Acoustical Comparisons of Sackbuts and Trombones[1]

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The sound quality of a brass instrument in performance depends on several factors: the player's technique and concept of an ideal sound, room acoustics, and the instrument together with the mouthpiece used with it. It is not possible to separate completely the contributions of these factors to timbral quality since they are to some extent interdependent, but some aspects can be analyzed and an assessment made of their effects on sound. This article treats the effects of instrument design (apart from the mouthpiece) on timbre. Mouthpiece selection is also important, being a large factor in response, endurance, and timbre: however there are contributions of the instrument to timbre that are independent of the very personal matter of mouthpiece choice of the player. This approach reflects the fact that players usually select an instrument first and then choose a mouthpiece that best enables them to realize their ideals in their envisaged performance situations.

Of the many differences between trombones and sackbuts (the latter term is used here to denote original or copies of Renaissance period instruments), some have a more important effect on timbre and dynamic range than others. This article concentrates on the following:

> The shape of the bore profile over the whole length of the instrument and the influence of non-linear propagation (brassiness)
>
> The absolute bore size, and the loss of sound energy at the inner wall of the instrument
>
> The bell flare and its effect on the radiation of sound from the instrument

It is not always realized that most of the sound energy in the air column of a brass instrument is trapped inside, and that only a small fraction escapes from the bell to delight the audience. When a trombone is played the sound pressure level inside the instrument can reach a deafening 150 decibels above the threshold of hearing. At such a level, the pressure variations are a significant proportion of atmospheric pressure, and the linear propagation of sound (which is a very good approximation at the levels of sound normal for spoken conversation) is replaced by a non-linear regime in which a sound wave starting from the mouthpiece reaches the bell with some of its energy converted to higher frequencies. At high dynamics, this can result in a shock wave which is heard as a brassy or *cuivré* sound. At moderate dynamics non-linear propagation is perceived as brightness in the sound: precisely the timbral characteristic that distinguishes a trombone from a euphonium.

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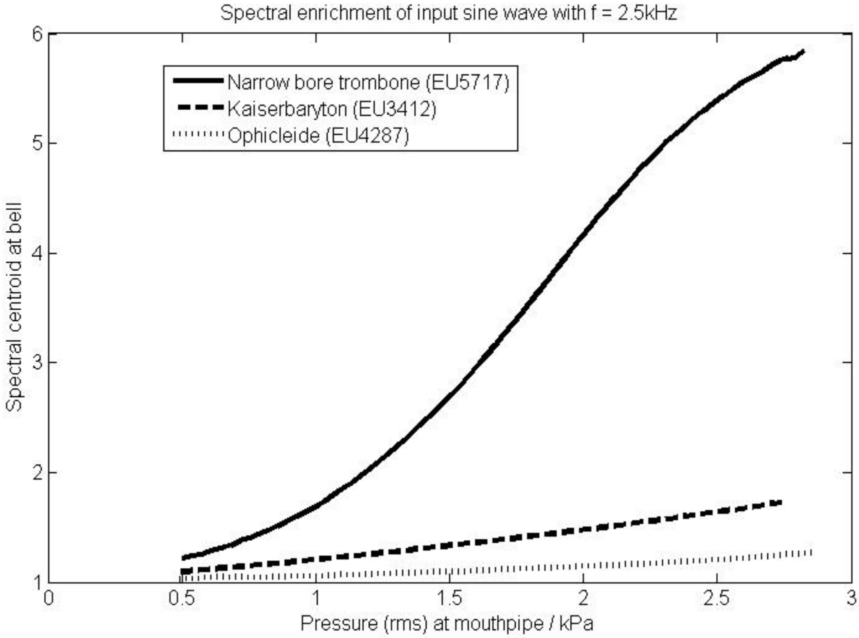

Figure 1: Spectral centroid at bell plotted against pressure at mouthpipe for different instruments.

In Figure 1 the spectral centroid at the bell is plotted against sound pressure level at the mouthpipe for various instruments. The spectral centroid is a widely used measure of the brightness of a sound.[2] Here, sound of a single frequency from a loudspeaker is injected at the mouthpiece receiver; the sound waves radiated from the bell are enriched with overtones. For all instruments the sound brightens as the sound level rises, but this is more pronounced in sackbuts and trombones than in euphoniums and ophicleides.

The degree to which an instrument engenders non-linear propagation is a function of its geometry: it is a direct consequence of the design. At the suggestion of the acoustician Robert Pyle, a "brassiness potential parameter" *B* has been defined.[3] *B* is a number that expresses the potential of an instrument to enrich the frequency spectrum of sound waves traveling along the length of the bore. For a given player, providing a given input with a given mouthpiece, instruments with a high value of brassiness potential parameter *B* will brighten the sound more rapidly in a crescendo than instruments with a low value of brassiness potential parameter.

$$B \approx \sum_{1}^{N} \frac{l_n}{L_{ecl}} \left(\frac{2D_0}{D_n + D_{n+1}} \right)$$

B can be determined for any instrument by measuring the bore diameter at a number of places spread over the length of the instrument and doing this sum. Here D_0 is the bore diameter at the beginning of the instrument—not the very beginning that receives the mouthpiece, but the minimum bore that occurs a little way in. L_{ecl} is the ideal acoustical length—the length of a pure cone with the frequency of its fundamental matching the nominal pitch of the instrument. Dividing the sounding length of the instrument into *N* manageable sections, D_n is the diameter at the start of section *n*, l_n is the length of section *n*. See the appendix for a worked example.

Note here that it is the inverse (reciprocal) of the bore diameter that appears. Each section of the whole length of the instrument makes a contribution, but the wide sections of tubing (high value of *D*) make relatively small contributions to non-linear propagation. Shock waves are mainly generated in the narrower sections of an instrument.

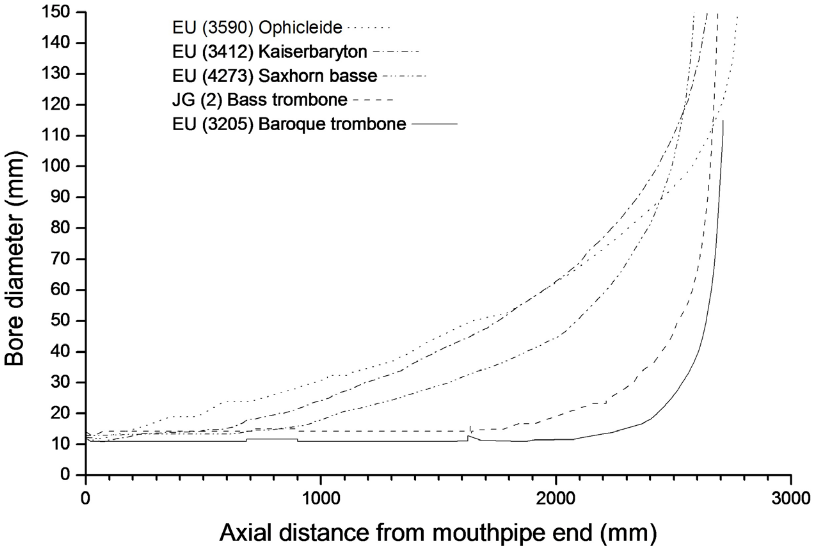

Figure 2: Graph of bore profiles of five eight-foot / nine-foot instruments.

Figure 2 shows the bore profiles of five instruments of nine-foot nominal pitch. The values of brassiness potential parameter *B,* based on simple measurements, are:

Instrument, Nominal Pitch EU = Edinburgh University Collection of Historic Musical Instruments JG = Joël Gilbert, private collection	**Maker, Place, Date**	***B***
EU3590 Ophicleide, keyed for A	Gautrot, Paris, ca. 1860	0.31
EU3412 Kaiserbaryton, 9-ft B♭	Červeny, Königgrätz, ca. 1900	0.37
EU4273 Saxhorn basse, 9-ft B♭	Ad. Sax, Paris, 1867	0.51
JG2 Bass trombone, 9-ft B♭	Courtois, Paris, 2000	0.67
EU3205 Tenor trombone, 9-ft B♭	Huschauer, Vienna, 1794	0.81

The values of *B* are well spaced. Looking at a larger sample, instruments recognized as euphoniums (or similar) have values of *B* in the range 0.37 to 0.47, instruments recognized as baritones or narrower-bore saxhorns have values of *B* in the range 0.47 to 0.6, and sackbuts and trombones have values of *B* in the range 0.6 to 0.82.

As discussed below, bore size is an independent variable affecting timbre. The bore profiles of the various brasswind families can be mapped by plotting brassiness potential against the minimum bore. Considering only instruments in eight-foot C and nine-foot B♭, Figure 3 shows how recognized species of instruments occupy distinct regions on the graph.

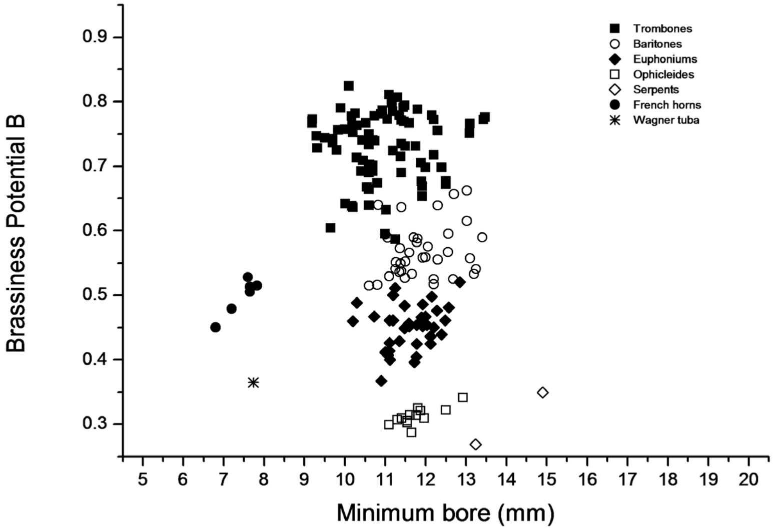

Figure 3: Scatter plot of *B* for instruments with nominal pitches of eight-foot C, nine-foot B♭, and ten-foot A.

Trombones cover quite a wide area of the graph; this is because sackbuts and all kinds of trombones have been lumped together. Figure 4 divides the sackbut and trombone population into broad categories. The results may seem at first counter-intuitive, with Renaissance period trombones (sackbuts) having higher values of *B* than modern trombones, although the sound of the sackbut is usually thought of as being less brassy. However, it has to be remembered that although at high dynamic levels some instruments are readily sounded in a *cuivré* (brassy) manner, non-linear propagation is also evident to some extent in playing at lower dynamic levels. Typical sackbut playing is at a fairly low dynamic level, and the high value of *B* engenders some non-linear propagation resulting in a rich timbre which blends well with that of instruments such as the cornett and with the human voice.

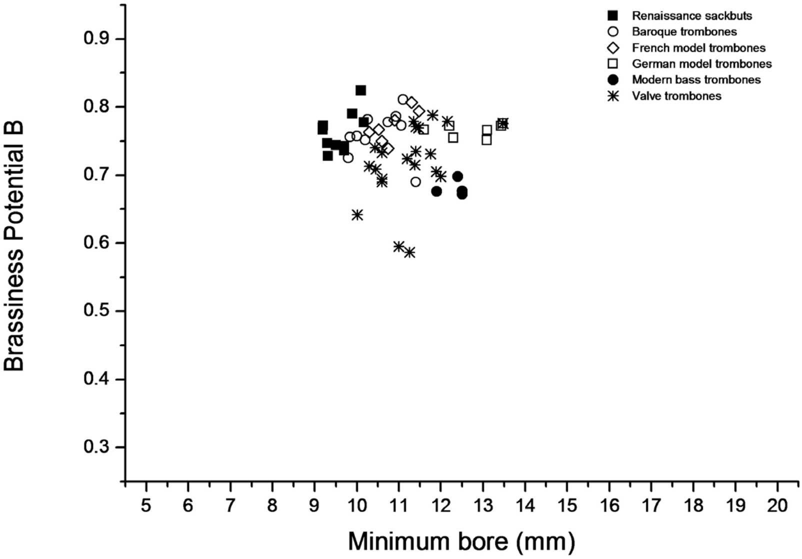

Figure 4: Scatter plot of *B* for typical examples from the various stages in the history of the trombone at eight-foot and nine-foot nominal pitches.

Modern trombones with their lower value of *B* are not "brassy" when played quietly, but for these models *B* is not so low that *cuivré* playing is out of the players' reach: it develops at the high dynamic levels which are common in modern trombone playing. In contrast, the modern trombone has little character in pianissimo. Nineteenth-century narrow and medium-bore trombones accommodated playing styles where *cuivré* playing was part of the idiom, but dynamic levels were generally somewhat lower than is common today.

Narrow-bore instruments are generally considered by musicians to have a brighter timbre than wide-bore instruments of comparable bore profile. So (for example) narrow-bore and wide-bore trombones can have the same value of *B* if they are similarly proportioned, but musicians will say that the narrow-bore instrument is brighter. To produce a given dynamic output, a narrow-bore instrument requires a higher sound pressure at the mouthpiece than a wide-bore instrument, and the higher sound pressure at the mouthpiece gives rise to more non-linear spectral enrichment. So in a performance situation where a certain dynamic level is required, the narrow-bore instrument will have a brighter timbre, other things being equal.

Previous experimental work and computer simulations have investigated the influences of absolute bore size and of the loss of sound energy at the inner wall of the instrument on non-linear spectral enrichment.[4] As a rough guide, narrowing the bore overall by 25% has an effect on spectral enrichment equivalent to increasing brassiness potential (*B*) by 10%, and widening the bore by 25% has an effect on spectral enrichment equivalent to decreasing *B* by 10%.

This more recent work has taken a complementary approach to studying the factors determining the timbre of radiated sounds. Bell size is the most obvious feature distinguishing sackbuts and trombones, but how important is it? Figure 5 shows the bell flares of a typical sackbut and a modern trombone.

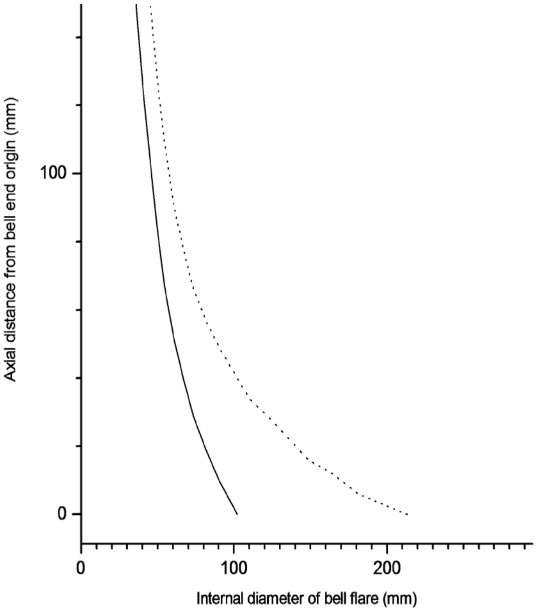

Figure 5: Bell profiles of a sackbut by Anton Schnitzer (1594) and a Conn 8H trombone (1978).

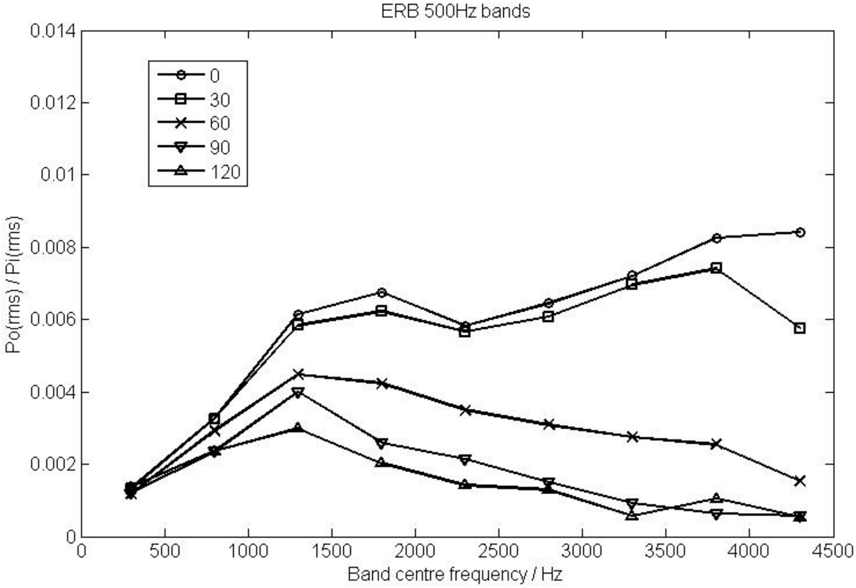

Figure 6a: Linear plots of transfer functions for a Tomes sackbut (1998) for different angles.

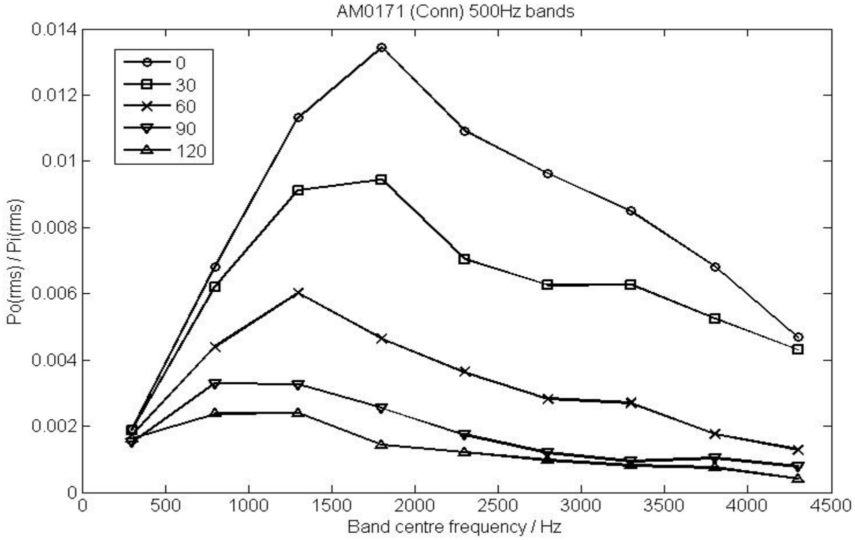

Figure 6b: Linear plots of transfer functions for a Conn 8H trombone (1978) for different angles.

As mentioned above, most of the sound energy inside a brass instrument is trapped inside; only a small fraction escapes from the bell. The size and shape of the bell has an effect on how much and in which directions sound is radiated. To investigate this effect the transfer function of the bell flare was measured for several instruments. The transfer function of a bell flare is the ratio of sound pressure level beyond the bell to sound pressure level inside the instrument. A number of sackbuts and trombones were tested in an anechoic chamber at low dynamic levels (to minimize non-linear effects) by attaching a loudspeaker in the place of the mouthpiece and injecting a pure sine wave swept over the frequency spectrum. For each instrument the sound pressure level at the mouthpiece end was measured with one microphone and the sound pressure level 50cm beyond the bell end was measured with another microphone; this far-field microphone was positioned on the axis of the bell, then at 30°, 60°, 90°, and 120° off-axis. The results for two typical instruments are shown in Figures 6a and 6b.

Overall, the sackbut is a much less efficient radiator of sound than the trombone. This is partly due to the greater visco-thermal losses in the narrow tubing of the sackbut and partly due to the smaller bell. However we can see that at high frequencies the wide-bore trombone becomes a less efficient radiator than the sackbut. This is probably because higher-order modes that do not radiate are excited in a large bell. These frequencies above 3000 Hz are of course well above the fundamental frequencies of the playing range, but they are frequencies at which the overtones (harmonics) contribute to the timbre of the instruments.

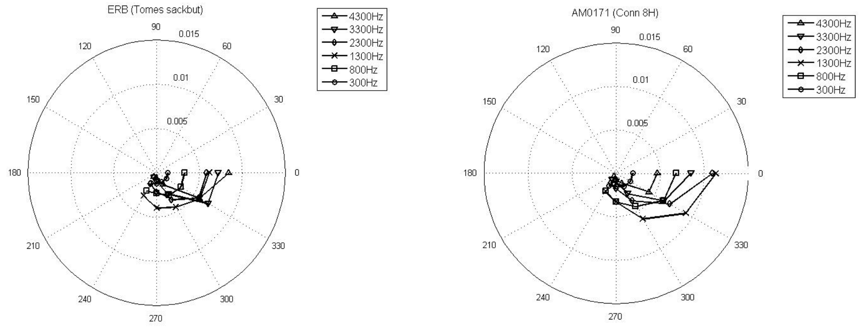

Figure 7: Polar plots of transfer functions for the Tomes sackbut (1998) and the Conn 8H trombone (1978) for different frequencies.

Figure 7 shows the same data plotted to show the directionality of sound radiation. As one would expect, high frequencies are radiated more directionally on-axis than low frequencies, and wide bells radiate sound more directionally than small bells. The directionality is not necessarily an important feature, since most music-making involving sackbuts and trombones takes place in reverberant rooms. The effect of playing in a reverberant space was obtained by weighted addition of the sound power output radiated in the measured directions, this was then plotted against frequency for a fixed input pressure level (100Pa) (see Figure 8).

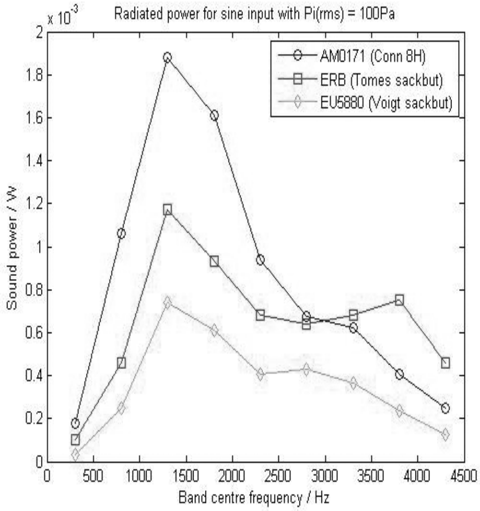

Figure 8: Radiated power for Voigt (ca. 1995) and Tomes (1998) sackbuts and the Conn 8H trombone (1978) plotted against frequency.

The trombone clearly delivers more energy than the sackbuts, largely due to its wider bore. The Tomes sackbut has a slide-bore diameter of 12.2mm, wider than that of Renaissance period Nuremberg sackbuts, whereas the Voigt sackbut has a slide-bore size of 9.8, more typical of Nuremberg tenor sackbuts (which range from 9.2 to 10.4). The two sackbuts have the same bell size.

To determine the effect of bell size in isolation, the bell of a medium-bore British trombone (Boosey & Hawkes Imperial model, made in 1970) was cut down to sackbut size in two stages (see Figure 9) and a German trombone (Alexander) bell was cut down to smaller than sackbut size in three stages. Removing the widest part of the bell flare has no effect on the absolute bore size and negligible effect on the brassiness potential parameter B, so the measured and audible effects are purely those of the difference in bell size.

From Figure 10 we see that the larger bell does indeed deliver more radiated sound than the cut-down bell, both in the range of frequencies of the fundamentals of the played notes and in the range of frequencies of the overtones. The effects of bell size reduction on the playability of the instrument are also of interest. The acoustic input impedance was measured before and after cutting using BIAS®; see Figures 11 and 12, in which the same data is presented using respectively linear and logarithmic scales for impedance. At low frequencies there is little difference, but at higher frequencies there are distinct peaks and troughs in the impedance of the cut-down trombone which will give the player more security in the very high register. This is more easily seen on a logarithmic scale.

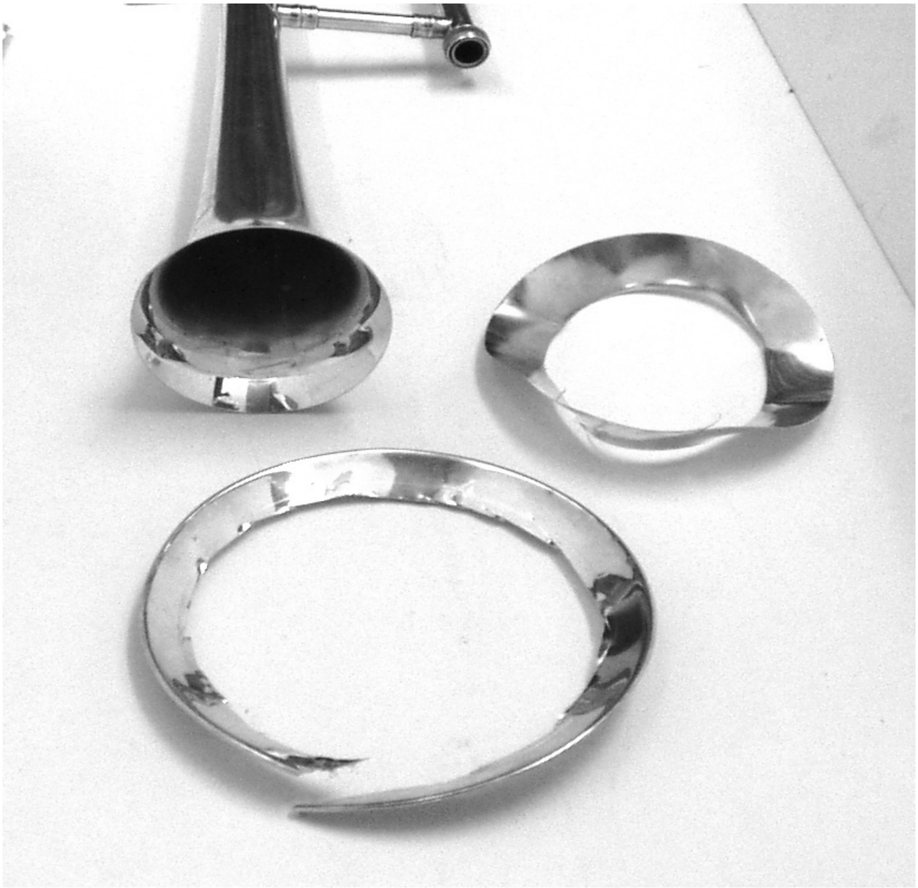

Figure 9: Boosey & Hawkes Imperial trombone (1970) and removed parts of the bell.

To compare sackbuts with narrow-bore trombones, the radiated power for a fixed input pressure level (100Pa) can be plotted over the relevant frequency range, see Figure 13. Of these, the Tomes sackbut has the largest bore. The Courtois trombone of 1865 and the late nineteenth-century Higham trombone both have a bore of 11.4mm, while the modern Voigt sackbut has the narrowest bore. The larger bells of the two trombones have increased power output which approaches that of the wide bore sackbut. The narrow-bore, small-bell Voigt sackbut delivers the least power. Measurements made in 2012 of a tenor sackbut by Geert Jan van der Heide after Anton Drewelwecz 1595 with bore diameter 10.0mm gave results close to those obtained with the Voigt sackbut.

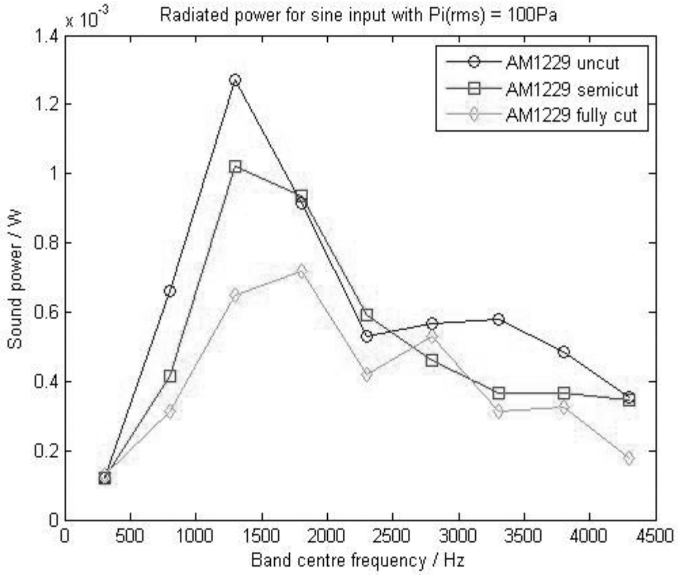

Figure 10: Radiated power for Boosey & Hawkes trombone (1970)—uncut, semi-cut, and fully cut down, plotted against frequency.

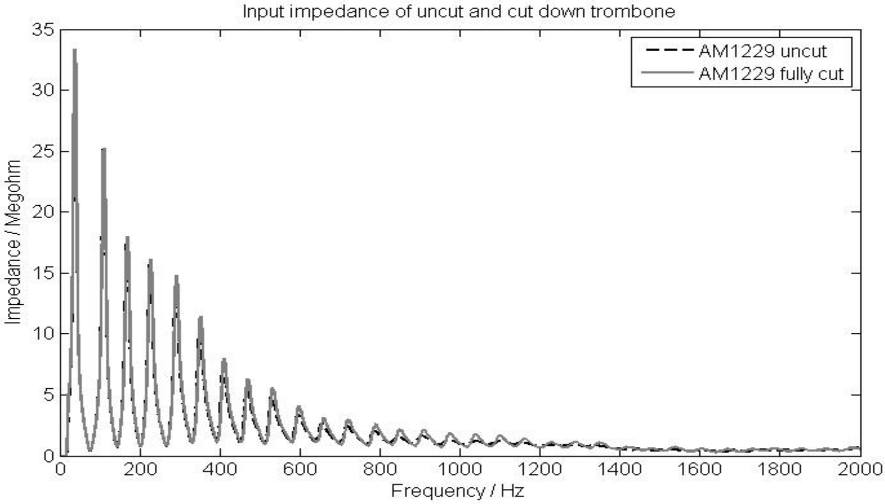

Figure 11: Superimposed impedance against frequency plots for complete and fully cut-down trombone, linear scale.

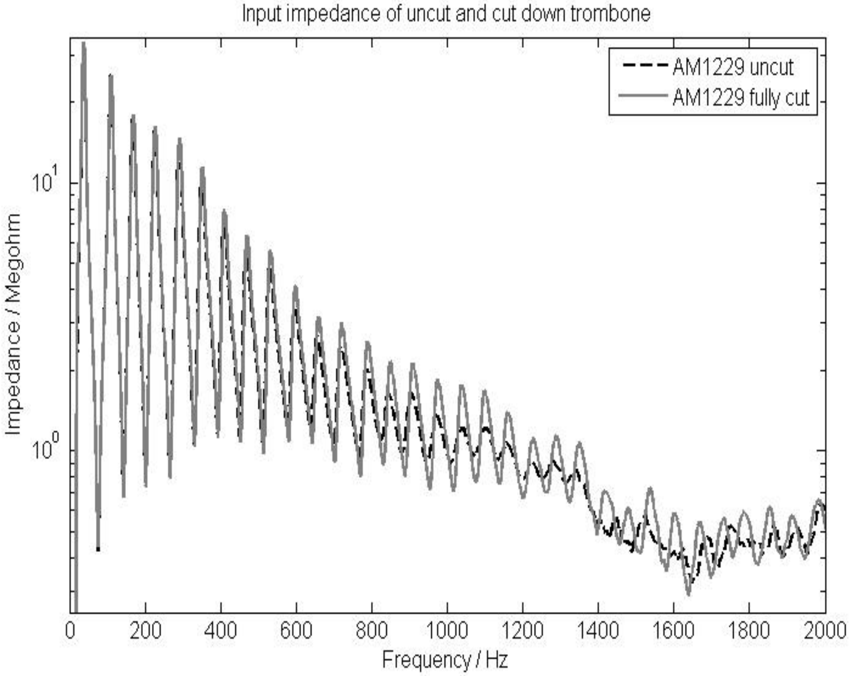

Figure 12: Superimposed impedance against frequency plots for complete and fully cut-down trombone, logarithmic scale.

Conclusion

To achieve a desired performance dynamic, an instrument of low radiating power will have to be played with a greater acoustic pressure at the mouthpipe end and will sound brighter due to non-linear propagation. A narrow-bore small-bell sackbut such as the Voigt we measured and surviving Renaissance sackbuts will in general have a brighter timbre than a narrow bore trombone. Alternatively, for a given brightness the sackbut has to be played at a lower dynamic.

More work needs to be done on measuring and modeling the effect of changes in bell shape on the radiation efficiency and its frequency dependence. In discussing the tonal characteristics of instruments such as sackbuts and modern trombones, both bell size and absolute bore size need to be taken into consideration as factors affecting spectral enrichment in the performance situation, alongside the shape of the bore profile as represented by the brassiness potential *B*. Merely reducing the bell size, as in the former practice of cutting the bell of a trombone or "sackbut" models with larger than authentic bore size, will not provide instruments that allow a player to achieve the sound of an original or close copy of a sackbut.

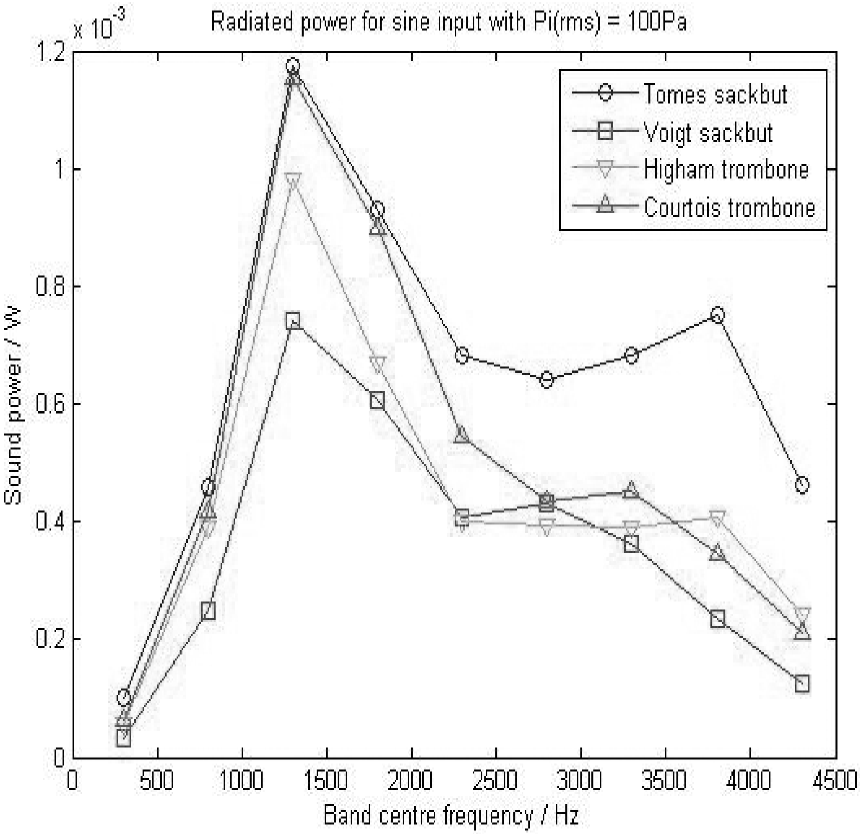

Figure 13: Radiated power for Tomes (1998) and Voigt (ca. 1995) sackbuts and Courtois (1865) and Higham (ca. 1887) narrow-bore trombones plotted against frequency.

The authors thank Robert Pyle (Boston) and Joël Gilbert (Laboratoire d'Acoustique de l'Université du Maine, CNRS, Le Mans) who are collaborating in brassiness research, Shona Logie (University of Edinburgh) for help with measurements, William Phillips for the loan of the Voigt sackbut, William Giles for the loan of a van der Heide sackbut, and the professional staff of numerous museums worldwide, and individual collectors and musicians, for access to historic instruments.

Murray Campbell studied physics at the University of Edinburgh, and was appointed to the teaching staff there in 1971. In 1985 he founded the Musical Acoustics Research Group at the University of Edinburgh, and in 2000 was appointed Professor of Musical Acoustics. He is now Professor Emeritus and Senior Professorial Fellow at Edinburgh, where he continues to carry out research on the acoustics of lip-excited wind instruments. He is a Fellow of the Royal Society of Edinburgh, the Acoustical Society of America, and the Institute of Physics. He has served on the Editorial Boards of Acta Acustica united with Acustica *and the* Journal of the Acoustical Society of America, *and has co-authored two textbooks and numerous articles on the acoustics of musical instruments. He was awarded the Médaille Étrangère by the Societé Francaise d'Acoustique in 2000 and the Rossing Prize for Acoustics Education by the Acoustical Society of American in 2008.*

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Arnold Myers completed his doctorate at the University of Edinburgh with research into acoustically based techniques for taxonomic classification of brass instruments. He has contributed articles to the New Grove Dictionary of Musical Instruments *and chapters for the books* The Cambridge Companion to Brass Instruments *and* The British Brass Band: a Musical and Social History, *and was co-author of* Musical Instruments: History, Technology and Performance of Instruments of Western Music. *He is Professor Emeritus in the University of Edinburgh and is Senior Research Fellow at the Royal Conservatoire of Scotland. He serves as Vice-President of the Council of Association RIdIM (Répertoire International d'Iconographie Musicale) and as Vice-President of the Galpin Society. He was the recipient of the 2007 Curt Sachs Award and the 2014 Frances Densmore Prize of the American Musical Instrument Society, and the 2014 Christopher Monk Award of the Historic Brass Society.*

Notes

[1] This article includes material presented in the paper "Is the Sackbut Merely a Narrow-bore Trombone?" presented at the conference of the Historic Brass Society, New York, 12 July 2012, by Murray Campbell and Arnold Myers (University of Edinburgh).
[2] James Beauchamp, "Synthesis by spectral amplitude and 'Brightness' matching of analyzed musical instrument tones," *Journal of the Audio Engineering Society* 30 (June 1982): 396–406.
[3] Arnold Myers, Robert W. Pyle Jr., Joël Gilbert, D. Murray Campbell, Shona Logie, and John P. Chick, "Effects of nonlinear sound propagation on the characteristic timbres of brass instruments," *Journal of the Acoustical Society of America* 131, Issue 1 (2012): 678–88.
[4] Beauchamp, "Synthesis by spectral amplitude."

Appendix

Worked example of the calculation of the brassiness potential parameter *B*

The bore profile of the tenor trombone in nine-foot B♭ by Joseph Huschauer, Vienna, 1794 (Edinburgh University Collection of Historic Musical Instruments 3205) with the slide in closed position was measured in 36 sections (37 measurement points). In the following table the first column is the distance from the mouthpiece receiver (mm), the second column is the bore diameter (mm), and the third column is the contribution $2ln / (D_n+D_{n+1})$ of the preceding section.

0	11.9	
22.5	11.0	1.97
684	11.0	60.14
684	11.6	0.00
900	11.6	18.62
900	11.0	0.00
1534	11.0	57.64
1626	11.2	8.29
1626	12.8	0.00
1680	11.3	4.50
1871	11.0	17.13
1908	11.4	3.30
2077	11.6	14.70
2109	12.2	2.69
2204	13.5	7.41
2239	13.8	2.56
2365	16.7	8.34
2403	18.2	2.18
2431	20.1	1.47
2457	22.2	1.23
2484	24.5	1.16
2512	27.1	1.09
2536	30.0	0.84
2563	33.1	0.86
2587	36.6	0.69
2607	40.5	0.52
2624	44.7	0.40
2637	49.4	0.28

2649.5	54.6	0.24
2660	60.4	0.18
2670	66.7	0.16
2679	73.7	0.13
2686	81.5	0.09
2694	90.2	0.09
2701.5	99.5	0.08
2708.5	110.0	0.07
2711	115.0	0.02

The biggest contributions (60.14 and 57.64) are for the long cylindrical inner slides of the trombone.

The instrument plays in B♭ at a^1 = 440Hz, for which the equivalent cone length (given equal temperament and a speed of sound in air of 346ms^{-1}) is 2969mm. Using the minimum bore diameter D_0 of 11.0mm, performing the sum

$$B \approx \sum_{1}^{N} \frac{l_n}{L_{ecl}} \left(\frac{2D_0}{D_n + D_{n+1}} \right)$$

where N is 36 gives a value of B = 0.81. The calculations are easily performed using a spreadsheet.