horn	Boosey (?)	London	l.19	1624

		Instrument	Maker	Place	Date	Volume
HW	DW4B	Cornet	Wick 4B	UK	l.20	1626
OB	75	Circular trumpet	Jahn (?)		e.19	1627
LHC	115	Keyed bugle	Holles (?)	Britain (?)	m.19	1629
LHC	307	Horn	Bull (?)	Britain (?)	l.17	1635
OB	622	Cornet	Pask	London	m.19	1657
FT	197a	Cornopean	Baker (?)	London	c 1840	1674
FT	171	Keyed bugle in 3½-ft Eflat	Pace (?)	London	c 1840	1683
EU	650	Trumpet	Key (?)	London	c 1850	1686
OP	3827	Keyed bugle	Garrett	London	e.19	1694
FT	046a	Cornet, regular model	Courtois	Paris	l.19	1705
EU	3216	Trumpet	Kohler	London	m.19	1713
OP	3834	Keyed bugle	Greenhill (?)	London	e.19	1723
EU	993	Bugle			l.19	1752
JW	TSK	Slide trumpet [silver]	Kohler	London	m.19	1784
EU	3287	Trumpet	Pace (?)	London	c 1840	1801
LHC	150	Trumpet	Sandbach & Wyatt (?)	Britain (?)	m.19	1816
EU	3478	Cornet	Courtois	Paris	c 1870	1817
BK	191B	Slide trumpet	F. Besson	London	c 1890	1819
BK	191A	Slide trumpet	F. Besson	London	c 1890	1832
FT	134	Cornet	Kohler (?)	London	c 1855	1835
JW	TSL	Slide trumpet [wood]	Kohler	London	m.19	1848
LHC	37	Keyed bugle	Metzler (?)	Britain (?)	e.19	1849
OB	B	Cornet	Conn, `Levy model'	USA	c 1900	1850
EU	3476	Cornet	Courtois	Paris	c 1855-60	1865
EU	906	Cornet	Higham	Manchester	c 1900	1876
FT	197b	Cornopean	Baker (?)	London	c 1840	1882
EU	3281	Trumpet		Britain (?)	19	1903
OB	684	Cornet	Kohler (?)	London	m.19	1910
FT	046b	Cornet, hornplayer's model	Courtois	Paris	l.19	1913
EU	3238	Keyed bugle	Köhler	London	m.19	1919
EU	642	Cornopean	Kohler	London	m.19	1921
EU	2781	Cornet	Butler	London	c 1880	1924

		Instrument	Maker	Place	Date	Volume
JW	BKK	Keyed bugle	Kohler	London	m.19	1932
EU	3479	Cornet	Courtois	Paris	c 1870	1963
FT	225	Cornet	Distin	London	c 1850	1981
OB	624	Post horn or bugle	Courtois	Paris	1863	1997
FT	197c	Cornopean	Baker (?)	London	c 1840	2021
OB	633	Keyed bugle	Tabard (?)	Lyon (?)	e.19	2047
EU	866	French horn		Germany (?)	l.19/e.20	2051
EU	908	Keyed bugle	Possibly Halari	Paris	c 1830	2178
LHC	92	Soprano saxhorn	Distin	London	m.19	2309
EU	2374	Alto trumpet	Weidlich (?)	Regensburg	l.19	2313
OB	64	French horn / trompe	Besson	Paris	l.19	2338
EU	3497	French horn	Bach	New York	l.19	2447
BK	156	Trompe	F. Périnet 0½	Paris	e.20	2453
LHC	198	Cornet	Distin (?)		m.19	2514
JW	BQA	Quinticlave		France (?)	e.19	2532
OB	65	French horn [ivory]	Courtois (?)	Paris (?)	19	2604
JW	IKC	Koenig horn in 6ft F	Courtois	Paris	c 1870	2667
EU	2628	French horn	Winkings (?)	London	c 1740	2722
EU	3546	Tenor tuba	Distin	London	c 1860	2768
JW	CBR	Vocal horn	Rudall Carte	London	l.19	2784
OB	6b	French horn			19	2795
LHC	239	Bugle horn	Fürst (?)			2925
EU	3349	Ballad horn	Boosey & Co	London	c 1895	2998
EU	890	Vocal horn	Rudall Carte	London	c 1885	3024
EU	3493	Trompe de chasse	Milliens	France	l.20	3027
EU	3240	Quinticlave		France (?)	m.19	3038
OB	x78	Trumpet	Beale (?)	London (?)	1667 (?)	3048
JW	IMC	Melody horn in 6ft F	Courtois / Mille	Paris	l.19	3129
EU	635	French horn	Kersten	Dresden	c 1830	3161
FT	136	Ballad horn	Keat (?)	London	c 1890	3167
EU	2696	Sackbut	Büchel	Germany	l.20	3203
JW	CBS	Vocal horn	Rudall Carte	London	l.19	3218

		Instrument	Maker	Place	Date	Volume
LHC	314	Trombone	Roth (?)			3258
OB	6a	French horn			l.18/e.19	3565
EU	2962	Tenor trombone	Salvation Army	Luton	m.20	3747
OB	603	French horn	Bennett (?)		c 1700	3760
OB	506	a.w. Serpent forveille	H. Keat & Sons	London	l.19	3775
BK	179	Vocal horn	Rudall Carte	London	c 1870	3777
JW	PAC	Alto trombone	Courtois / Mille	Paris	l.19	3778
LHC	161	Tenor cor	Distin (?)		m.19	3790
LHC	91	Tenor saxhorn				3877
EU	3759	Cornophone basse	Besson	France	l.19	3914
LHC	246	Russian bassoon				4006
OB	B1	Cor basse			e.19	4022
EU	2825	Alto trombone		Britain (?)	l.19/e.20	4033
EU	656	French horn	Kohler (?)	London	1856	4124
EU	846	French horn		Britain (?)	e.19	4140
LHC	206	Clavicor			c 1845	4323
JW	PAH	Alto trombone	Hawkes	London	l.19	4385
EU	3670	Trombone	Werma	Germany	m.20	4610
EU	665	Trombone	Selmer	London	m.20	4615
EU	3206	Tenor trombone		Austria (?)	19	4619
EU	1586	Tenor trom / Tenorhorn		Austria	e.20	4721
EU	1123	Trombone	Boosey & Hawkes	London	m.20	4948
EU	3547	Tenor tuba	Distin	London	c 1860	5057
BK	232	Ophimonocleide [ivory]		France (?)	e.19	5181
BK	28	Clavicor		France (?)	c 1850	5269
EU	3311	Serpent or bass horn		Britain (?)	e.19	5289
EU	3100	Tenor trombone	Courtois	Paris	l.19/e.20	5308
EU	3308	Russian bassoon		Britain (?)	c 1840	5535
EU	2983	Trombone	Besson		l.19/e.20	5706
AM	688	Bass sackbut	Thein	Germany	c 1980	5788
OB	605	French horn	Haas (?)			5866
FT	94	Tenor trombone	Higham	Manchester	c 1865	5873

		Instrument	Maker	Place	Date	Volume
EU	3306	Bass horn			m.19	5919
LHC	171	Trombone				5924
OB	503	Bass horn		Britain (?)	e.19	5951
EU	3535	Tenor trombone		France	l.19/e.20	5956
FT	79	Serpent	Roe (?)	Liverpool (?)	e.19	6177
EU	3368	Ophicleide	T. Glen (?)	Edinburgh	c 1860	6277
EU	3595	Trombone	Besson	London	e.20	6292
EU	1289	Tenor trombone	Bach 18	USA	m.20	6361
EU	3353	Baritone saxhorn	Courtois	Paris	c 1855	6447
AM	189	Trombone	Bach 6½AL	USA	c 1975	6550
EU	2830	Tenor trombone	Besson	London	l.19/e.20	6556
EU	3520	Trompe de chasse basse		France	l.19/e.20	6591
LHC	223	Serpent				6834
FT	AL	Sackbut	Tomes	London	1997	6904
LHC	124	Bass horn			e.19	6955
OP	8618	Serpent				7226
OB	x502	Serpent [ivory]		Britain (?)	e.19	7390
EU	1007	Serpent			e.19	7413
EU	3373	Serpent	Metzler (?)	London	c 1825	7576
LHC	106	Ophicleide	Gautrot (?)	France	m.19	7659
EU	3314	Ophicleide		Britain (?)	c 1850	7901
LHC	262	Serpent	Bilton (?)	Britain (?)	m.19	7941
JW	BOC	Ophicleide	Collin (?)	Paris (?)	e.19	7965
EU	3304	Serpent		France (?)	c 1750	7990
AM	192	Trombone	Remington	USA	c 1977	7995
EU	3027	Bass trombone			c 1835	8013
EU	1296	Ophicleide or b. trom		Britain (?)	e.19	8275
EU	3256	G Bass trombone	Boosey & Hawkes	London	c 1951	8576
EU	624	Serpent	Taylor (?)	Glasgow	c 1815	8668
FT	104	Serpent [metal]	Key, Rudall (?)	London	c 1858	8712
EU	2158	Ophicleide	Higham	Manchester	m.19	8803
EU	677	Bass trombone	Courtois	Paris	c 1900	8882

		Instrument	Maker	Place	Date	Volume
OP	5011	Ophicleide	Higham	Manchester	m.19	9066
OB	B2	Euphonium	Courtois / Mille	Paris	l.19	9081
BK	40	Serpent Forveille		France (?)	c 1830	9230
LHC	235	Serpent				10137
EU	1898	Serpent			e.19	10427
BK	234	Contrabass trombone	Courtois (?)	France (?)	c 1895	10722
CRB	410	Contrabass trombone	Thibouville-Lamy (?)	France	c 1900	10741
EU	1161	Bombardon	Distin	London	m.19	10980
EU	627	Bass horn		Britain (?)	c 1825	12258
EU	3532	Contrabass	Nikkan	Japan	l.20	16685
EU	2930	Contrabass serpent	Wood brothers	Huddersfield	c 1840	19572

Appendix F

Mouthpieces ranked by Shape Quotient

This table lists the Shape Quotients of selected mouthpieces in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Maker**, **Place** and **Date**

These are the same specimens as those in Appendix E.

Shape

This is the dimensionless Shape Quotient calculated as defined in Equation 7.3.

The considerations of accuracy are as for Appendix E.

		Instrument	Maker	Place	Date	Shape
EU	635	French horn	Kersten	Dresden	c 1830	0.660
EU	846	French horn		Britain (?)	e.19	0.707
OB	6b	French horn			19	0.748
LHC	307	Horn	Bull (?)	Britain (?)	l.17	0.770
OB	6a	French horn			l.18/e.19	0.771
BK	179	Vocal horn	Rudall Carte	London	c 1870	0.773
OB	603	French horn	Bennett (?)		c 1700	0.842
FT	136	Ballad horn	Keat (?)	London	c 1890	0.864
JW	CBS	Vocal horn	Rudall Carte	London	l.19	0.878
EU	656	French horn	Kohler (?)	London	1856	0.892
OB	B1	Cor basse			e.19	0.901
OB	605	French horn	Haas (?)			0.918
EU	3493	Trompe de chasse	Milliens	France	l.20	0.942
OB	65	French horn [ivory]	Courtois (?)	Paris (?)	19	0.942
HW	16	Cornett	Monk	UK	l.20	1.000
OB	633	Keyed bugle	Tabard (?)	Lyon (?)	e.19	1.000
EU	908	Keyed bugle	Possibly Halari	Paris	c 1830	1.000
OB	64	French horn / trompe	Besson	Paris	l.19	1.000
BK	156	Trompe	F. Périnet 0½	Paris	e.20	1.000
EU	2628	French horn	Winkings (?)	London	c 1740	1.000
EU	890	Vocal horn	Rudall Carte	London	c 1885	1.000
JW	PAC	Alto trombone	Courtois / Mille	Paris	l.19	1.000
EU	3100	Tenor trombone	Courtois	Paris	l.19/e.20	1.000
JW	IKC	Koenig horn in 6ft F	Courtois	Paris	c 1870	1.021
EU	3535	Tenor trombone		France	l.19/e.20	1.037
LHC	75	Lied horn	Boosey (?)	London	l.19	1.038
EU	3430	Soprano saxhorn	Gautrot (?)	Paris	l.19	1.042
EU	866	French horn		Germany (?)	l.19/e.20	1.044
EU	648	Trumpet	Glen (?)	Edinburgh	1855 (?)	1.048
EU	3314	Ophicleide		Britain (?)	c 1850	1.050
LHC	74	Posthorn				1.062
JW	CBR	Vocal horn	Rudall Carte	London	l.19	1.062

		Instrument	Maker	Place	Date	Shape
EU	3593	Cornet with trumpet cup			e.20	1.072
EU	3759	Cornophone basse	Besson	France	l.19	1.078
EU	3497	French horn	Bach	New York	l.19	1.082
EU	3502	Soprano cornet	Higham	Manchester	l.19	1.087
EU	3478	Cornet	Courtois	Paris	c 1870	1.087
JW	IMC	Melody horn in 6ft F	Courtois / Mille	Paris	l.19	1.089
EU	3520	Trompe de chasse basse		France	l.19/e.20	1.094
EU	642	Cornopean	Kohler	London	m.19	1.100
LHC	198	Cornet	Distin (?)		m.19	1.105
HW	DE	Cornett	Delmas	France	l.20	1.105
EU	1287	Soprano trombone	Couesnon (?)	Paris	c 1925	1.109
LHC	92	Soprano saxhorn	Distin	London	m.19	1.110
LHC	115	Keyed bugle	Holles (?)	Britain (?)	m.19	1.117
LHC	201	Cornet simple	Kretschmann (?)	France	e.19	1.117
OB	622	Cornet	Pask	London	m.19	1.117
OB	506	a.w. Serpent forveille	H. Keat & Sons	London	l.19	1.118
OB	503	Bass horn		Britain (?)	e.19	1.119
BK	28	Clavicor		France (?)	c 1850	1.123
EU	3368	Ophicleide	T. Glen (?)	Edinburgh	c 1860	1.124
RP	MC	Mute cornett	Monk	UK	l.20	1.125
FT	046b	Cornet, hornplayer's model	Courtois	Paris	l.19	1.126
EU	3268	Cornet	Courtois	Paris	m.19	1.128
OB	621	Post horn in 3½-ft Eflat	Rudall Carte	London	l.19	1.130
HW	DW3E	Trumpet	Wick 3E	UK	l.20	1.133
OB	624	Post horn or bugle	Courtois	Paris	1863	1.134
EU	3238	Keyed bugle	Köhler	London	m.19	1.144
EU	3240	Quinticlave		France (?)	m.19	1.149
OB	B	Cornet	Conn, `Levy model'	USA	c 1900	1.150
EU	3353	Baritone saxhorn	Courtois	Paris	c 1855	1.155
JW	BQA	Quinticlave		France (?)	e.19	1.156
EU	3306	Bass horn			m.19	1.159
EU	906	Cornet	Higham	Manchester	c 1900	1.161

		Instrument	Maker	Place	Date	Shape
LHC	106	Ophicleide	Gautrot (?)	France	m.19	1.161
LHC	246	Russian bassoon				1.161
EU	2962	Tenor trombone	Salvation Army	Luton	m.20	1.163
EU	3479	Cornet	Courtois	Paris	c 1870	1.167
EU	993	Bugle			l.19	1.168
EU	672	Trumpet			l.19/e.20	1.169
FT	046a	Cornet, regular model	Courtois	Paris	l.19	1.169
OP	3827	Keyed bugle	Garrett	London	e.19	1.172
EU	3349	Ballad horn	Boosey & Co	London	c 1895	1.173
EU	2781	Cornet	Butler	London	c 1880	1.175
HW	VB7C	Trumpet	Bach 7C	USA	l.20	1.179
FT	197b	Cornopean	Baker (?)	London	c 1840	1.184
EU	1296	Ophicleide or b. trom		Britain (?)	e.19	1.188
EU	3546	Tenor tuba	Distin	London	c 1860	1.188
LHC	314	Trombone	Roth (?)			1.189
EU	3500	Swedish kornett	Ahlberg & Ohlsson	Sweden	l.19 /e.20	1.189
EU	3516	Trumpet	Zottola	USA	l.20	1.189
FT	197c	Cornopean	Baker (?)	London	c 1840	1.190
EU	904	Bugle		Germany	c 1914	1.195
OB	684	Cornet	Kohler (?)	London	m.19	1.197
HW	VB1C	Trumpet	Bach 1C	USA	l.20	1.198
AM	189	Trombone	Bach 6½AL	USA	c 1975	1.198
EU	3515	Trumpet	Bach	New York	m.20	1.199
EU	2830	Tenor trombone	Besson	London	l.19/e.20	1.207
LHC	206	Clavicor			c 1845	1.208
FT	225	Cornet	Distin	London	c 1850	1.212
FT	242	Trumpet	Rudall Carte	London	c 1930	1.213
OP	3834	Keyed bugle	Greenhill (?)	London	e.19	1.215
EU	1586	Tenor trom / Tenorhorn		Austria	e.20	1.217
FT	134	Cornet	Kohler (?)	London	c 1855	1.218
JW	BOC	Ophicleide	Collin (?)	Paris (?)	e.19	1.219
FT	197a	Cornopean	Baker (?)	London	c 1840	1.222

		Instrument	Maker	Place	Date	Shape
EU	3670	Trombone	Werma	Germany	m.20	1.223
LHC	161	Tenor cor	Distin (?)		m.19	1.223
EU	3492	Cornett	Monk	UK	l.20	1.224
FT	104	Serpent [metal]	Key, Rudall (?)	London	c 1858	1.224
FT	171	Keyed bugle in 3½-ft Eflat	Pace (?)	London	c 1840	1.225
EU	997	Trumpet	Haas (?)	Nürnberg	c 1700	1.225
HW	C	Cornett	Monk	UK	l.20	1.226
EU	3294	Cornopean			m.19	1.227
LHC	37	Keyed bugle	Metzler (?)	Britain (?)	e.19	1.228
LHC	91	Tenor saxhorn				1.228
EU	3532	Contrabass	Nikkan	Japan	l.20	1.228
CRB	410	Contrabass trombone	Thibouville-Lamy (?)	France	c 1900	1.231
OB	B2	Euphonium	Courtois / Mille	Paris	l.19	1.240
HW	DW4B	Cornet	Wick 4B	UK	l.20	1.240
EU	677	Bass trombone	Courtois	Paris	c 1900	1.242
EU	1123	Trombone	Boosey & Hawkes	London	m.20	1.244
HW	E	Cornett	Monk	UK	l.20	1.245
EU	2469	Bugle	Honsuy	Spain	1985	1.247
EU	2983	Trombone	Besson		l.19/e.20	1.252
EU	3281	Trumpet		Britain (?)	19	1.257
OP	8618	Serpent				1.258
LHC	223	Serpent				1.261
FT	94	Tenor trombone	Higham	Manchester	c 1865	1.264
EU	3476	Cornet	Courtois	Paris	c 1855-60	1.266
JW	BKK	Keyed bugle	Kohler	London	m.19	1.267
LHC	235	Serpent				1.275
EU	2344	Bugle	Honsuy	Spain	1984	1.277
BK	385	Trumpet	Kretzschmann (?)	France (?)	e.19	1.278
LHC	150	Trumpet	Sandbach & Wyatt (?)	Britain (?)	m.19	1.281
EU	2696	Sackbut	Büchel	Germany	l.20	1.285
EU	3595	Trombone	Besson	London	e.20	1.292
BK	191B	Slide trumpet	F. Besson	London	c 1890	1.296

		Instrument	Maker	Place	Date	Shape
JW	TSB	Slide trumpet	Besson	London	m.19	1.300
OB	x502	Serpent [ivory]		Britain (?)	e.19	1.307
EU	1161	Bombardon	Distin	London	m.19	1.310
EU	3547	Tenor tuba	Distin	London	c 1860	1.313
BK	234	Contrabass trombone	Courtois (?)	France (?)	c 1895	1.316
JW	PAH	Alto trombone	Hawkes	London	l.19	1.319
AM	192	Trombone	Remington	USA	c 1977	1.322
EU	2158	Ophicleide	Higham	Manchester	m.19	1.326
BK	191A	Slide trumpet	F. Besson	London	c 1890	1.331
EU	1007	Serpent			e.19	1.332
EU	2374	Alto trumpet	Weidlich (?)	Regensburg	l.19	1.335
EU	3019	Post-horn		Germany	l.19/e.20	1.336
EU	2825	Alto trombone		Britain (?)	l.19/e.20	1.338
LHC	262	Serpent	Bilton (?)	Britain (?)	m.19	1.344
EU	650	Trumpet	Key (?)	London	c 1850	1.344
EU	3256	G Bass trombone	Boosey & Hawkes	London	c 1951	1.357
JW	TSK	Slide trumpet [silver]	Kohler	London	m.19	1.366
EU	3206	Tenor trombone		Austria (?)	19	1.367
EU	1289	Tenor trombone	Bach 18	USA	m.20	1.371
LHC	239	Bugle horn	Fürst (?)			1.371
EU	3027	Bass trombone			c 1835	1.372
EU	665	Trombone	Selmer	London	m.20	1.379
EU	3308	Russian bassoon		Britain (?)	c 1840	1.384
FT	AL	Sackbut	Tomes	London	1997	1.392
JW	TSL	Slide trumpet [wood]	Kohler	London	m.19	1.394
OB	x78	Trumpet	Beale (?)	London (?)	1667 (?)	1.396
LHC	171	Trombone				1.398
EU	3287	Trumpet	Pace (?)	London	c 1840	1.398
LHC	124	Bass horn			e.19	1.399
EU	1898	Serpent			e.19	1.423
AM	688	Bass sackbut	Thein	Germany	c 1980	1.427
EU	3216	Trumpet	Kohler	London	m.19	1.428

		Instrument	Maker	Place	Date	Shape
EU	3373	Serpent	Metzler (?)	London	c 1825	1.457
FT	79	Serpent	Roe (?)	Liverpool (?)	e.19	1.461
OP	5011	Ophicleide	Higham	Manchester	m.19	1.464
EU	2930	Contrabass serpent	Wood brothers	Huddersfield	c 1840	1.475
BK	232	Ophimonocleide [ivory]		France (?)	e.19	1.507
OB	75	Circular trumpet	Jahn (?)		e.19	1.528
EU	3304	Serpent		France (?)	c 1750	1.569
EU	624	Serpent	Taylor (?)	Glasgow	c 1815	1.598
BK	40	Serpent Forveille		France (?)	c 1830	1.642
EU	3311	Serpent or bass horn		Britain (?)	e.19	1.684
EU	627	Bass horn		Britain (?)	c 1825	1.750

Appendix G

Mouthpieces ranked by Resonance Factor

This table lists the Resonance Factors of selected mouthpieces in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Maker**, **Place** and **Date**

These are the same specimens as those in Appendix E.

R factor

This is the Resonance Factor calculated as defined in Equation 7.4, given in m^{-1}.

The considerations of accuracy are as for Appendix E.

		Instrument	Maker	Place	Date	R factor
RP	MC	Mute cornett	Monk	UK	l.20	25.31
JW	TSK	Slide trumpet [silver]	Kohler	London	m.19	15.48
EU	3515	Trumpet	Bach	New York	m.20	13.20
HW	DW3E	Trumpet	Wick 3E	UK	l.20	12.14
EU	650	Trumpet	Key (?)	London	c 1850	12.12
EU	997	Trumpet	Haas (?)	Nürnberg	c 1700	12.08
EU	3502	Soprano cornet	Higham	Manchester	l.19	11.66
LHC	74	Posthorn				11.64
EU	3287	Trumpet	Pace (?)	London	c 1840	11.48
EU	3268	Cornet	Courtois	Paris	m.19	11.29
EU	3216	Trumpet	Kohler	London	m.19	11.05
BK	385	Trumpet	Kretzschmann (?)	France (?)	e.19	10.87
JW	TSL	Slide trumpet [wood]	Kohler	London	m.19	10.62
EU	2696	Sackbut	Büchel	Germany	l.20	10.52
EU	3500	Swedish kornett	Ahlberg & Ohlsson	Sweden	l.19 /e.20	10.47
EU	3492	Cornett	Monk	UK	l.20	10.06
FT	197a	Cornopean	Baker (?)	London	c 1840	10.06
LHC	201	Cornet simple	Kretschmann (?)	France	e.19	9.87
EU	1287	Soprano trombone	Couesnon (?)	Paris	c 1925	9.86
HW	E	Cornett	Monk	UK	l.20	9.86
JW	TSB	Slide trumpet	Besson	London	m.19	9.76
HW	DE	Cornett	Delmas	France	l.20	9.76
EU	3593	Cornet with trumpet cup			e.20	9.69
LHC	150	Trumpet	Sandbach & Wyatt (?)	Britain (?)	m.19	9.47
FT	046a	Cornet, regular model	Courtois	Paris	l.19	9.29
HW	C	Cornett	Monk	UK	l.20	9.24
EU	993	Bugle			l.19	9.24
OP	3827	Keyed bugle	Garrett	London	e.19	9.18
EU	2469	Bugle	Honsuy	Spain	1985	9.00
OB	621	Post horn in 3½-ft Eflat	Rudall Carte	London	l.19	8.98
OB	x78	Trumpet	Beale (?)	London (?)	1667 (?)	8.97
HW	16	Cornett	Monk	UK	l.20	8.97

		Instrument	Maker	Place	Date	R factor
EU	2962	Tenor trombone	Salvation Army	Luton	m.20	8.94
EU	2344	Bugle	Honsuy	Spain	1984	8.91
JW	CBR	Vocal horn	Rudall Carte	London	l.19	8.91
JW	BKK	Keyed bugle	Kohler	London	m.19	8.83
FT	242	Trumpet	Rudall Carte	London	c 1930	8.78
FT	134	Cornet	Kohler (?)	London	c 1855	8.74
HW	VB7C	Trumpet	Bach 7C	USA	l.20	8.69
HW	DW4B	Cornet	Wick 4B	UK	l.20	8.68
EU	3516	Trumpet	Zottola	USA	l.20	8.66
EU	642	Cornopean	Kohler	London	m.19	8.65
FT	197b	Cornopean	Baker (?)	London	c 1840	8.64
EU	3546	Tenor tuba	Distin	London	c 1860	8.58
OB	506	a.w. Serpent forveille	H. Keat & Sons	London	l.19	8.52
EU	3019	Post-horn		Germany	l.19/e.20	8.49
EU	3238	Keyed bugle	Köhler	London	m.19	8.36
OB	624	Post horn or bugle	Courtois	Paris	1863	8.36
EU	3478	Cornet	Courtois	Paris	c 1870	8.33
OB	6b	French horn			19	8.19
EU	904	Bugle		Germany	c 1914	8.17
LHC	75	Lied horn	Boosey (?)	London	l.19	8.13
FT	197c	Cornopean	Baker (?)	London	c 1840	8.12
LHC	115	Keyed bugle	Holles (?)	Britain (?)	m.19	8.10
BK	191B	Slide trumpet	F. Besson	London	c 1890	8.10
OP	3834	Keyed bugle	Greenhill (?)	London	e.19	8.04
FT	171	Keyed bugle in 3½-ft Eflat	Pace (?)	London	c 1840	8.00
EU	3476	Cornet	Courtois	Paris	c 1855-60	7.97
LHC	307	Horn	Bull (?)	Britain (?)	l.17	7.88
EU	2781	Cornet	Butler	London	c 1880	7.80
EU	890	Vocal horn	Rudall Carte	London	c 1885	7.77
EU	672	Trumpet			l.19/e.20	7.74
OB	B	Cornet	Conn, `Levy model'	USA	c 1900	7.67
JW	IKC	Koenig horn in 6ft F	Courtois	Paris	c 1870	7.66

		Instrument	Maker	Place	Date	R factor
EU	648	Trumpet	Glen (?)	Edinburgh	1855 (?)	7.63
HW	VB1C	Trumpet	Bach 1C	USA	l.20	7.63
EU	906	Cornet	Higham	Manchester	c 1900	7.53
BK	191A	Slide trumpet	F. Besson	London	c 1890	7.49
OB	622	Cornet	Pask	London	m.19	7.40
EU	3281	Trumpet		Britain (?)	19	7.35
EU	3308	Russian bassoon		Britain (?)	c 1840	7.19
LHC	37	Keyed bugle	Metzler (?)	Britain (?)	e.19	7.14
FT	046b	Cornet, hornplayer's model	Courtois	Paris	l.19	7.04
LHC	206	Clavicor			c 1845	6.98
OB	684	Cornet	Kohler (?)	London	m.19	6.91
EU	635	French horn	Kersten	Dresden	c 1830	6.77
JW	BQA	Quinticlave		France (?)	e.19	6.76
EU	656	French horn	Kohler (?)	London	1856	6.58
OB	633	Keyed bugle	Tabard (?)	Lyon (?)	e.19	6.45
EU	3240	Quinticlave		France (?)	m.19	6.41
JW	IMC	Melody horn in 6ft F	Courtois / Mille	Paris	l.19	6.40
OB	65	French horn [ivory]	Courtois (?)	Paris (?)	19	6.38
FT	225	Cornet	Distin	London	c 1850	6.28
AM	688	Bass sackbut	Thein	Germany	c 1980	6.27
OB	603	French horn	Bennett (?)		c 1700	6.27
EU	3497	French horn	Bach	New York	l.19	6.21
EU	3353	Baritone saxhorn	Courtois	Paris	c 1855	6.19
EU	3349	Ballad horn	Boosey & Co	London	c 1895	6.16
JW	PAH	Alto trombone	Hawkes	London	l.19	6.15
EU	3479	Cornet	Courtois	Paris	c 1870	6.15
EU	3294	Cornopean			m.19	6.14
EU	2374	Alto trumpet	Weidlich (?)	Regensburg	l.19	6.13
OB	75	Circular trumpet	Jahn (?)		e.19	6.08
FT	79	Serpent	Roe (?)	Liverpool (?)	e.19	6.07
EU	3547	Tenor tuba	Distin	London	c 1860	6.07
EU	866	French horn		Germany (?)	l.19/e.20	6.07

		Instrument	Maker	Place	Date	R factor
EU	3430	Soprano saxhorn	Gautrot (?)	Paris	l.19	6.04
JW	CBS	Vocal horn	Rudall Carte	London	l.19	6.03
LHC	92	Soprano saxhorn	Distin	London	m.19	6.00
EU	2983	Trombone	Besson		l.19/e.20	6.00
EU	2830	Tenor trombone	Besson	London	l.19/e.20	5.94
LHC	246	Russian bassoon				5.93
EU	2628	French horn	Winkings (?)	London	c 1740	5.92
EU	2825	Alto trombone		Britain (?)	l.19/e.20	5.91
LHC	262	Serpent	Bilton (?)	Britain (?)	m.19	5.86
OB	503	Bass horn		Britain (?)	e.19	5.84
LHC	161	Tenor cor	Distin (?)		m.19	5.82
FT	136	Ballad horn	Keat (?)	London	c 1890	5.81
LHC	91	Tenor saxhorn				5.69
BK	179	Vocal horn	Rudall Carte	London	c 1870	5.64
JW	BOC	Ophicleide	Collin (?)	Paris (?)	e.19	5.62
EU	3368	Ophicleide	T. Glen (?)	Edinburgh	c 1860	5.62
EU	3100	Tenor trombone	Courtois	Paris	l.19/e.20	5.54
LHC	124	Bass horn			e.19	5.53
EU	665	Trombone	Selmer	London	m.20	5.53
EU	1123	Trombone	Boosey & Hawkes	London	m.20	5.53
EU	846	French horn		Britain (?)	e.19	5.43
JW	PAC	Alto trombone	Courtois / Mille	Paris	l.19	5.41
EU	908	Keyed bugle	Possibly Halari	Paris	c 1830	5.37
CRB	410	Contrabass trombone	Thibouville-Lamy (?)	France	c 1900	5.33
OB	6a	French horn			l.18/e.19	5.29
AM	189	Trombone	Bach 6½AL	USA	c 1975	5.22
BK	28	Clavicor		France (?)	c 1850	5.19
EU	3314	Ophicleide		Britain (?)	c 1850	5.14
EU	1586	Tenor trom / Tenorhorn		Austria	e.20	5.01
EU	3535	Tenor trombone		France	l.19/e.20	4.91
EU	2930	Contrabass serpent	Wood brothers	Huddersfield	c 1840	4.90
LHC	314	Trombone	Roth (?)			4.88

		Instrument	Maker	Place	Date	R factor
EU	3670	Trombone	Werma	Germany	m.20	4.79
LHC	198	Cornet	Distin (?)		m.19	4.75
OB	605	French horn	Haas (?)			4.66
EU	3595	Trombone	Besson	London	e.20	4.64
EU	3311	Serpent or bass horn		Britain (?)	e.19	4.64
EU	3520	Trompe de chasse basse		France	l.19/e.20	4.64
LHC	106	Ophicleide	Gautrot (?)	France	m.19	4.47
OB	B1	Cor basse			e.19	4.46
EU	3759	Cornophone basse	Besson	France	l.19	4.43
EU	3304	Serpent		France (?)	c 1750	4.41
BK	234	Contrabass trombone	Courtois (?)	France (?)	c 1895	4.37
EU	3256	G Bass trombone	Boosey & Hawkes	London	c 1951	4.36
LHC	235	Serpent				4.36
EU	3206	Tenor trombone		Austria (?)	19	4.22
EU	3306	Bass horn			m.19	4.18
FT	AL	Sackbut	Tomes	London	1997	4.16
OB	B2	Euphonium	Courtois / Mille	Paris	l.19	4.12
EU	1289	Tenor trombone	Bach 18	USA	m.20	3.97
OB	x502	Serpent [ivory]		Britain (?)	e.19	3.95
EU	624	Serpent	Taylor (?)	Glasgow	c 1815	3.95
OB	64	French horn / trompe	Besson	Paris	l.19	3.88
LHC	171	Trombone				3.87
EU	1161	Bombardon	Distin	London	m.19	3.81
OP	8618	Serpent				3.78
EU	677	Bass trombone	Courtois	Paris	c 1900	3.78
FT	94	Tenor trombone	Higham	Manchester	c 1865	3.76
EU	3027	Bass trombone			c 1835	3.65
AM	192	Trombone	Remington	USA	c 1977	3.60
OP	5011	Ophicleide	Higham	Manchester	m.19	3.59
EU	2158	Ophicleide	Higham	Manchester	m.19	3.57
EU	1898	Serpent			e.19	3.48
EU	3532	Contrabass	Nikkan	Japan	l.20	3.40

		Instrument	Maker	Place	Date	R factor
EU	1296	Ophicleide or b. trom		Britain (?)	e.19	3.08
BK	40	Serpent Forveille		France (?)	c 1830	2.98
EU	3373	Serpent	Metzler (?)	London	c 1825	2.87
EU	1007	Serpent			e.19	2.81
FT	104	Serpent [metal]	Key, Rudall (?)	London	c 1858	2.80
LHC	239	Bugle horn	Fürst (?)			2.75
BK	156	Trompe	F. Périnet 0½	Paris	e.20	2.51
EU	3493	Trompe de chasse	Milliens	France	l.20	2.34
LHC	223	Serpent				2.22
EU	627	Bass horn		Britain (?)	c 1825	1.97
BK	232	Ophimonocleide [ivory]		France (?)	e.19	1.55

Appendix H

Instruments ranked by value of parameter K

This table lists the values of parameter K for selected instruments in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, Nominal pitch, Maker, Place and **Date**

Specimens have been sought which are typical of their place and period and have survived without significant modification. Further information on these instruments is in many cases given in the catalogues of the respective museums and in other appendices to this study.

Mid bore

This is the bore diameter in millimetres at a point mid-way between the two ends of the instrument, (no slides extended, keys opened or valves operated) excluding any mouthpiece and ignoring local irregularities.

K

This is dimensionless parameter K calculated as defined in Equation 8.2, being the ratio of the cross-sectional area at the midway point of the windway to the minimum cross-sectional area (near the mouthpiece receiver).

The measurement of the overall length of the instrument by flexible measuring tools and rulers has inherent inaccuracies; instruments with long straight sections such as trombones can be measured to an accuracy of $\pm$ 10mm (better than $\pm$ 1%) but for instruments with many coils such as french horns measurement of L is hardly possible to obtain better than $\pm$ 25mm. The use of pulse reflectometry increases accuracy for these instruments, but since the bore reconstruction technique breaks down for acutely flaring sections of tube, it is always necessary to graft physically measured bell section data onto the bore reconstruction, again with an accuracy of ± 10mm (better than ± 1%). The identification of the midway point of the windway will be on average determined with half the error of the measurement of *L*.

The accuracy of the bore measurements and thus of *K* depend very much on the configuration of the instrument. With many instruments the minimum bore can be measured using expanding bore gauges inserted into the mouthpipe to ± 0.2mm, (approximately ± 2%); using pulse reflectometry any local irregularities can be recognised and avoided and an accuracy of ± 0.1mm for bore diameter achieved (better than ± 1%) (Sharp 1996).

The accuracy of the mid bore measurement of slide trombones can be as good as ± 2% since the bore is cylindrical and there is ready access to the foot of the ascending main slide for an expanding bore gauge. Even for rapidly-expanding instruments such as flugelhorns the identification of the midway point is not a significant source of error, since the expansion over a distance of 10mm (about 0.2mm) is not as large as the error in estimating the diameter. If the midway point is on a curved section it may be necessary to measure the external diameter and estimate the wall thickness, reducing the accuracy to ± 0.5mm. Thus the value of the mid bore diameter in the worst cases can only be given to ± 5%, which will translate into an error of ± 10% in *K*.

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*
LG	1885	Alto trombone	6½-ft Eb	Ehe	Nürnberg	c 1720	9.50	1.00
EU	2695	Tenor trombone	9-ft Bb	Schnitzer	Nürnberg	1594	9.60	1.00
LG	1884	Alto trombone	6½-ft Eb	Stark	Nürnberg	1690	9.90	1.00
LG	1896	Tenor trombone	9-ft Bb	Ehe	Nürnberg	1668	10.00	1.00
EU	3770	Natural trumpet	7-ft D	Bauer	Prague	1818	10.50	1.00
EU	3770	Natural trumpet crooked in Bb	9-ft Bb	Bauer	Prague	1818	10.50	1.00
EU	3205	Tenor trombone	9-ft Bb	Huschauer	Vienna	1794	10.80	1.00
BK	385	Trompette demilune	5½-ft G	Kretzschmann	Strasbourg	e.19	10.80	1.00
EU	3738	O.T.S. tenor trombone, bell to rear	9-ft Bb		France or Belgium (?)	e.19	11.50	1.00
EU	3738	O.T.S. tenor trombone, bell to front	9-ft Bb		France or Belgium (?)	e.19	11.50	1.00
BG	2011	O.T.S. tenor trombone	8-ft C	Van Engelen	Belgium	c 1840	11.70	1.00
EU	3753	Tenor trombone	9-ft Bb	Mitsching Alschausky	Germany	c 1935	12.30	1.00
EU	901	Bass trombone	11-ft G		England (?)	c 1850	12.45	1.00
EU	3026	Bass trombone	11-ft G	Green	London	c 1835	12.95	1.00
JW	PQP	Tenorbass trombone	9-ft Bb	Penzel Nachfolger	Leipzig	c 1900	13.10	1.00
FT	94	Tenor valve trombone	8-ft C	Higham	Manchester	c 1865	11.50	1.01
JW	PLR	Bass trombone, double slide	11-ft G	Rudall Carte	London	c 1880	12.34	1.01
EU	3747	Tenor trombone	9-ft Bb	Courtois	Paris	1865	11.40	1.02
EU	3247	Trumpet	7-ft D	Huschauer	Wien	1794	11.30	1.02
LG	1897	Tenor trombone	9-ft Bb	Ehe	Nürnberg	c 1720	9.20	1.02
PC	980	Alto trombone	6½-ft Eb	Van Engelen	Lierre	m.19	11.60	1.03
LG	1910	Bass trombone	11-ft G	Birckholtz	Nürnberg	1650	11.40	1.04
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	11.68	1.04
LG	1909	Bass trombone	12-ft F	Goltbeck	Cottbus	1635	11.60	1.05
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	11.50	1.05
LG	1899	Tenor trombone	9-ft Bb	Eschenbach	Markneukirchen	1796	11.20	1.06
PC	1252	Tenor trombone	9-ft Bb	Courtois frères	Paris	pre 1845	10.80	1.06
PC	620	O.T.S. alto trombone	6½-ft Eb	Riedloker	Paris	c 1810	10.35	1.06
LG	4139	Tenorbass trombone	9-ft Bb	Sattler	Leipzig	1841	14.00	1.06
PC	2224	Tenor trombone	9-ft Bb	Halary	Paris	1837	11.30	1.06
EU	3534	Tenor trombone	9-ft Bb	Riedlocker	Paris	c 1810	11.30	1.07

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*
EU	519	Bass trombone	11-ft G	Besson	London	c 1890	12.35	1.08
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	12.00	1.08
EU	2991	Tenor trombone	9-ft Bb	Besson	London	c 1900	11.60	1.09
EU	887	Tenor saxhorn	6-ft F	Ad. Sax (?)	Paris (?)	c 1850	12.00	1.11
LG	4137	Alto trombone	6½-ft Eb	Sattler	Leipzig	1841	11.00	1.12
EU	215	Cornopean	4½-ft Bb	Glen	Edinburgh	c 1840	12.00	1.13
BK	234	Contrabass trombone	18-ft Bb	Courtois	Paris	c 1895	11.90	1.13
EU	3207	Tenor trombone	9-ft Bb	R. Schopper	Leipzig	c 1910	13.30	1.13
EU	1556	Alto trombone	6½-ft Eb	Boosey & Co	London	1885-86	11.50	1.13
EU	2438	Trumpet	4½-ft Bb	Micol-Montagna	Trieste	m.20	10.70	1.14
JW	PVM	Contrabass trombone	12-ft F	Mahillon	Brussels	c 1900	14.16	1.15
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	11.40	1.16
PC	630	Bass trombone	11-ft G	Courtois	Paris	post 1872	12.35	1.16
CRB	408	Tenor/bass trombone	9-ft Bb	Courtois	Paris	c 1903	11.40	1.18
FT	122	Clavicor	7½-ft Db	Pace	London	c 1840	12.02	1.19
JW	PAC	Alto trombone	6½-ft Eb	Courtois / Mille	Paris	c 1880	10.60	1.19
EU	599	Trumpet	4½-ft Bb	Schediwy	Ludwigsburg	c 1921	11.50	1.20
PC	711	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1850	12.42	1.21
EU	218	Cornopean	4½-ft Bb		England	c 1845	12.20	1.23
EU	2502	Orchestral cornet	4½-ft Bb	Hall & Quinby	Boston	c 1870	12.26	1.24
LG	4138	Tenor trombone	9-ft Bb	Sattler	Leipzig	1841	13.40	1.25
EU	3269	Cornet à pistons, wide mouthpipe	4½-ft Bb		France	c 1840	11.00	1.26
EU	3212	Trumpet	4½-ft Bb	Boosey & Hawkes	London	c 1931	11.24	1.26
EU	1553	Cornopean, narrow mouthpipe	4½-ft Bb	Metzler	London	c 1842	9.00	1.27
AM	171	Tenor trombone, 8H model	9-ft Bb	Conn	Elkhart	1978	13.80	1.28
BK	201	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1867	12.70	1.29
BK	327	Piccolo cornet	2-ft C		France (?)	c 1900	10.10	1.31
EU	1701	Trumpet	4½-ft Bb	Vega	Boston	c 1955	11.60	1.31
WAG	1	Bass trumpet	8-ft C	Alexander	Mainz	c 1985	12.00	1.31
PH	1	Trumpet	4½-ft Bb	Amati	Czech Republic	c 1992	11.50	1.32
CRB	326	Valve trumpet, `Handelian' model	4½-ft Bb	Kohler	London	c 1895	11.70	1.37

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	14.20	1.40
EU	1770	Tenor trombone	9-ft Bb	G.H. Pace	London	c 1895	11.45	1.42
JW	HWM	Wagner tuba	12-ft F	Mahillon	Brussels	c 1900	13.28	1.51
EU	3052	Post horn	4-ft C	Kretzschmann	Strasbourg	c 1830	10.36	1.52
EU	889	Vocal horn	8-ft C	Rudall Carte	London	c 1885	13.10	1.53
EU	229	Bass trumpet	9-ft Bb		Germany (?)	c 1900	14.40	1.60
EU	2704	Cornet	4½-ft Bb	Boosey & Co	London	c 1922	11.50	1.60
EU	2858	Bass trumpet	9-ft Bb	Cerveny	Königgrätz	c 1900	14.90	1.65
EU	3487	Double-bell euphonium (small bell)	9-ft Bb	Conn	Elkhart	m.20	14.20	1.67
AM	1112	Clairon basse	9-ft Bb	Couesnon	Paris	c 1975	15.60	1.72
EU	3460	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1927	11.84	1.73
EU	3694	Cornet, conical-bore	4½-ft Bb	Couturier	USA	c 1920	11.92	1.75
EU	2869	Cornet	4½-ft Bb	Besson	London	c 1897	11.40	1.76
CRB	410	Contrabass trombone	16-ft C	Thibouville-Lamy	Paris	c 1900	12.90	1.79
EU	3275	Cornet	4½-ft Bb	York	Michigan	c 1935	11.80	1.80
FT	155	Tenor valve trombone	9-ft Bb	Higham	Manchester	c 1880	15.13	1.81
EU	2988	Cornet, PCB model	4½-ft Bb	Rudall Carte	London	1907	11.60	1.82
OB	x616	Soprano saxhorn	3¼-ft Eb	Ad. Sax	Paris	c 1870	13.70	1.84
FT	183	Slide cornet	4½-ft Bb	Conn	Elkhart	e.20	11.60	1.85
EU	3352	Baryton	8-ft C	Aug. Courtois	Paris	c 1855	15.80	1.86
EU	3352	Baryton, slide pulled to Bb	9-ft Bb	Aug. Courtois	Paris	c 1855	15.80	1.86
JW	CLK	Cornet	4½-ft Bb	Kohler	London	c 1865	11.39	1.88
EU	3257	Bass trumpet	9-ft Bb	Conn	Elkhart	1929-30	12.20	1.90
BK	28	Clavicor	8-ft C	Guichard	Paris	c 1850	15.00	1.95
NSB	1	Cornet	4½-ft Bb	Besson	UK	1997	11.80	1.97
EU	3710	Cornet	4½-ft Bb	Courtois	Paris	1862-71	12.00	1.98
OB	662	Baritone saxhorn	9-ft Bb	Ad. Sax	Paris	c 1865	16.80	1.99
BK	211	Cornet	4-ft C	Ch. Sax	Brussels	c 1840	15.96	2.00
OB	711	Trumpet, PCB model	4½-ft Bb	Rudall Carte	London	c 1925	12.60	2.00
EU	3273	Cornet	4½-ft Bb	Conn	Elkhart	1924	12.20	2.01
RD	6488	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1928	12.06	2.01

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*
EU	3091	Baritone	9-ft Bb		Germany (?)	c 1900	16.70	2.04
EU	3737	Bayley's acoustic cornet	4½-ft Bb	Kohler	London	c 1865	11.69	2.09
EU	1704	Sonorophone	9-ft Bb	Metzler	London	c 1865	16.80	2.17
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	16.50	2.29
CRB	354	Bugle alto	6-ft F	Courtois	Paris	c 1885	14.70	2.30
EU	3441	Double horn, Bb side	9-ft Bb	Couesnon	Paris	c 1914	12.20	2.33
EU	1804	Double horn, Bb side	9-ft Bb	Alexander	Mainz	c 1950	11.90	2.39
JW	ITC	Melody horn	6-ft F	Courtois / Mille	Paris	c 1880	14.87	2.43
RC	3265	Flugelhorn	4-ft C	Ebblewhite	London	l.19	15.53	2.46
AM	1111	Trompe basse	14-ft D	Couesnon	Paris	m.20	17.87	2.56
EU	3344	Aïda trumpet	4½-ft B natural	Ad. Sax	Paris	c 1870	16.06	2.58
EU	3664	Flugelhorn	4½-ft Bb	Cerveny	Königgrätz	c 1900	17.00	2.62
EU	3441	Double horn, valved in C	8-ft C	Couesnon	Paris	c 1914	13.00	2.64
EU	3592	Flugelhorn	4½-ft Bb	Besson & Co	London	c 1900	16.59	2.70
EU	3697	Baritone saxhorn	9-ft Bb	Besançon	Paris	c 1860	18.00	2.94
EU	554	Tenor flugelhorn	8-ft C	Riedl	Nürnberg	l.19	19.60	2.96
JW	PLC	Cimbasso	18-ft Bb	Cazzani	Milan	20	22.85	3.18
EU	2711	Baritone	9-ft Bb	Higham	Manchester	c 1890	19.80	3.30
EU	1710	Koenig horn	8-ft C	Courtois	Paris	c 1860	20.00	3.63
AM	1135	Saxhorn basse	8-ft C	Fischer	Paris	c 1860	22.40	4.00
PC	309	Valved ophicleide	8-ft C		probably France	c 1840	24.00	4.28
EU	907	Keyed bugle	4-ft C	Halari	Paris	c 1830	22.80	4.30
EU	3115	Saxhorn nouveau basse	8-ft C	Ad. Sax	Paris	1867	24.60	4.35
EU	531	Orchestral hand horn, Bb crook	9-ft Bb	Kretzschmann	Strasbourg	c 1830	15.80	4.56
EU	3189	Cornett	2½-ft G		Italy (?)	17th C (?)	16.85	4.67
EU	3721	Tenorhorn	9-ft Bb	Kruspe	Erfurt	c 1900	25.20	5.06
EU	2776	Euphonium	9-ft Bb	Higham	Manchester	c 1880	26.00	5.59
EU	2107	Saxhorn contrebasse	13-ft Eb	Courtois	Paris	c 1860	32.70	6.33
EU	3487	Double-bell euphonium (large bell)	9-ft Bb	Conn	Elkhart	m.20	29.70	7.29
EU	3758	Cornophone basse	8-ft C	Besson	Paris	c 1890	20.00	7.51
EU	2515	Wagner tuba	9-ft Bb	Alexander	Mainz	c 1930	21.70	7.94

		Instrument	Nom Pitch	Maker	Place	Date	Mid bore	*K*
EU	2131	Tuba	12-ft F	Higham	Manchester	c 1910	38.00	9.86
EU	3229	Saxhorn contrebasse	18-ft Bb	Ad. Sax	Paris	1867	45.00	10.33
EU	3097	Alphorn	11-ft G	Oberli	Zwischenflüh	c 1935	37.00	11.74
EU	3606	Serpent d'eglise	8-ft C	Baudouin	Paris	c 1820	43.00	13.51
EU	1160	Ophicleide	8-ft C	Geo. Smith	Birmingham	c 1840	46.50	13.84

Appendix I

Instruments ranked by value of parameter *C*

This table lists the values of parameter *C* for selected instruments in several museums and private collections. The columns give data for:

Source and **Specimen number**

Full details of the sources of specimens are give in Appendix J.

Instrument, **Nominal pitch**, **Maker**, **Place** and **Date**

Specimens have been sought which are typical of their place and period and have survived without significant modification. Further information on these instruments is in many cases given in the catalogues of the respective museums and in other appendices to this study.

L

This is the overall length of the windway between the two ends of the instrument, (no slides extended, valves operated or keys opened) excluding any mouthpiece and ignoring local irregularities.

C

This is the dimensionless parameter *C* calculated as defined inscribed in Section 8.5, being the proportion of the overall tube length of the windway up to the point in the air column where the cross-sectional area is double that at the mid-point. *C* is necessarily between 0.5 and 1.0.

The considerations of accuracy in Appendix H apply to the measurement of the overall tube length and the bore at the midway point of the windway. The critical measurements here are determining the point where the bore diameter is $\sqrt{2}$ times the diameter at the midway point, and measuring the length along the windway to it from the midway point.

However, any errors in finding the absolute position of the midway point are not critical, only errors in measuring the length along the windway between two points. Again, the accuracy varies from one configuration to another. With slide trombones, the point at distance *CL* from the proximal end of the windway is usually in the bell section and can be found to the nearest 5mm by direct measurement as described in Chapter 6. The use of pulse reflectometry allows accurate measurement and permits local irregularities to be recognised and avoided. In the case of less amenable instruments, any errors introduced by estimating the wall thickness at the mid-point tend to be cancelled out in measuring the wall thickness at the point at distance *CL* from the proximal end of the windway.

As with the parameter *K*, therefore, the determination of *C* is least accurate for instruments which are most 'conical' and most accurate or instruments which are most 'cylindrical'. The value of the *C* in the worst cases can only be give to $\pm$ 10%.

		Instrument	Nom Pitch	Maker	Place	Date	*L*	*C*
EU	3352	Baryton	8-ft C	Aug. Courtois	Paris	c 1855	2490	0.54
EU	887	Tenor saxhorn	6-ft F	Ad. Sax (?)	Paris (?)	c 1850	1752	0.56
EU	3352	Baryton, slide pulled to Bb	9-ft Bb	Aug. Courtois	Paris	c 1855	2733	0.58
BK	28	Clavicor	8-ft C	Guichard	Paris	c 1850	2382	0.60
EU	3721	Tenorhorn	9-ft Bb	Kruspe	Erfurt	c 1900	2657	0.61
PC	309	Valved ophicleide	8-ft C		probably France	c 1840	2406	0.61
EU	3091	Baritone	9-ft Bb		Germany (?)	c 1900	2730	0.62
EU	3812	Saxhorn basse	8-ft C	Fischer	Paris	c 1860	2364	0.62
EU	2107	Saxhorn contrebasse	13-ft Eb	Courtois	Paris	c 1860	3959	0.62
EU	2131	Tuba	12-ft F	Higham	Manchester	c 1910	3417	0.63
EU	3758	Cornophone basse	8-ft C	Besson	Paris	c 1890	2471	0.63
EU	3115	Saxhorn nouveau basse	8-ft C	Ad. Sax	Paris	1867	2551	0.64
EU	2776	Euphonium	9-ft Bb	Higham	Manchester	c 1880	2630	0.64
EU	1704	Sonorophone	9-ft Bb	Metzler	London	c 1865	2644	0.64
EU	2515	Wagner tuba	9-ft Bb	Alexander	Mainz	c 1930	2758	0.65
JW	HWM	Wagner tuba	12-ft F	Mahillon	Brussels	c 1900	3594	0.65
EU	3229	Saxhorn contrebasse	18-ft Bb	Ad. Sax	Paris	1867	5270	0.65
EU	3697	Baritone saxhorn	9-ft Bb	Besançon	Paris	c 1860	2646	0.66
EU	3487	Double-bell euphonium (large bell)	9-ft Bb	Conn	Elkhart	m.20	2727	0.66
OB	x616	Soprano saxhorn	3¼-ft Eb	Ad. Sax	Paris	c 1870	930	0.66
OB	x615	Contralto saxhorn	4½-ft Bb	Ad. Sax	Paris	c 1870	1236	0.67
EU	3664	Flugelhorn	4½-ft Bb	Cerveny	Königgrätz	c 1900	1340	0.67
EU	907	Keyed bugle	4-ft C	Halari	Paris	c 1830	1205	0.68
EU	2711	Baritone	9-ft Bb	Higham	Manchester	c 1890	2572	0.68
EU	2502	Orchestral cornet	4½-ft Bb	Hall & Quinby	Boston	c 1870	1238	0.68
EU	3097	Alphorn	11-ft G	Oberli	Zwischenflüh	c 1935	3195	0.69
JW	ITC	Melody horn	6-ft F	Courtois / Mille	Paris	c 1880	1747	0.69
EU	3592	Flugelhorn	4½-ft Bb	Besson & Co	London	c 1900	1314	0.70
EU	3344	Aïda trumpet	4½-ft B natural	Ad. Sax	Paris	c 1870	1220	0.70
EU	3441	Double horn, valved in C	8-ft C	Couesnon	Paris	c 1914	2496	0.70
EU	1804	Double horn, Bb side	9-ft Bb	Alexander	Mainz	c 1950	2835	0.71

		Instrument	Nom Pitch	Maker	Place	Date	*L*	*C*
BK	211	Cornet	4-ft C	Ch. Sax	Brussels	c 1840	1148	0.71
EU	3441	Double horn, Bb side	9-ft Bb	Couesnon	Paris	c 1914	2780	0.72
EU	2858	Bass trumpet	9-ft Bb	Cerveny	Königgrätz	c 1900	2700	0.72
EU	1160	Ophicleide	8-ft C	Geo. Smith	Birmingham	c 1840	2465	0.72
EU	229	Bass trumpet	9-ft Bb		Germany (?)	c 1900	2624	0.72
EU	599	Trumpet	4½-ft Bb	Schediwy	Ludwigsburg	c 1921	1218	0.72
CRB	354	Bugle alto	6-ft F	Courtois	Paris	c 1885	1750	0.72
BK	327	Piccolo cornet	2-ft C		France (?)	c 1900	593	0.73
OB	662	Baritone saxhorn	9-ft Bb	Ad. Sax	Paris	c 1865	2622	0.73
EU	1710	Koenig horn	8-ft C	Courtois	Paris	c 1860	2350	0.73
EU	889	Vocal horn	8-ft C	Rudall Carte	London	c 1885	2419	0.74
EU	1553	Cornopean, narrow mouthpipe	4½-ft Bb	Metzler	London	c 1842	1360	0.74
EU	3606	Serpent d'eglise	8-ft C	Baudouin	Paris	c 1820	2207	0.75
EU	519	Bass trombone	11-ft G	Besson	London	c 1890	3070	0.75
EU	3753	Tenor trombone	9-ft Bb	Mitsching Alschausky	Germany	c 1935	2685	0.76
EU	218	Cornopean	4½-ft Bb		England	c 1845	1280	0.76
JW	PVM	Contrabass trombone	12-ft F	Mahillon	Brussels	c 1900	3677	0.76
EU	531	Orchestral hand horn, Bb crook	9-ft Bb	Kretzschmann	Strasbourg	c 1830	2711	0.77
EU	1701	Trumpet	4½-ft Bb	Vega	Boston	c 1955	1309	0.77
EU	3275	Cornet	4½-ft Bb	York	Michigan	c 1935	1342	0.77
JW	PQP	Tenorbass trombone	9-ft Bb	Penzel Nachfolger	Leipzig	c 1900	2668	0.77
EU	3212	Trumpet	4½-ft Bb	Boosey & Hawkes	London	c 1931	1286	0.77
EU	3710	Cornet	4½-ft Bb	Courtois	Paris	1862-71	1272	0.78
AM	1111	Trompe basse	14-ft D	Couesnon	Paris	m.20	4165	0.78
NSB	1	Cornet	4½-ft Bb	Besson	UK	1997	1293	0.78
WSAM	656	Tenor Posaune	9-ft Bb	Riedl		e.19	2610	0.78
EU	215	Cornopean	4½-ft Bb	Glen	Edinburgh	c 1840	1268	0.78
FT	122	Clavicor	7½-ft Db	Pace	London	c 1840	2255	0.78
AM	171	Tenor trombone, 8H model	9-ft Bb	Conn	Elkhart	1978	2779	0.78
EU	3207	Tenor trombone	9-ft Bb	R. Schopper	Leipzig	c 1910	2734	0.79
AM	1112	Clairon basse	9-ft Bb	Couesnon	Paris	c 1975	2679	0.79

		Instrument	Nom Pitch	Maker	Place	Date	*L*	*C*
PH	1	Trumpet	4½-ft Bb	Amati	Czech Republic	c 1992	1294	0.79
BK	234	Contrabass trombone	18-ft Bb	Courtois	Paris	c 1895	5437	0.79
RD	6488	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1928	1303	0.79
EU	3269	Cornet à pistons, wide mouthpipe	4½-ft Bb		France	c 1840	1400	0.79
LG	1909	Bass trombone	12-ft F	Goltbeck	Cottbus	1635	3538	0.79
EU	3694	Cornet, conical-bore	4½-ft Bb	Couturier	USA	c 1920	1354	0.79
EU	3273	Cornet	4½-ft Bb	Conn	Elkhart	1924	1330	0.80
PC	630	Bass trombone	11-ft G	Courtois	Paris	post 1872	3267	0.80
EU	2438	Trumpet	4½-ft Bb	Micol-Montagna	Trieste	m.20	1466	0.80
EU	3052	Post horn	4-ft C	Kretzschmann	Strasbourg	c 1830	1278	0.80
EU	3737	Bayley's acoustic cornet	4½-ft Bb	Kohler	London	c 1865	1339	0.80
EU	2704	Cornet	4½-ft Bb	Boosey & Co	London	c 1922	1407	0.80
JW	CLK	Cornet	4½-ft Bb	Kohler	London	c 1865	1267	0.80
JW	PLR	Bass trombone, double slide	11-ft G	Rudall Carte	London	c 1880	3231	0.80
EU	2695	Tenor trombone	9-ft Bb	Schnitzer	Nürnberg	1594	2583	0.81
EU	3472	Armee Posaune	9-ft Bb	Schamal	Prague	c 1880	2881	0.81
CRB	408	Tenor/bass trombone	9-ft Bb	Courtois	Paris	c 1903	2623	0.81
FT	183	Slide cornet	4½-ft Bb	Conn	Elkhart	e.20	1354	0.81
CRB	326	Valve trumpet, `Handelian' model	4½-ft Bb	Kohler	London	c 1895	1296	0.81
BG	2011	O.T.S. tenor trombone	8-ft C	Van Engelen	Belgium	c 1840	2530	0.81
BK	201	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1867	2710	0.81
EU	3460	Webster trumpet	4½-ft Bb	Rudall Carte	London	c 1927	1280	0.81
EU	1556	Alto trombone	6½-ft Eb	Boosey & Co	London	1885-86	1964	0.82
LG	1884	Alto trombone	6½-ft Eb	Stark	Nürnberg	1690	1908	0.82
WAG	1	Bass trumpet	8-ft C	Alexander	Mainz	c 1985	2343	0.82
PC	980	Alto trombone	6½-ft Eb	Van Engelen	Lierre	m.19	2033	0.82
EU	3487	Double-bell euphonium (small bell)	9-ft Bb	Conn	Elkhart	m.20	2798	0.82
LG	1897	Tenor trombone	9-ft Bb	Ehe	Nürnberg	c 1720	2575	0.82
WGDM	433	Tenor Posaune	9-ft Bb	Geyer	Wien	1671	2601	0.83
EU	1770	Tenor trombone	9-ft Bb	G.H. Pace	London	c 1895	2629	0.83
LG	4139	Tenorbass trombone	9-ft Bb	Sattler	Leipzig	1841	2740	0.83

		Instrument	Nom Pitch	Maker	Place	Date	*L*	*C*
OB	711	Trumpet, PCB model	4½-ft Bb	Rudall Carte	London	c 1925	1288	0.83
EU	3257	Bass trumpet	9-ft Bb	Conn	Elkhart	1929-30	2925	0.83
EU	3026	Bass trombone	11-ft G	Green	London	c 1835	3165	0.83
LG	1899	Tenor trombone	9-ft Bb	Eschenbach	Markneukirchen	1796	2585	0.83
PC	711	Valve trombone, 6-valve	9-ft Bb	Ad. Sax	Paris	c 1850	2814	0.83
LG	1910	Bass trombone	11-ft G	Birckholtz	Nürnberg	1650	3242	0.83
LG	1896	Tenor trombone	9-ft Bb	Ehe	Nürnberg	1668	2540	0.83
JW	PAC	Alto trombone	6½-ft Eb	Courtois / Mille	Paris	c 1880	1948	0.83
EU	901	Bass trombone	11-ft G		England (?)	c 1850	3149	0.84
FT	94	Tenor valve trombone	8-ft C	Higham	Manchester	c 1865	2306	0.84
PC	1694	Valve trombone (3 Berlin valves)	8-ft C	Ad. Sax	Paris	c 1855	2395	0.84
EU	2991	Tenor trombone	9-ft Bb	Besson	London	c 1900	2589	0.84
WSAM	706	Tenor Posaune	9-ft Bb	Neuschel	Nürnberg	1557	2600	0.84
EU	3534	Tenor trombone	9-ft Bb	Riedlocker	Paris	c 1810	2720	0.84
OB	732	Bass trombone	12-ft F		Germany	1814	3444	0.84
EU	2730	Tenor trombone	9-ft Bb	Hawkes & Son	London	c 1923	2612	0.85
PC	2224	Tenor trombone	9-ft Bb	Halary	Paris	1837	2690	0.85
EU	3738	O.T.S. tenor trombone, bell to front	9-ft Bb		France or Belgium (?)	e.19	2664	0.85
EU	3747	Tenor trombone	9-ft Bb	Courtois	Paris	1865	2668	0.85
EU	3738	O.T.S. tenor trombone, bell to rear	9-ft Bb		France or Belgium (?)	e.19	2685	0.85
EU	606	Tenor trombone	9-ft Bb	Courtois	Paris	c 1880	2701	0.85
WGDM	199	Tenor Posaune	9-ft Bb	Uhlmann	Wien	e.19	2625	0.85
PC	620	O.T.S. alto trombone	6½-ft Eb	Riedloker	Paris	c 1810	2025	0.85
WSAM	255	Tenor Posaune	9-ft Bb	Leichamschneider	Wien	1732	2600	0.85
EU	3205	Tenor trombone	9-ft Bb	Huschauer	Vienna	1794	2695	0.85
PC	1252	Tenor trombone	9-ft Bb	Courtois frères	Paris	pre 1845	2577	0.85
LG	4138	Tenor trombone	9-ft Bb	Sattler	Leipzig	1841	2738	0.86
WGDM	198	Alt Posaune	6½-ft Eb	Schmidt	Nürnberg	1675	1943	0.86
JW	PTS	Tenor trombone, slide	9-ft Bb	Ad. Sax	Paris	c 1870	2799	0.86
LG	4137	Alto trombone	6½-ft Eb	Sattler	Leipzig	1841	2034	0.86
BK	385	Trompette demilune	5½-ft G	Kretzschmann	Strasbourg	e.19	1600	0.86

		Instrument	Nom Pitch	Maker	Place	Date	*L*	*C*
EU	3770	Natural trumpet	7-ft D	Bauer	Prague	1818	2114	0.86
CRB	410	Contrabass trombone	16-ft C	Thibouville-Lamy	Paris	c 1900	4759	0.86
OB	731	Tenor trombone	9-ft Bb		Germany	1814	2601	0.88
LG	1885	Alto trombone	6½-ft Eb	Ehe	Nürnberg	c 1720	2045	0.88
EU	3247	Trumpet	7-ft D	Huschauer	Wien	1794	2130	0.88
EU	3189	Cornett	2½-ft G		Italy (?)	17th C (?)	576	0.89
FT	155	Tenor valve trombone	9-ft Bb	Higham	Manchester	c 1880	2621	0.89
EU	3770	Natural trumpet crooked in Bb	9-ft Bb	Bauer	Prague	1818	2692	0.89
EU	554	Tenor flugelhorn	8-ft C	Riedl	Nürnberg	1.19	2417	0.90
JW	PLC	Cimbasso	18-ft Bb	Cazzani	Milan	20	5526	0.92

Appendix J

Sources of specimens

The following are the source collections of instruments investigated.

AM	Arnold Myers, Edinburgh
AS	Ann Arbor: Stearns Collection, University of Michigan
BG	Boston Museum of Fine Arts, Leslie Lindsay Mason (Galpin) Collection
BK	Bruno Kampmann, Paris
CEB	City of Edinburgh Band
CRB	Christopher Baines, Burford
DB	Dave Butcher, Edinburgh
DMC	Murray Campbell, Edinburgh
EU	Edinburgh University Collection of Historic Musical Instruments
FT	Frank Tomes, Merton Park
G	Graz: Steierisches Landesmuseum
GBC	Glasgow: Burrell Collection
GS	Gerhard Stradner, Wien
HC	Holton Co., Elkhorn, Wisonsin
JC	John Creed
JK	Jonathan Korzun, U.S.A.
JM	Jeremy Montagu, Oxford
JW	John Webb, Padbrook
LC	Leblanc Corporation, Kenosha, Wisconsin
LG	Leipzig: Grassi Museum, Univerität Leipzig
LSA	London: Salvation Army Heritage Centre
LH	London: Horniman Museum
LHC	London: Horniman Museum, Carse Collection
MB	Mole Benn, per Frank Tomes
NSB	Newtongrange Silver Band
OB	Oxford: Bate Collection, University of Oxford
PC	Paris: Musée de la Musique (formerly the Paris Conservatoire collection)
PH	University of Edinburgh Department of Physics and Astronomy
RC	Royal College of Music, London
RD	John R.T. Davies, per Frank Tomes
SR	Steve Reed, per Frank Tomes
SSC	Simon Carlyle, Edinburgh
TRM	Trondheim: Ringve Museum
WAG	William Giles, Rosyth
WGDM	Kunsthistorisches Museum, Vienna: instruments on loan from the Gesellschaft der Freunde Musik
WSAM	Kunsthistorisches Museum, Vienna: Sammlung Alter Instrument

The acquisition numbers of museums and other collections have been used where they exist. However in some cases the numbers have been abbreviated since they have been incorporated in computer file names of limited length in the course of this study.

Appendix K

Table of tube lengths

Note that the actual tube lengths given in Appendix I are significantly shorter than the length given here for instruments of the same nominal pitch. This is partly because *L* was measured without the mouthpiece and partly because end-corrections need to be applied. Nevertheless, this table, in conjunction with Appendix I and knowledge about prevailing pitch standards, can be used to estimate the nominal pitch of instruments which cannot be sounded for any reason.

Nominal size	Fundamental		Equivalent cone length (mm)
6-in C	C_6	1047 Hz	165.2
6½-in B	B_5	987.8 Hz	175.1
7-in B♭	$B\flat_5$	932.3 Hz	185.6
7½-in A	A_5	880.0 Hz	196.6
8-in A♭	$A\flat_5$	830.6 Hz	208.4
8½-in G	G_5	784.0 Hz	220.7
9-in G♭	$G\flat_5$	740.0 Hz	233.8
9½-in F	F_5	698.5 Hz	247.7
10-in E	E_5	659.3 Hz	262.4
10½-in E♭	$E\flat_5$	622.3 Hz	278.0
11-in D	D_5	587.3 Hz	301.9
11½-in D♭	$D\flat_5$	555.4 Hz	311.5
12-in C	C_5	523.2 Hz	330.7
13-in B	B_4	493.9 Hz	350.3
14-in B♭	$B\flat_4$	466.2 Hz	371.1
15-in A	A_4	440.0 Hz	393.2
16-in A♭	$A\flat_4$	415.3 Hz	416.6
17-in G	G_4	392.0 Hz	441.3
18-in G♭	$G\flat_4$	370.0 Hz	467.6
19-in F	F_4	349.2 Hz	495.4
20-in E	E_4	329.6 Hz	524.9
21-in E♭	$E\flat_4$	311.3 Hz	555.7
22-in D	D_4	293.7 Hz	589.0
23-in D♭	$D\flat_4$	277.2 Hz	624.1
2-ft C	C_4	261.6 Hz	661.3
2¼-ft B	B_3	246.9 Hz	700.7
2¼-ft B♭	$B\flat_3$	233.1 Hz	742.2
2½-ft A	A_3	220.0 Hz	786.4
2½-ft A♭	$A\flat_3$	207.7 Hz	833.3
2¾-ft G	G_3	196.0 Hz	882.7
2¾-ft G♭	$G\flat_3$	185.0 Hz	935.1
3-ft F	F_3	174.6 Hz	990.6
3¼-ft E	E_3	164.8 Hz	1050
3¼-ft E♭	$E\flat_3$	155.6 Hz	1112
3½-ft D	D_3	146.8 Hz	1178

3¾-ft D♭	$D\flat_3$	138.6 Hz	1248
4-ft C	C_3	130.8 Hz	1323
4¼-ft B	B_2	123.5 Hz	1401
4½-ft B♭	$B\flat_2$	116.5 Hz	1485
5-ft A	A_2	110.0 Hz	1573
5-ft A♭	$A\flat_2$	103.8 Hz	1666
5½-ft G	G_2	98.00 Hz	1765
5½-ft G♭	$G\flat_2$	92.50 Hz	1870
6-ft F	F_2	87.31 Hz	1981
6½-ft E	E_2	82.41 Hz	2099
6½-ft E♭	$E\flat_2$	77.78 Hz	2224
7-ft D	D_2	73.42 Hz	2356
7½-ft D♭	$D\flat_2$	69.30 Hz	2496
8-ft C	C_2	65.41 Hz	2645
8½-ft B	B_1	61.74 Hz	2802
9-ft B♭	$B\flat_1$	58.27 Hz	2969
9½-ft A	A_1	55.00 Hz	3145
10-ft A♭	$A\flat_1$	51.91 Hz	3333
11-ft G	G_1	49.00 Hz	3531
11-ft G♭	$G\flat_1$	46.25 Hz	3741
12-ft F	F_1	43.65 Hz	3963
13-ft E	E_1	41.20 Hz	4199
13-ft E♭	$E\flat_1$	38.89 Hz	4448
14-ft D	D_1	36.71 Hz	4713
15-ft D♭	$D\flat_1$	34.65 Hz	4993
16-ft C	C_1	32.70 Hz	5291
17-ft B	B_0	30.87 Hz	5604
18-ft B♭	$B\flat_0$	29.14 Hz	5945
19-ft A	A_0	27.50 Hz	6291
20-ft A♭	$A\flat_0$	25.96 Hz	6664
21-ft G	G_0	24.50 Hz	7061
23-ft G♭	$G\flat_0$	23.12 Hz	7483
24-ft F	F_0	21.83 Hz	7925
25-ft E	E_0	20.60 Hz	8398
27-ft E♭	$E\flat_0$	19.45 Hz	8895
28-ft D	D_0	18.35 Hz	9428
30-ft D♭	$D\flat_0$	17.32 Hz	9988
32-ft C	C_0	16.35 Hz	10581

Lengths calculated for equal-temperament at $A_4 = 440$ Hz, speed of sound in free air $c = 346ms^{-1}$.