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3aID1. Objective evaluation of musical instrument quality: A grand challenge in musical acoustics.

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Over the last few decades, increasingly sophisticated experimental and computational studies have clarified the processes involved in sound production in musical instruments. One of the principal goals of this research effort has, however, remained tantalisingly elusive: the establishment of clear and unambiguous relationships between objectively measured properties of an instrument and judgements of its musical qualities by an experienced player. This is partly because player evaluation is a subtle and highly subjective process in which many different aspects of the instrument's performance may be tested. Early studies concentrated on the steady state spectra of sound recorded in the far field of the instrument. More recently it has been recognised that transient aspects of an instrument's performance are important in judgements of quality made by performers. These aspects include the ease with which a stable regime of oscillation can be initiated, and the flexibility with which pitch, amplitude and timbre can be modified during performance. Attempts to define "playability" of an instrument in scientific terms, and to relate these scientific metrics to the vocabulary used by performers in judgements of playability, have been partially successful, but many questions remain unanswered.
INTRODUCTION

Why Study Musical Acoustics?

Music, in its widest sense, is perhaps the most universal human art form. The first exchanges between a mother and her new-born child are already musical in nature [1], and our most profound emotional and spiritual experiences throughout life are often enriched and transformed by music. It is therefore hardly surprising that from the time of the Ancient Greeks to the present day philosophers and scientists have been attracted to the study of musical sound and musical sound sources. This is the field of research which is now generally described as musical acoustics.

Most of the current work in musical acoustics falls into one of three broad categories. The first is concerned with the physics of musical instruments and other sound sources; the second deals with the transmission of sound from source to listener, including the important topics of concert hall acoustics and sound recording and reproduction; the third considers the psychoacoustics of musical sound perception. There are many motivations for research work in these different areas, but two of the strongest are common to almost all studies in musical acoustics. One is simple scientific curiosity: the desire to understand how the relatively simple laws of physics lead to such rich and complex phenomena as are evident in a musical performance. Musically important aspects of sound production, transmission or perception often involve very subtle features of the underlying mechanisms, and therefore provide particularly stringent tests of simplifications and approximations. The other is the desire to be able to offer well-founded guidance to those engaged in the practical business of music making: players, teachers, musical instrument makers, sound recording engineers and designers of spaces for musical performance. Such professionals have developed a wealth of experience and skill, often the fruit of generations of trial and error. The hope of the musical acoustician is to find ways of supplementing this practical knowledge with scientific principles and tools which will lead to more cost-effective and reliable methods of achieving the goal of musical excellence.

Can Musical Instrument Quality Be Measured Scientifically?

Factors Involved in Judgements of Quality

This talk reviews attempts to isolate and describe scientifically the factors which make an instrument musically excellent. It is important at the outset to recognise that what may seem to be an obvious improvement in an instrument from the scientific point of view may not be accepted as such by musicians, who must be the ultimate arbiters of musical quality. An instructive example is provided by the work of the nineteenth century instrument maker and acoustician Theobald Boehm, who in 1832 revolutionised the design of the flute by introducing a cylindrical bore incorporating much larger tone holes than earlier instruments. The increase in tone hole area resulted in a significant increase in radiated sound power, which was welcomed by musicians and widely adopted. In 1844 Louis August Buffet, assisted by Boehm, introduced a new design of oboe with similarly enlarged tone holes; the redesigned instrument was certainly louder, but its sound was generally considered too bright and strident. It did not replace the traditional design of oboe in the orchestra, although it had some use in outdoor performances by military bands [2].

The example of the Boehm oboe illustrates that the timbre of an instrument is at least as important as its sound power in musical quality evaluation. Initial scientific studies of musical instrument timbre were largely concerned with spectral analysis of steady state sounds. Early attempts in musical sound synthesis revealed the importance of transients in perception of instrumental sounds and the identification of specific instruments. In recent years it has been increasingly recognised that factors relating to the player's interaction with the instrument are of particular importance in judgement of instrument quality by a player. These factors include the ease with which a note may be initiated, the uniformity of response over the playing range, and the flexibility which is available for modulating the pitch, loudness and timbre of the sound. These factors are frequently grouped together under the general term 'playability'.
Requirements for the Investigation of Instrument Quality

The major problem in evaluating musical instrument quality is that of relating subjective judgements by players to objective scientific measurements. This task requires that a number of conditions are satisfied:

1. Experimental arrangements for scientific measurements must be devised which are not too divorced from musical practice.

2. A sufficiently high level of accuracy must be achieved to explore subtle but musically significant effects.

3. Numerical models must be developed which are not too simplified to be musically relevant.

4. The language(s) used by players to describe judgements of musical instrument quality must be interpreted and related to scientific terminology.

5. Musicians of sufficiently high calibre must be willing to collaborate if musically meaningful results are to be obtained from player tests.

6. Psychoacoustic evaluation studies must be devised which take fully into account possible player bias and inconsistency.

To illustrate the ways in which these problems have been tackled, the results that have been obtained and the areas still requiring study, we focus on three areas in which a significant amount of work has been done, and which are still fields of active research: pianos, bowed string instruments and brass instruments.

STUDIES OF PIANO QUALITY

A Simple Model of Piano Sound Production

At first sight, the science of sound production in a piano seems straightforward. A force applied to one of the keys is transmitted to a pivoted hammer by a lever system known as the action. The construction of the action is such that the hammer is accelerated to a velocity which depends on the applied key force, and then released; after release it swings freely, and its felt-covered head hits and rebounds from either one string or a small group of strings tuned in unison. A check mechanism holds the rebounding hammer, preventing a double hit. The impulsive excitation of a string by a blow from the hammer head imparts energy to the normal modes of the string, which decay in free vibration. The string is coupled through a bridge to the piano soundboard, which in turn vibrates and radiates sound.

The pianist has no contact with the hammer or string at the point of impact, and the nature of the string vibration is determined by a single variable, the hammer head velocity. It thus appears possible to model piano sound production in terms of a linear system taking account of the position of striking on the string and the resonance characteristics of the soundboard. To make such a model musically realistic, however, a number of complicating factors have to be taken into account [3].

Refinements of the Simple Piano Model

The hammer-String Interaction

Modern piano hammer heads are covered by several layers of felt, which has nonlinear compressive behaviour [4, 5]. The way in which the loudness and timbre of the piano sound changes with key force therefore depends strongly on the way in which the hammer head has been treated, and on its history of use. The spectral content of the string vibration is affected by the time of contact of the hammer head with the string, which also depends on the state of the felt covering. The flexibility of the hammer shank has also been shown to affect the transfer of energy from hammer head to string [6].
String Inharmonicity

The finite stiffness of steel piano strings leads to inharmonicity of the string normal mode frequencies. [7]. The deviation from perfectly harmonic frequency components increases with mode number, and has a significant effect on the timbre of piano sound. String inharmonicity also affects the way that pianos are tuned: careful measurements of expertly tuned concert grand pianos have shown that the tuning is ‘stretched’, with an octave ratio slightly greater than 2. Interestingly, these deviations from perfect harmonicity contribute desirable features to the piano sound quality; synthesised sounds with harmonic frequency components are judged by musicians to lack liveness and warmth [8].

The sound quality of upright pianos is generally considered to be inferior to that of full sized grand pianos, especially in the bass register. This has frequently been attributed to the fact that the bass strings on an upright piano are much shorter than those on a grand piano, and therefore have a much higher degree of inharmonicity. Recent research has suggested that differences in spectral envelope related to the absence of low frequency resonances in the soundboard of the upright may be more influential than inharmonicity in such comparisons of piano quality [9].

Effect of String Coupling on Amplitude Envelopes

One of the most desirable features of piano sound is the ‘singing’ quality associated with a slow decay rate. Piano strings typically display a double decay rate - a fast initial decay followed by a slowly decaying aftersound. This is partly due to differences in the way that vertically and horizontally polarized string vibrations couple to the bridge and soundboard, but Gabriel Weinreich showed that coupling between strings nominally in unison could lead to an extended decay time through mode locking if the strings were slightly mistuned [10]. In fact small deviations (of the order of 1.5 cents) from strict unison tuning of the three strings in piano trichords had already been observed in the practice of expert tuners [11]. The perceived smoothness of the decay can also be enhanced by subtle mistuning of trichords [12, 13].

Piano Actions and Piano Touch

The term ‘touch’ is used by pianists to describe the nature of the gesture used to depress a key on the piano. Many players believe that by altering the gesture (for example, by stroking rather than hitting the key) it is possible to change the timbre of a single piano tone without modifying its loudness. It is difficult to find objective justification for this, since the only variable which affects the string vibration is the speed of the hammer head at impact.

One factor to bear in mind is that the player is very close to the instrument, and will be able to hear subtle effects, such as the noise made by the key hitting its bed, which will not be significantly radiated into the far field. More importantly, it must be recognised that the player depends totally on the action and damping mechanisms of the piano to create and control the musical performance. The perceived playability of the instrument is intimately bound up with its mechanical performance, and cross-modal interaction between kinesthetic and auditory feedback can lead players to misinterpret the sources of quality cues.

A striking example of the effect of cross-modality was provided by experiments reported by Alexander Galembo [14]. In the late 1970s the Leningrad piano factory conducted a number of tests in which twelve professional pianists played three different grand pianos (Steinway, Bechstein and Leningrad) in the Leningrad Conservatory concert hall. The pianists were asked to play freely, and to rate the quality of the pianos in terms of tone quality, dynamic range and playing comfort. The players agreed that the Steinway was much superior in tone to the Leningrad piano, but made no clear distinction between the playing comfort of the instruments. However, when the players were asked to listen to single tones, scales and chords played behind an acoustically transparent curtain they were unable to identify which instrument was being played. In a further test, the three pianos were put into a triangular arrangement with a rotating piano stool at the centre, and each blindfolded pianist was presented with the pianos in a random order. In this test the performers could correctly identify the pianos even when deafened by white noise in headphones.

The conclusion drawn by Galembo was that the quality judgements, which the players had attributed to timbral differences in the free playing test, were in fact based on differences in mechanical response. This
illustrates one of the most significant problems in scientific evaluation of musical instrument quality: judgements by musicians are clearly of paramount importance, but are often hard to interpret.

**STUDIES OF QUALITY OF BOWED STRING INSTRUMENTS**

**Descriptions of Violin Timbre**

The question of musical instrument quality has special significance when the instrument under consideration is the violin. The financial value of a Stradivari or Guarneri violin is typically two orders of magnitude greater than the cost of an instrument from a modern maker of the highest reputation. Many non-musical factors are involved in this price differential, but a lively debate continues as to whether old Italian violins are superior in musical quality to the best violins of the present day. Acousticians have contributed to this debate for several decades, but objective criteria for assessing violin quality have proved elusive.

A number of studies have attempted to relate musical quality judgements to the strengths of sound radiation in specific frequency bands. Dünnwald [15] reported measurements of frequency spectra of the sound radiation from several hundred violins of varying age and quality. The bridge of each instrument was excited sinusoidally by an electromagnetic driver. He identified four frequency bands, and proposed that each was associated with a specific tonal characteristic (See Table 1).

<table>
<thead>
<tr>
<th>Band number</th>
<th>Frequency range</th>
<th>Timbral characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190–650 Hz</td>
<td>fullness of sound</td>
</tr>
<tr>
<td>2</td>
<td>650–1300 Hz</td>
<td>nasality</td>
</tr>
<tr>
<td>3</td>
<td>1300–4200 Hz</td>
<td>brilliance, clarity</td>
</tr>
<tr>
<td>4</td>
<td>4200–6400 Hz</td>
<td>harshness, lack of clarity</td>
</tr>
</tbody>
</table>

Dünnwald’s approach has had a considerable influence on later work on violin timbre, but his association of timbral character with frequency bands has not proved robust. For example, the violin maker and acoustician Martin Schleske has proposed a somewhat different scheme [16], illustrated in Table 2. Schleske notes that these judgements are likely to vary significantly from one listener to another.

<table>
<thead>
<tr>
<th>Band number</th>
<th>Frequency range</th>
<th>Too strong</th>
<th>Too weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270 Hz</td>
<td>dull, hollow</td>
<td>thin, chirpy</td>
</tr>
<tr>
<td>2</td>
<td>450–550 Hz</td>
<td>hollow, wolf tendency</td>
<td>flat, weak</td>
</tr>
<tr>
<td>3</td>
<td>700–1000 Hz</td>
<td>not specified</td>
<td>not specified</td>
</tr>
<tr>
<td>4</td>
<td>1000–1800 Hz</td>
<td>vulgar, nasal</td>
<td>powerless, covered</td>
</tr>
<tr>
<td>5</td>
<td>2000–3500 Hz</td>
<td>harsh, vulgar</td>
<td>dull, covered</td>
</tr>
</tbody>
</table>

**Input Admittance of Violins**

In attempting to relate the perceived quality of the sound of bowed string instruments to physical characteristics of the instruments, measurement of the bridge admittance (also known as mobility) has proved to be one of the most useful techniques [17, 18, 19]. In one version of this technique, a calibrated impulse is applied to the treble corner of the violin bridge and the resulting bridge velocity is recorded by a laser vibrometer. The admittance is defined as the frequency domain ratio of bridge velocity to applied force. A typical violin bridge admittance curve is shown in Figure 1.

Specific features of the admittance curve can be related to structural vibration properties of the violin [20], but while an admittance curve without significant resonance peaks would be an indication of a very poor
instrument, it has not proved possible to find features which discriminate unambiguously between violins judged excellent and instruments which are of only average quality. After an exhaustive study of 17 violins of widely varying quality, including mobility and radiativity measurements, George Bissinger [21] concluded that the only features which appeared to characterise the very best instruments were a relatively uniform spread of resonances and a strong response in the lowest frequency band.

A recent set of studies by Fritz et al. [22] revisited the relationship between spectral response and quality judgements using the “virtual violin” technique [23]. In this approach the acoustical response of a good quality modern violin was modelled as a sum of 54 vibration modes. The amplitudes, frequencies and quality factors of the modes were deduced from a bridge admittance measurement. The model was then used to compute a finite impulse response digital filter simulating the transient response of the violin. A force signal recorded at the bridge of a violin when played normally was fed through the filter to a pair of headphones. The amplitudes of the model modes in specified frequency bands were then increased or diminished, and a panel of 14 musically expert listeners assessed the resulting timbral changes. Three descriptors were chosen on the basis of a previous semantic study: these were bright, harsh, and nasal. For comparison with the results of Dünnwald, the descriptor clear was also included.

<table>
<thead>
<tr>
<th>Band number</th>
<th>Frequency range</th>
<th>Increased Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190–380 Hz</td>
<td>more nasal (Group 1n), less nasal (Group 2n)</td>
</tr>
<tr>
<td>2</td>
<td>380–760 Hz</td>
<td>less bright, more nasal (Group 1n), less nasal (Group 2n)</td>
</tr>
<tr>
<td>3</td>
<td>760–1520 Hz</td>
<td>less bright, more nasal (Group 1n), less nasal (Group 2n)</td>
</tr>
<tr>
<td>4</td>
<td>1520–3040 Hz</td>
<td>brighter, harsher, less nasal (Group 1n), more nasal (Group 2n)</td>
</tr>
<tr>
<td>5</td>
<td>3040–6080 Hz</td>
<td>brighter, harsher, less nasal (Group 1n), more nasal (Group 2n)</td>
</tr>
</tbody>
</table>

The results of Fritz et al. are summarised in Table 3. Evaluations of clarity and brightness appeared to be judgements on the same timbral dimension in these tests, so the dependence of clarity on frequency band has not been included in Table 3. Judgements of brightness and harshness were broadly consistent across the group of test subjects. Judgements of nasality were clearly made on a different basis by two approximately equal subgroups: Group 1n found nasality to increase with increased amplitude in Bands 1-3 and decreased amplitude in Bands 4-5, while Group 2n found the reverse. Neither subgroup associated nasality specifically with Band 3, as would have been expected from the results of Dünnwald. These inconsistencies are further examples of the problems involved in relating timbral properties to acoustical response.
Playability of Bowed String Instruments

In the last two decades, considerable research effort has been devoted to studying the criteria which players use when judging violins and other bowed string instruments. Woodhouse [24, 25] noted that a violin player evaluating a new instrument considers not only its sound quality but also the various aspects of the physical interaction between player and instrument which contribute to judgements of playability. One important issue is the ease and smoothness with which the periodic string vibration known as Helmholtz motion can be initiated and sustained. Schelleng's work [26] on theoretical maximum and minimum limits on the force exerted by the bow hair on the string has been extended by Guettler [27] and Woodhouse [28] to consider the interdependent effects of bow force and bow acceleration on the length of starting transients in stringed instruments. Identifying other aspects of playability which are salient in player judgements of quality, and relating these to structural properties of the instrument, remain outstanding challenges in violin acoustics.

A recent study of player evaluations of high quality violins [29] has highlighted the problem of interpreting correctly the results of such tests. 21 experienced violinists were asked to compare six violins, three of which were Stradivari or Guarneri instruments and three of which were by leading contemporary makers. The players compared the instruments in free playing in a dry room, with low illumination and wearing goggles which prevented visual identification of the instruments. Players were asked to rate the instruments using various criteria, including playability, response and tone colour. The new violins were rated more highly than the old Italian instruments for playability and response, but there was no significant distinction for tone colour. It has frequently been stated that an experienced player can immediately distinguish an antique violin from a new one [30], but the players in this test were generally unable to tell whether the instrument they were playing was old or new. The shielding from visual cues was obviously crucial in the experiment, not only because the players might identify the instruments visually but also because of the possibility of cross-modal effects altering the players' perceptions of timbre and playability.

STUDIES OF QUALITY OF BRASS INSTRUMENTS

Descriptions of Brass Instrument Timbre

There is one aspect of brass instrument timbre which has been recognised as strongly characteristic of the family in both musical and acoustical studies [31, 32, 33, 34]. This is the increase in brightness of the sound which occurs during a crescendo on a brass instrument. Brightness is associated with a high value of the spectral centroid \( SC \), defined for a sound with discrete spectral component frequencies \( f_i \) and amplitudes \( A_i \) as

\[
SC = \frac{\sum_i A_i f_i}{\sum_i A_i}.
\]

The spectrum of a brass instrument played quietly is typically dominated by a few low amplitude harmonics. As the dynamic level increases, higher frequency harmonics become increasingly important; for a trumpet blown fortissimo more than 40 components of significant amplitude can be observed [35]. For other types of brass instrument, such as the saxhorn, the brightness increases much more gradually with increasing loudness.

It is significant that this most striking characteristic of a brass instrument is not a fixed degree on a perceptual timbre scale (brightness), but rather a relationship between two dimensions (brightness and loudness) which colours the perception of transient features related to musical expression. Experiments carried out in the 1970s using computer synthesised versions of recorded musical instrument sounds [36, 37] revealed that transient features were particularly important in the recognition of a musical instrument from its timbre. Low frequency, low amplitude inharmonic components in the attack transient were associated with the brass family, as was tapering of the onsets of higher harmonics and associated spectral fluctuations.
Input impedance

The input impedance of a wind instrument is defined as

\[ Z(f) = \frac{p_i(f)}{u_i(f)} \]

(2)

where \( p_i \) is the acoustic pressure at the input and \( u_i \) is the acoustic volume velocity into the instrument for a sine wave input at frequency \( f \). The input impedance curve shown in Figure 2 illustrates the linear acoustic response of a tenor trombone measured at the mouthpiece entrance plane. Measurements of this type have been used for several decades in studies of brass instruments, and are currently used for quality control in the brass instrument manufacturing industry [38, 39].

**Figure 2:** Input impedance curve for a Conn 8H orchestral tenor trombone

**Figure 3:** Input impedance curves for an alphorn in Ab
Acoustic Resonances and Playing Frequencies

The input impedance curve for a brass instrument resembles the bridge admittance curve for a stringed instrument in that each describes the linear acoustic response of the instrument to a sinusoidal input signal. There is however a fundamental difference in the relationship between the resonances shown in the two type of curve and the playing characteristics of the instruments concerned. In the case of a stringed instrument the coupling between the body and the sound source (the vibrating string) is relatively weak, and only in the pathological case of a wolf note does feedback from body vibrations significantly perturb the stick-slip interaction between bow hair and string [28]. In contrast, there is a strong nonlinear coupling between the air column resonances in a brass instrument and the vibrations of the player's lips. Since the lip vibration generates the sound through modulation of the air flow into the instrument, the acoustic resonances of the brass instrument air column play a major role in determining both the frequency and the timbre of a played note.

The nature of the input impedance curve is determined by the internal bore profile of the instrument. Inspection of the trombone input impedance curve in Figure 2 shows that there are around 15 recognisable peaks. From the second to the fifteenth peak, the frequencies satisfy the approximate harmonic relation

\[ f_n \approx 57.7n, \quad n \geq 2. \] (3)

The lowest peak, at 39 Hz, is not a member of this series. This feature is characteristic of instruments with a large proportion of cylindrical tubing. For instruments in which the tubing is mostly conical the lowest peak also satisfies the approximate harmonic relationship; Figure 3 illustrates the example of the alphorn.

To sound a note, a brass player normally adjusts the muscles controlling the mechanical resonance frequencies of the lips in such a way that the flow of air between them induces a bifurcation to an oscillating regime with frequency close to one of the acoustic resonances. The lips and air column then lock into a stable periodic vibration. It is important to note, however, that the playing frequency is not simply the frequency of the nearest acoustic resonance. The nonlinear nature of the coupling means that higher frequency resonances can also exert an influence on the intonation. It is even possible to play a note for which there is no acoustic resonance close to the playing frequency. An important example is the trombone pedal note. On the instrument whose input impedance is shown in Figure 2, a strong note can be played at a frequency of 57.7 Hz, the oscillation regime being supported by the acoustic resonances at integer multiples of the playing frequency. The timbre is characteristically bright, with little spectral energy at the fundamental frequency.

Measurements of acoustic resonance frequencies thus provide a valuable guide to intonation quality of brass instruments, and have been used to generate targets for optimization programs [40, 41, 42]. Questions remain, however, about the detailed relationship between measured acoustic resonance frequencies and musical judgements of intonation accuracy [43, 44].

Wall material

The walls of wind instruments vibrate when the instruments are played. Wall vibrations of a clarinet or trombone played loudly can be felt by the fingers of the musician, and many players and instrument makers believe that these vibrations also contribute significantly to the sound quality of the instrument. Recent theoretical and experimental work on a simplified clarinet model [45] has suggested that although wall vibrations can couple to acoustic resonances to produce audible changes in input impedance and radiated sound, these effects are unlikely to have a noticeable influence on the sound quality of normal woodwind instruments. In an important set of experiments on brass instruments, Kausel et al. [46] found measurable changes in sound spectrum caused by damping the walls while the instruments were artificially blown. It is suggested that this is not due to direct sound radiation from the walls, but rather to coupling of acoustic resonances with relatively broad axial resonances of the bell [47].

Further work is required to establish the extent to which the views of instrument makers and players about the effects of changes in wall thickness, metal composition and finish on timbral quality can be understood scientifically. A salutary warning of the potential difficulty of such a task is provided by a study undertaken over three decades ago by Richard Smith [48]. A set of six trombone bells were made on the same mandrel, but with varying wall thickness (from 0.3 mm to 0.5 mm). Tests with an artificial sound source
showed that spectral differences of the order of several decibels at a position corresponding to a player’s left ear were related to differences in bell wall thickness. He then carried out a double blind playing test involving ten leading trombonists. The players were blindfolded, and precautions taken to equalise the weight and balance of the instruments. Under these conditions the players were unable to distinguish between instruments with different bell thicknesses. When a pure copper bell was included in the test set, it was not recognised as significantly different in timbral quality, although Smith reports that “when subsequently played in non-blind tests it gained magical properties!” This is yet another example of the importance of cross-modal influences on judgements of musical instrument quality.

Nonlinear sound propagation

The amplitude of the pressure waves generated in a brass instrument played loudly can exceed 10 kPa. At this level, the timbre of the instrument is significantly affected by nonlinear sound propagation. In instruments with long sections of cylindrical tubing (trumpets and trombones) wave steepening can even lead to shock wave formation, with concomitant transfer of energy to very high frequency air column modes [49]. Nonlinear propagation is then the dominant factor in the sound timbre, which is described as ‘brassy’ (French ‘cuivrée’). Since the distortion arising from nonlinear propagation is cumulative, its effects are less important in instruments with shorter tube length. Instruments with conical bores are also less affected by nonlinear propagation, since the sound pressure level diminishes as the cross-sectional area increases.

While the most striking consequence of nonlinear propagation is the brilliant blare of a fortissimo trumpet, it is also an important aspect of brass instrument quality even at moderate sound levels. Myers et al. [50] have proposed a taxonomy of brass instruments based on the rate at which nonlinear distortion increases during a crescendo. Each instrument is characterised by a brassiness potential parameter \( B \), which takes into account the variation of bore diameter \( D \) with axial distance \( x \) from the entrance plane:

\[
B = \frac{1}{L_{ecl}} \int_0^{L} \frac{D_0}{D(x)} dx,
\]

where \( D_0 \) is the minimum bore diameter and \( L_{ecl} \) is the equivalent cone length of the instrument (equal to \( c/2f \) where \( c \) is the speed of sound and \( f \) is the nominal fundamental frequency of the instrument). For all conventional brass instrument bores, \( B \) is a number between 0 and 1. Figure 4 illustrates the spread of values for a number of instruments playing in approximately the same pitch range as the trombone.

The development of brightness in a crescendo also depends directly on the absolute radial scale of the bore, for two reasons. To achieve a given radiated sound level, the player of a narrow bore instrument must generate a larger input pressure amplitude than a player of a wider bore instrument with similar relative bore profile; this leads to greater nonlinear distortion in the narrower instrument. However viscothermal losses are also greater for narrower diameter tubes, and since these losses increase with frequency they preferentially damp the higher harmonics. For the normal range of bores used in brass instruments the former effect dominates, so that the French horns shown in Figure 4 have a more rapid development of brightness that their low \( B \) values would suggest because of their small input diameter.

Many questions remain to clarify concerning the relationships between these aspects of brass instrument timbre and players’ judgements of quality. In the twentieth century most orchestral trombone players adopted large bore diameter trombones in the quest for higher sound output without excessive brassiness; some players, however, consider that these instruments lack character at low dynamic levels compared with the narrow bored instruments commonly used in earlier periods. The musical context must be carefully considered in discussions of instrumental quality.

Playability of Brass Instruments

The relationship between player and instrument is particularly intimate in the case of brass instruments, since the player’s lips are the essential components in the sound source [51]. When a player starts a note several periods of the lip vibration may occur before the sound wave reflected from the bell returns to the mouthpiece and a standing wave is established [52]. An important aspect of playability is the ease with which
FIGURE 4: Scatter plot of the brassiness potential parameter $B$ computed from physical measurements, plotted against the minimum diameter $D_0$, for 26 instruments of conventional design in Edinburgh University Collection of Historic Musical Instruments [50].

a note may be started. The strength of a regime of oscillation is enhanced when the acoustic resonances are harmonically aligned; players then talk of the notes being ‘well centred’. It seems plausible that harmonic alignment of the modes is linked to ease of starting a note, but this hypothesis remains to be fully tested.

Strong centring of notes is usually considered a desirable quality in a brass instrument, but the relationship between centring and flexibility requires further investigation. The latter quality is related to the ease with which the player can ‘bend’ the pitch of a note, or make a smooth transition from one regime of oscillation to another [53]. It has been suggested that harmonically aligned resonances with high Q values may result in an instrument being judged ‘stiff’ rather than flexible. This could be a particular problem in instruments such as the baroque trumpet, on which the eleventh acoustic mode has to support two pitches a semitone apart [54].

On an instrument in which the acoustic resonances are significantly inharmonic, the nonlinear nature of the coupling between lip and air column can lead to instability and pitch drift as the dynamic level is increased. An example of such an instrument is the serpent. Although this instrument is usually made from wood and is equipped with finger holes, it is considered acoustically to be part of the brass family since it is excited by lip vibration in a cup mouthpiece. Figure 5 shows the input impedance for a serpent with the lowest three finger holes open. The strongly inharmonic nature of the resonances is a consequence of the small diameter and irregular spacing of the side holes, and is typical of measurements carried out on many original and reproduction instruments. A virtuoso performer can play the serpent with good intonation and an attractive mellow timbre; exactly how this unlikely feat is achieved is a subject currently under study.

One playing technique which could partly explain the ability of an expert player to sound notes without apparent support from the acoustic resonances of the instrument involves modification of the vocal tract. The player's mouth cavity and throat have resonances which are upstream of the player's lips, but which couple to the lips in the same way as the downstream resonances of the instrument. It has been shown that expert saxophone players tune vocal tract resonances in high register performance [55], and recent measurements have confirmed that vocal tract resonances appear to be significant in trombone playing over most of the register [56].

The final word on brass instrument quality evaluation must be on mouthpiece design, which most
players believe to have a strong effect on the overall quality of the instrument. A brass instrument mouthpiece serves a number of functions; it acts as a support to the lips, and its rim defines the limit of possible lip vibration. The mouthpiece also boosts the heights of impedance peaks in a range slightly below its own acoustic resonance frequency: this effect is strongly evident in Figure 3. The aeroacoustics of the mouthpiece are less well understood. The jet of air which emerges from the lips of the player is usually considered to dissipate its energy without pressure recovery some distance before it reaches the throat which connects the mouthpiece to the main tubing of the instrument, but this hypothesis requires verification. Many players and manufacturers believe that the wall thickness and overall mass of the mouthpiece have a major effect on the playability and timbre of the instrument, but possible causes for such a dependence are hard to identify. The relationship between mouthpiece design parameters and musical quality judgements is a topic ripe for serious scientific scrutiny.

CONCLUSION

The basic physics of the musical instruments discussed here is well understood, but many musically important aspects require finer measurements and greater understanding of the language and requirements of musicians. Time domain modelling is poised to play an important role in exploring the perceptual significance of specified small changes in the design of an instrument, but models of the sound generating mechanisms require further refinement before the sound output from a complete instrument model is sufficiently realistic to be musically useful. Optimisation methods for musical instruments are improving, but need more musically relevant targets. The ultimate aim of this work is to explain scientifically why an instrument is judged to be musically excellent, and to offer guidance to makers wishing to achieve and maintain excellence in musical instrument manufacture.

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REFERENCES


