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P.T.O.
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THE ASSESSMENT OF BRASS INSTRUMENT QUALITY

by


ABSTRACT

The work described in this thesis comprises three parts: devising an original method capable of making absolute measurements of acoustic impedance (both modulus and phase) for brass instruments; developing formal subjective assessment procedures enabling the subjective dimensions of trombone quality to be quantified; discovering the extent to which the acoustic impedance of an instrument may be used to predict its subjective quality.

The impedance measurement systems of various authors are reviewed, and the limitations imposed by such systems discussed. The computer controlled system devised by the author, which uses a hot-wire anemometer to measure particle velocity, is then described in detail including transducer calibration and measurement accuracy.

The factors governing the subjective quality of trombones, based on interviews with players, are introduced, and the techniques used to quantify subjective characteristics (Semantic Differential Scaling and Multidimensional Scaling) are presented together with a discussion of the advantages and disadvantages of each method. The results of a series of subjective experiments are given.

Several hypotheses relating the subjective quality of an instrument to its impedance are discussed. For the trombone, the degree of harmonicity of the impedance maxima and the envelope of the impedance curve are shown to have an important effect on players' assessment.
I would like to express my gratitude to Dr. J.M. Bowsher for his advice and encouragement throughout this study. I would also like to acknowledge the assistance of the following people: Mr. K.R. Knight and Ms. C.J. Stannard for their programming support; Mr. F. Bristowe and his colleagues in the Mechanical Workshop for the construction of the wind tunnel and associated apparatus; Mr. E.A. Worpe for the design and construction of the Automatic Level Control and the Binary-to-BCD converter; Dr. L. Bradbury for initiating me in the black art of hot-wire anemometry; Dr. R.M. Edwards for his assistance in the analysis of the experimental data; all those who took part in the subjective experiments; Ms. C.J. Stannard for typing this thesis.
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<tr>
<td>2-21</td>
<td>8</td>
<td>$W^P = A + BV^2$</td>
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<td>3, 6, 7, 9</td>
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</tr>
</tbody>
</table>

**Figure 66** The numbers giving the order on the SD scales relate to the alphabetical order of the instruments used e.g. B+H prototype = 1, Yamaha = 5.
## CONTENTS

<table>
<thead>
<tr>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
</tr>
<tr>
<td>1-1</td>
</tr>
<tr>
<td>1-1</td>
</tr>
<tr>
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<td>1-3</td>
</tr>
<tr>
<td>1-4</td>
</tr>
<tr>
<td>1-5</td>
</tr>
</tbody>
</table>

## 1 INTRODUCTION

1.1 Statement of the problem

1.2 The Trombone

1.3 Trombone Quality

1.4 Design procedure for a new instrument

1.5 Towards an improved design procedure

1.6 Outline of proposed research

## 2 THE MEASUREMENT OF ACOUSTIC IMPEDANCE

2.1 Definition of Acoustic Impedance

2.2 Resonance measurement

2.3 The plane of measurement

2.4 Resonance frequencies, Impedance maxima frequencies and playing frequencies

2.5 Existing Impedance measurement systems

2.5.1 Variation of Backus

2.5.2 Variation of Coltman

2.5.3 Variation of Merhaut

2.5.4 Variation of Fransson

2.5.5 Variation of Wogram

2.6 Limitations of these methods

2.7 The impedance tube method

2.8 The measurement of velocity

2.8.1 The hot-wire anemometer

2.9 The measurement of pressure in confined spaces
2.10 Early experiments conducted by the author
2.10.1 The Mark 1 system (Variation of Pratt)
2.10.2 The Mark 2 system
2.10.3 A new approach
2.11 The Mark 3 (final) system
2.12 Calibration Procedures
2.12.1 Calibration of the probe microphone
2.12.2 Calibration of the Hot-Wire Anemometer
2.13 Effect of non-uniform velocity profile
2.14 Measurement accuracy
2.14.1 Calibration errors
2.14.2 System errors
2.15 Comparison with theory
2.16 Summary

3 THE SUBJECTIVE ASSESSMENT OF TROMBONE QUALITY
3.1 Introduction
3.2 Test environment
3.3 Quantifying subjective characteristics
3.4 Multidimensional Scaling (MDS)
3.4.1 MDS - data collection
3.4.2 MDS - data reduction
3.5 Semantic Differential Scaling (SDS)
3.5.1 SDS - data collection
3.5.2 SDS - data reduction (Factor Analysis)
3.6 Comparison of MDS and SDS
3.7 Requirements for a subjective rating procedure 3-6
3.8 Review of timbre assessment 3-6
  3.8.1 Review of papers using MDS 3-7
  3.8.2 Summary of MDS experiments 3-10
3.9 Review of papers using SDS 3-10
3.10 Factors governing trombone quality 3-13
3.11 Experimental procedure 3-15
  3.11.1 Experiment 1 3-16
  3.11.2 Experiment 2 3-19
  3.11.3 Experiment 3 3-22
  3.11.4 Experiment 4 3-25
3.12 Summary of experimental results 3-27
3.13 Selection of subjects 3-28
3.14 Summary 3-29

4 THE OBJECTIVE ASSESSMENT OF TROMBONE QUALITY 4-1
4.1 Introduction 4-1
4.2 Summary of the sound production mechanism of brass instruments 4-1
4.3 The "Sum Function" 4-2
4.4 Hypotheses (a) and (b) 4-4
4.5 Two case histories 4-5
  4.5.1 A comparative study of two large bore tenor trombones 4-5
  4.5.2 Improving the timbre and responsiveness of a bass trombone 4-7
4.6 A comparative study of seven medium bore trombones 4-10

4.6.1 Hypothesis (c) 4-10
4.6.2 Selection of the instruments 4-10
4.6.3 Objective measurement 4-11
4.6.4 Subjective assessment 4-11
4.6.5 Comparison with the objective hypotheses (a) to (c) 4-12
  4.6.5.1 Hypothesis (a) 4-13
  4.6.5.2 Hypothesis (b) 4-13
  4.6.5.3 Hypothesis (c) 4-14
4.6.6 Comparison with straight tube 4-14
4.7 Search for alternative hypotheses 4-14
4.8 Further evidence supporting the subjective assessment results 4-16
4.9 An examination of the effect of certain parameters on quality 4-17
  4.9.1 Internal bore cleanliness 4-17
  4.9.2 The mouthpiece 4-18
    4.9.2.1 Theoretical inclusion of the mouthpiece cup volume 4-19
    4.9.2.2 Throat diameter 4-19
    4.9.2.3 Subjective experiment 4-20
  4.9.3 The mouthpipe 4-21
  4.9.4 Gross perturbation to the tuning slide 4-21
  4.9.5 Material finish 4-22
  4.9.6 D.C. airflow 4-22
4.9.7 Slide position 4-23
4.10 Summary 4-24

5 DISCUSSION AND CONCLUSIONS 5-1
5.1 Improving the impedance measurement system 5-1
5.2 Plane of measurement 5-2
5.3 The time domain behaviour of a trombone 5-3
5.4 Subjective assessment 5-4
5.5 Conclusion 5-5

APPENDIX A DISK FILE TITLES A-1
APPENDIX B MUSICAL IMAGERY B-1
APPENDIX C PROGRAM LISTINGS C-1

FIGURES F-1
REFERENCES R-1
1.1 Statement of the problem

A central aim of musical acousticians is to improve the quality of musical instruments; however this can only be done if the factors governing instrument quality are understood. In addition quantitative assessment techniques are required, for without them it is impossible to ascertain whether a genuine improvement in quality has been made. It is the opinion of the author that the almost total lack of suitable assessment techniques is the most important factor hindering the progress of instrument design and development. For this reason the work presented here was directed towards the identification and quantification of the factors governing brass instrument quality. The trombone was selected for investigation primarily at the request of Boosey and Hawkes (the industrial sponsor), in order to complement the work of another CASE student who was studying the intonation of the trumpet [1].

1.2 The Trombone

A detailed account of the history and construction of the trombone is given by Bate [2], hence only a brief description will be given here. The tenor trombone in Bb is the most widely used member of the trombone family, and was therefore chosen for this study. A typical instrument is about 2.7m in length and is made in three bore sizes; small, medium and large, where the bore of the instrument is conventionally taken to be the inside diameter of the inner slide section. These bore sizes correspond approximately to 12.3mm, 12.7mm
and 13.9mm respectively, but it should be noted that the exact values used by instrument makers are governed by changes in fashion and national preferences. The instrument is coupled to the players lips via a detachable mouthpiece. The construction of the instrument and mouthpiece are shown in Figure 1.

1.3 Trombone Quality

The quality of an instrument may be separated into two categories, subjective and objective. Subjective quality is a player's (or listener's) personal assessment of an instrument, and includes such factors as timbre, responsiveness and intonation. These factors may be rated quantitatively using Multidimensional Scaling (MDS) and Semantic Differential Scaling (SDS). The precise nature of these factors and details of how they may be quantified are given in Chapter 3. Objective quality is a general term used to denote the physical characteristics that are thought to govern the subjective quality of an instrument. From this definition it can be seen that the concept of objective quality cannot exist in isolation. Only when physical correlates to the many dimensions of subjective quality have been established will it be possible to describe an instrument as having a particular objective quality. The objective quality depends ultimately on two physical characteristics; the geometry of the instrument, and its material composition. It is extremely difficult however to relate these physical characteristics directly to the dimensions of subjective quality. For this reason it is appropriate to investigate additional physical characteristics which are capable of being related to both subjective and objective quality, thereby establishing links
between them. It will be shown how the existence of such characteristics, together with formal subjective assessment procedures, will greatly assist the design and development of a new instrument. First the design procedure used by Boosey and Hawkes is described.

1.4 Design procedure for a new instrument

During the last four years, Boosey and Hawkes have been developing a medium bore Professional Model B♭ tenor trombone. They commenced this programme by constructing several prototypes, some of which were based on existing components from their student models, and the remainder of which were copies of designs from their more successful competitors. A professional player was then invited to the factory to test various prototypes. Instruments produced by other manufacturers may also be included in this test as a basis for comparison. It is the custom to design a new model in conjunction with a particular player, who subsequently takes part in the promotion of the instrument. After playing the instrument the player then gives his opinion of it by using a variety of verbal descriptors (eg. stuffy, bright, responsive, thin, etc.). It is the task of the instrument's designer (who in this case also built the prototypes) to relate these adjectives describing the instrument to its geometry and construction, and then attempt to correct any faults and generally improve the subjective quality. During my four years of working in co-operation with Boosey and Hawkes, and after many visits to their factory, it has become evident that they do not understand the relationship between the subjective dimensions of the instrument and its construction. Since they are therefore unsure what modifications are required
to improve the instrument, this stage of the design can become very lengthy. When the designer has carried out certain modifications and made what he considers a significant improvement in quality to one or more of the prototypes, the player is invited back to reappraise them. This process of testing and readjustment is continued until the player is satisfied with the instrument. This part of the design procedure may be summarised by the flowchart shown in Figure 2. As a final check it is customary for Boosey and Hawkes to make a small pre-production batch of about six instruments for evaluation by a larger sample of players. From their comments, further minor adjustments, usually of a non-acoustical nature (e.g., position of stays, balance, and finish) may be made before the instrument enters full-scale production.

1.5 Towards an improved design procedure

There are two ways in which the design procedure could be improved:

(a) by developing a quantitative, subjective assessment technique for trombones;

(b) by introducing an objective measurement which could relate the geometry and construction of an instrument to its subjective dimensions.

The acoustic impedance of an instrument is the best choice for the objective measurement. There are two reasons for this; firstly, the concept of impedance is fundamental to an explanation of the sound production mechanism of brass instruments, and a full discussion of this mechanism may be found in Chapter 4. Secondly, it can be related
to the instrument geometry, although papers examining this topic have
considered almost exclusively the frequency location of the impedance
maxima, and paid far less attention to their amplitudes and Q factors
[3,4].

It is interesting to note that very little work has been
published relating the impedance of brass instruments to their subjec­tive quality. As a result authors presenting impedance data experience considerable difficulty when interpreting their results. This is
perhaps best illustrated by a quotation from a recent (1976) paper by
Backus [5], who states; "Input impedance curves have been run on a
number of trumpets. They show variations in the matching of resonances
with harmonic frequencies, and in values of input impedances; however
the formidable job of correlating these variations with the quality of
the trumpet as judged by the player has not yet been undertaken".
These remarks are perhaps even more applicable to the trombone, since
Backus measured the input impedance of only a single Bb tenor instrument.
The work described in this thesis is directed towards the "formidable
job" of investigating quantitatively and systematically the relation­ship between the impedance of an instrument and its subjective quality.

1.6 Outline of proposed research

The investigation comprises three basic parts:

(a) to devise an original, improved impedance measurement
system capable of providing absolute values for acoustic impedance
(both modulus and phase);

(b) to establish the subjective dimensions of trombone
quality, and develop formal subjective assessment procedures which
will enable players to quantify these dimensions;

(c) to discover the extent to which the acoustic impedance of an instrument may be used to predict its subjective quality.

This last problem is tackled by assembling a range of trombones of differing quality, and searching for relationships between their impedance curves and the results of subjective assessment experiments performed on a number of players. If the impedance of the instrument can be related independently to its subjective dimensions (by conducting SDS or MDS experiments), and also to its geometry and construction (using perturbation theory), then the link between subjective and objective quality will have been established, allowing the design and development of new instruments to proceed in a more rational manner (see Figure 3).
CHAPTER 2 THE MEASUREMENT OF ACOUSTIC IMPEDANCE

2.1 Definition of Acoustic Impedance

The term "impedance" was introduced by Heaviside [6] towards the end of the last century in connection with the analysis of electrical circuits. The concept was extended in 1919 by A.G. Webster [7] who introduced acoustic impedance in a study of the theory of horns and the phonograph. It is necessary to define what is meant by the term acoustic impedance for the purposes of this study, since modern practice differs from Webster's original definition. The Acoustic Impedance \( Z \), at a given section, is the complex quotient of the Acoustic Pressure \( P \) divided by the Volume Velocity \( U \):

\[
Z = \frac{P}{U} \quad \text{Kg.m}^{-4}.\text{s}^{-1} \quad \text{or Acoustic Ohms (S.I.)}
\]

Since \( Z \) is complex, this equation may be re-written as:

\[
Z = |Z| e^{j\phi}
\]

or \( Z = R + jX \)

This corresponds, for example, with the usage of Kinsler and Frey [8].

Normally it is the quantity \(|Z|\) to which musical acousticians refer as acoustic or "input" impedance. The measurement of \( \phi \), the phase angle, is usually neglected.

2.2 Resonance Measurements

It is important to make clear the difference between Resonance and Impedance measurement systems. Resonance measurements are
conducted by exciting an instrument sinusoidally via a loudspeaker placed at one end of the instrument, and monitoring the resultant pressure signal at the other end. Impedance measurements require both the excitation and pressure monitoring functions to be performed at the mouthpiece end of the instrument, and further have the advantage of being independent of the room acoustics since all measurements are taken inside the instrument.

The resonance systems described by J.C. Webster [9], Igarashi and Koyasu [10] and Carmichael [11] apply the excitation to the mouthpiece end of the instrument, and a microphone situated outside the bell of the instrument measures the response signal. Alternatively Backus [12] describes a system whereby the excitation is applied externally to the bell, and the response microphone is placed inside the mouthpiece. Resonance curves obtained using this method were found to vary with the exact location of the loudspeaker. The degree of variation was particularly noticeable when examining the resonances of brass instruments. For this reason Backus [13] abandoned the Resonance method, and switched in 1971 to an impedance measuring system similar to the one devised by Kent. Backus was therefore in the unique position of being able to measure a set of instruments using both systems. After conducting a comparative study of the trumpet he concluded; "... the (Resonance) method gave curves having higher (frequency) resonances that were subsequently determined to be spurious. Furthermore the external excitation gives only the resonance frequencies and does not give quantitative results of its input impedance".

The author has experimented with a resonance system similar to
that of J.C. Webster, where the instrument is driven at the mouthpiece end, and confirmed that the resonance frequencies vary with position of the response microphone. It should be noted that the author's experiments, and also those of Backus, were not carried out in an anechoic chamber. The experiments performed by Carmichael, and Igarashi and Koyasu, did use anechoic conditions and no variations in the results with microphone position were reported.

Thus it may be seen that without an anechoic chamber, considerable difficulty will be experienced when using the Resonance method to provide accurate, repeatable data. Since the author did not have access to such a facility this method was not considered further.

2.3 The plane of measurement

Before describing impedance measuring systems in detail, it is important to define a plane of measurement. The implicit aim of many such systems devised hitherto has been to measure the impedance "seen" by the player. This aim has not been realised in practice for two reasons:

(a) the turbulent airflow provided by the player is likely to have a significant effect on the measurement of impedance [14];

(b) the time-varying impedance function of the lips represents, in effect, a time varying boundary condition. The position of the lips in the mouthpiece cup varies for different playing frequencies, thus altering the effective mouthpiece cup volume.

It is clearly unrealistic therefore to expect to be able to measure the impedance seen by the player, when such experiments are performed with the instrument excited artificially.
The most popular plane of measurement is (nominally) that of the mouthpiece rim, and the impedance measured is that of the instrument and mouthpiece combined. This plane is used by Kent [15], Coltman [15], Merhaut [15] and Wogram [16]. Consequently, the volume of air displaced by the lips is neglected, and Backus [17] partially rectifies this problem by inserting the recording microphone part-way into the mouthpiece cup, although the volume thus displaced does not change with frequency, as in the case of the lips. Diagrams detailing the methods of Kent, Coltman and Merhaut are given in reference [15], and a closer examination of these systems, together with that of Wogram [16], reveals that only Coltman does indeed measure impedance precisely in the plane of the mouthpiece rim, the remainder place the response microphone upstream of the mouthpiece rim, thus effectively increasing the mouthpiece cup volume. This increase is small in the case of Wogram, but in the case of Merhaut, it is considerably larger than the original cup volume! Thus the plane in which measurements are taken is often inadequately defined. Carmichael and J.C.Webster used the mouthpiece throat (the narrowest section of the mouthpiece) as their measurement plane, giving as their reason that the resulting resonance frequencies correlate well with the frequencies observed when the instrument is played normally.

In this study the mouthpiece throat was chosen as the primary reference plane for the following reasons:

(a) it is a well defined position for the instrument;
(b) it enables data to be collected when the instrument is played normally.

Although this decision eliminates the effect of the mouthpiece
cup volume, it will be shown in Chapter 4 how the effect of this volume may be included theoretically.

2.4 Resonance frequencies, Impedance maxima frequencies and Playing frequencies

For clarification the terms are defined below:

(a) Resonance frequencies: the frequencies at which a maximum amplitude of the pressure response signal is obtained, when using a Resonance measurement system;

(b) Impedance maxima frequencies: similar to (a), but using an Impedance measurement system;

(c) Playing frequencies: the frequencies obtained when the instrument is played normally. These frequencies will vary with different players, and will also vary on different occasions for a given player.

In general none of the above categories of frequency will bear a truly harmonic relationship.

2.5 Existing impedance measurement systems

The measurement of acoustic impedance of brass instruments has received attention from several workers, all employing a basically similar technique. A typical system, devised by Kent and his co-workers at Conn. Co., the musical instrument manufacturers, and later adopted by Benade, is shown in Figure 4 [15]. The output of a variable frequency sine wave oscillator is fed via a controlled attenuator and power amplifier to a horn loudspeaker unit. This unit is coupled through a glass-fibre filled tube to a cylindrical
capillary and finally to the mouthpiece of the instrument under test. A control microphone placed at the loudspeaker end of the capillary is incorporated in a feedback loop which maintains a constant pressure amplitude at that point. Since the impedance of the capillary is high this in effect produces a constant volume velocity source at the mouthpiece. A chart recorder coupled to a response microphone placed upstream of the mouthpiece rim records the pressure while the oscillator is swept over the frequency range of interest and its output will therefore be an uncalibrated signal directly proportional to |Z|. A number of workers have used a similar approach, the main difference is usually the way in which the constant volume velocity source is derived. These variations will be examined in turn.

2.5.1 Variations of Backus

Backus has adopted a system identical to that of Kent, except that he uses an annular capillary to connect the loudspeaker to the instrument [17,18]. The diameter of the capillary is 1.78mm, its thickness is 0.1mm and the length is 63mm. The characteristics of this capillary do not change with frequency as much as the characteristics of a cylindrical capillary. The resistance is quoted as 240 Ω with a variation of less than 6% over the frequency range 100-2300 Hz. Since the resistance is known, absolute values for |Z| may be obtained if the control and response microphones are calibrated.

2.5.2 Variations of Coltman

Coltman [15] derives a volume velocity signal by mounting a secondary coil (suspended between magnets) on the piston connected to
the loudspeaker driver coil. This secondary coil thus provides a signal proportional to the motion of the loudspeaker, and is used as the error signal in the feed-back loop.

2.5.3 Variation of Merhaut

Merhaut [15] places a thin mylar diaphragm, driven by a loudspeaker, upstream of the mouthpiece cup. The diaphragm is coated with aluminium and forms one electrode of a condenser microphone, the other electrode being held rigid. The motion of the diaphragm produces a signal proportional to the diaphragm displacement, which may then be differentiated to create a signal proportional to the diaphragm velocity. This forms the error signal in the feed-back circuit providing a constant volume velocity source.

2.5.4 Variation of Fransson

The STL Ionophone [19] invented by Fransson, employs a gaseous discharge as an acoustic source. It comprises a plexiglass insulator with two brass pins to which the electrodes are attached, at a separation of 1.5mm. The device is activated by a high tension supply (typically 3 KV.) modulated to provide an a.c. signal. This device has an impedance of approximately 1 MΩ, and behaves as a point source providing a constant volume velocity signal. Fransson claims that this device eliminates the need for a feed-back loop, but this seems unlikely to be the case for brass instruments whose impedance maxima are typically 30 MΩ.

The ionophone has been used to measure the acoustic impedance of flutes, but the data presented are uncalibrated [20]. Dekan [21]
has used the ionophone to measure the resonance frequencies of brass instruments.

2.5.5 Variation of Wogram

Wogram [16] has shown how the method of Kent may be used to give absolute data for acoustic impedance. First the impedance (both modulus and phase) of a 55m cylindrical tube was measured. The modulus was derived in the normal way, and the phase angle between the control and response microphones was measured using a phase meter coupled to a chart recorder. Assuming the tube to be infinitely long, a value for its characteristic impedance may be obtained from the expression \( \rho c/S \). The impedance is further assumed to be real, thus the phase angle between the control and response microphone must be zero. If an instrument is now measured, the response signal may be calibrated using the results from the experiment on the long tube to give absolute values for \( |Z| \). Similarly a corrected value for the phase angle may be obtained by subtracting the phase angle measurement of the long tube experiment from those of the instrument. This method is not entirely satisfactory as it does not permit an independent, experimental check on the assumptions made concerning the long tube.

2.6 Limitations of these methods

All the systems just described suffer from a number of limitations. Firstly, the technique discourages absolute calibration, since the volume velocity signal is derived indirectly. Although Kent had started to develop the basic method in 1945, it was not until...
1974 that calibrated data from Backus [17] first appeared. Secondly, the plane of measurement is poorly defined, making it impossible to compare the results of different experimenters. Thirdly, the effect of airflow through the instrument is totally neglected, although this has been shown to be significant [14]. Fourthly, extracting phase information cannot be accomplished directly. Finally it is not possible to collect pressure and velocity data when the instrument is blown by a player. All these limitations can be overcome if the velocity is measured directly.

2.7 The impedance tube method

Before leaving the topic of earlier impedance measurements it should be noted that Backus and Hundley [22] have used the impedance tube method to measure the real and imaginary parts of the impedance of a trumpet, although this method is generally employed for determining the acoustic impedance of absorbing materials. The method yields calibrated data for the acoustic impedance, but it is very laborious to perform, especially if a resolution of less than 1 Hz is required. This method is therefore not suitable where comparisons between many instruments are to be made.

2.8 The measurement of velocity

From the study of impedance measurement systems given above, the desirability of measuring velocity directly is apparent. Three anemometry systems were considered;

(a) Ionisation anemometry

(b) Laser-doppler anemometry
(c) Hot-wire anemometry

An ionisation anemometer comprises an α particle emitter and detector. These are placed on opposite sides of a duct and the number of α particles detected is a function of the flow velocity. The laser-doppler system also has an emitter and detector, but in this case a velocity signal is derived from the doppler shift of light from a laser source as it is scattered from minute dust particles in the medium. Neither of these systems was entirely appropriate for this study. The ionisation system was not available commercially, and involved the use of radio-active materials. The laser-doppler was too expensive and would require the construction of transparent mouth-pieces. The hot-wire anemometer is a comparatively cheap and readily available device. Its small physical size and good sensitivity make it ideal for the measurement of velocity inside brass instruments.

2.8.1 The hot-wire anemometer

The system purchased for this study is a DISA Constant Temperature Anemometer (CTA), type 55D05. The transducer is a 5mm diameter tungsten wire 1.25mm long, suspended between two prongs attached to the body of the probe. The probe has a resistance of about 3.5 Ω at 18°C, rising to about 7 Ω at 250°C. The probe is placed in one leg of a self-balancing Wheatstone bridge. Thus by altering the resistance of the appropriate leg, the probe may be set at an elevated temperature. If the probe is inserted in a moving stream of fluid it is cooled, and a feedback current is created which restores it to the equilibrium temperature. This feedback current is related to the fluid flow by the expression:
\[ I^2 = C + mw^p \]

where \( I \) is the feedback current.

\( w \) is the fluid velocity.

\( C, m, p \) are constants

Calibration and operation procedures are described later in this chapter.

2.9 The measurement of pressure in confined spaces

It is necessary to measure acoustic pressure, in addition to particle velocity, in order to calculate acoustic impedance. Since the mouthpiece throat has been selected as the primary reference plane, very small transducers are clearly required. The hot-wire probes are made small so that they have small thermal inertia, but a conventional microphone is too large to be used directly. For measuring pressure in confined spaces, the Probe Microphone was introduced. It comprises a conventional condenser microphone coupled to a cylindrical "probe tube". Bruel and Kjaer manufacture a probe kit for their \( \frac{1}{2} \) inch microphones and include a range of probe diameters from 1 mm to 4 mm. The addition of this probe tubing introduces resonance frequencies related to its length, but the effect of these resonances may be diminished by inserting loosely packed wire-wool into the probe. The device requires frequent calibration over the entire frequency range of interest since the wire-wool is easily dislodged. More seriously, the calibration varies with SPL, due to boundary layer losses.

Recently, Bruel and Kjaer have introduced a horn-coupled probe microphone (type 4170). The probe section is made up of
concentric cylindrical sections which reduce the ripple in the frequency response to less than 4dB. More importantly, the characteristics of this microphone do not vary with the SPL. The final section is 1.25mm in diameter and has a probe orifice impedance greater than 400 MΩ, and the distortion is less than 1% below 170 dB. One of the first of these instruments to arrive in England was purchased, and has been found to be ideal for this application.

2.10 Early experiments conducted by the author

2.10.1 Mark 1 System (variation of Pratt)

The first attempt at measuring acoustic impedance conducted by the author was based on the method of Kent. In this system the velocity signal from the hot-wire anemometer was used in the feedback circuit, thus producing a constant volume velocity drive. A mouthpiece was modified to accept the probe microphone and the hot-wire probe (see Figures 5 & 6). The instrument under test was driven by a 3 watt mechanical vibrator attached to a rubber diaphragm stretched over the mouthpiece rim, after the method of Carmichael (see Figure 7).

The absence of a steady airflow through the instrument resulted in the rectification of the hot-wire signal, since the device can only register the net cooling. By keeping this rectified signal constant while sweeping over the frequency range of interest, the output of the probe microphone becomes proportional to |Z|. Coupled analogue devices were used to conduct this experiment (Bruel and Kjaer Beat Frequency oscillator, type 1022, and a Level Recorder, type 2305), and a specimen trace is shown in Figure 8. The driving system was later
modified to allow a steady air flow to be introduced via a 4mm diameter tube inserted in a 10mm thick Paxolin washer which was placed between the mouthpiece rim and the rubber diaphragm. The proximity of this air inlet resulted in a very turbulent velocity signal, and this excitation method was consequently abandoned.

2.10.2 The Mark 2 System

Before discussing the Mark 2 experimental system, the computing equipment will be described. It comprises a Data General Nova 2 minicomputer, equipped with 2.5 M.byte moving head disk, a 150 K.byte floppy disk, a visual display unit (VDU), a lineprinter, and two channel analogue to digital (A/D) and digital to analogue (D/A) converters. The A/D converter has a resolution of 14 bits, and when used in conjunction with a multiplexer and parallel sample and hold circuits can digitise two channels of analogue data at a rate of 25000 samples/s/channel. The two D/A converters have the same conversion rate but with 15 bit resolution.

The Mark 2 experimental system was controlled by the computer, which also collected and analysed the data. This arrangement is very close to the final (Mark 3) version, which is discussed in Section 2.12, and so only the block diagram is given (see Figure 9). From this diagram it may be seen that the signal from the pressure and velocity transducers are both fed to R.M.S. meters, and thus the computer samples a d.c. voltage proportional to the R.M.S. value of the a.c. signal. Since an apparatus to calibrate the hot-wire anemometer had not yet been devised, the method did not provide
absolute values for \(|Z|\), nor was it capable of providing any phase information.

It will be shown in the following Section how a more flexible approach to the analysis problem is possible if the pressure and velocity waveforms are sampled directly. Accordingly, for the Mark 3 version, the R.M.S. meters were removed.

2.10.3 A new approach

A brass instrument may be characterised by the 2-port network shown in Figure 10. The system has a transfer function \((P_0/P_1)\) and input impedance \((P_1/U_1)\). Note that a brass instrument only becomes non-linear when coupled to a player's lips. If the pressure and velocity waveforms can be sampled directly and simultaneously, then the input impedance may be measured by applying one of several excitation functions \(U_1(f)\), and measuring \(P_1(f)\). Four possible excitation functions are:

(a) a step function;
(b) an impulse function;
(c) random noise;
(d) sine wave.

Since the impedance measurement systems devised hitherto are unable to measure the velocity directly, they may use only the sine wave excitation method. Absolute values for \(|Z|\) may only be obtained if the resistance of the capillary is known, or the results for an instrument compared with those for a long, straight, cylindrical tube.

An original apparatus using sine wave excitation has been developed by the author, but it may also be extended to use any of
the above excitation functions.

2.11 The Mark 3 (final) system

The final experimental procedures used to determine the acoustic impedance of a trombone will now be described. A diagram of the system is shown in Figure 9, and a photograph of the complete apparatus, including the computer is shown in Figure 11. A flowchart of the program (FRUN) used to run the experiment is shown in Figure 12. The mechanical vibrator has now been replaced by a 200 watt loudspeaker which is housed in a 1m cube constructed from 2 inch chipboard. A brass funnel connects the loudspeaker to a 0.65m tube, also constructed from brass. The air inlet for the d.c. air flow, required to avoid rectification of the hot-wire signal, is situated at the loudspeaker end of this tube, the other end of which is carefully machined to fit the mouthpiece of the instrument under test. The program initially requests the calibration constants for the hot-wire probe. The calibration of both the hot-wire anemometer and probe microphone is described in the next Section. The cross-sectional area of the mouthpiece throat is also entered (typical diameters fall in the range 5.80 to 7.35mm). The computer then sets the initial frequency (10 Hz.) on a programmable frequency oscillator (P.F.O). The oscillator used is an Adret Codasyn 201, whose frequency may be selected by a Binary Coded Decimal (BCD) input. The sine wave output from the oscillator is amplified (Quad 50) and then fed to the loudspeaker which in turn drives the instrument under test. Although this system does not require a constant volume velocity source since the velocity signal is measured, in practice some degree of control is
used to ensure that the signal from the hot-wire anemometer is adequate at all times. An automatic level control (ALC), shown in Figure 13, provides a smooth error signal which is fed to the amplitude modulation (a.m) input of the P.F.O. The R.M.S. value of the velocity waveform is thus kept to within 15% of any set value. The A/D converters are then instructed to acquire simultaneously 1 cycle of both the pressure and the velocity waveforms. Using the calibration constants for the hot-wire probe, the particle velocity may be calculated. This is transformed into the volume velocity by multiplying the particle velocity by the "effective" cross-sectional area of the mouthpiece throat. The area is effectively reduced owing to boundary layer losses. Since a brass instrument puts an unusual load on a conventional loudspeaker, a certain amount of distortion appears in both the pressure and the velocity waveforms near the frequencies of maximum impedance. This is filtered out digitally by expanding the sampled waveform as a Fourier Series and extracting only the fundamental. In addition a phase value for the fundamental component may also be extracted. The probe microphone is coupled to a power supply (Bruel and Kjaer type 2801) and an impulse precision sound level meter (Bruel and Kjaer type 2204) provides additional amplification. This arrangement has a combined sensitivity of approximately 120 Pa/volt and the pressure signal may be converted to Pascals, and then to dB. The pressure is then corrected using the data supplied by the National Gas Turbine Establishment, and the R.M.S. value calculated. By subtracting the velocity phase value from the pressure phase value (both values having been obtained from the Fourier Series analysis) the phase of velocity with respect to pressure may be obtained. This value is corrected by
taking the phase response of the probe microphone into account. The fully calibrated values for the pressure, volume velocity, $|Z|$ and $\phi$ are displayed on the VDU and held in a temporary store. The process of sampling the waveforms and computing these values is repeated eleven times, and the twelve results are averaged to improve the accuracy of the final result, which is stored in a disk file. The frequency is incremented by 1 Hz. and the process is repeated until the upper frequency limit of 768 Hz. is reached. From the results obtained from the Mark 1 system (see Figure 8), it may be seen that the cut-off frequency of the horn is approximately 800 Hz. The upper limit of 768 Hz. was chosen for practical convenience since the data is stored on disk in "blocks" containing 128 values. Thus the results for the pressure, volume velocity, $|Z|$ and $\phi$ can be accommodated in 24 blocks.

The results for a typical instrument (a Boosey and Hawkes prototype) are shown in Figure 14. The six character labelling system is described in Appendix A.

2.12 Calibration Procedures

Having described the operation of the experimental apparatus, the calibration procedures for both the probe microphone and the hot-wire probe will be described, since the accuracy of the measurements is naturally dependent on reliable calibration curves, and the use of hot-wire anemometry is not widespread in musical acoustic measurements.

2.12.1 Calibration of the probe microphone

A calibration curve for the probe microphone is supplied by
the manufacturers, but does not include the phase response. However a facility exists at the National Gas Turbine Establishment for calibrating probe microphones, and with their generous help and co-operation, the microphone used in the present work has been calibrated at three overall sound pressure levels; 120, 140 and 150 dB. The results show that its characteristics do not change appreciably with level. The probe microphone under test and a quarter inch Bruel and Kjaer condenser microphone (type 4135) are placed in a uniform sound field and excited by broadband noise. The signals from each device are compared, and the difference between them expressed as a correction in both amplitude (expressed in dB) and phase (expressed in degrees). The system was used to provide a calibration curve to cover the range 10 Hz. to 5 KHz., with a resolution of 10 Hz.

2.12.2 Calibration of the Hot-wire Anemometer

Although the behaviour of a hot-wire probe is understood theoretically, in practice each individual probe is always calibrated before use against a standard reference, such as a pitot tube. Since the characteristics of hot-wire probes may be severely affected by environmental contamination, it follows that any calibration procedure should ideally be quick as well as accurate. Commercial calibration units are available, but can cost substantially more than the anemometry system itself. For this reason the author decided to create a simple inexpensive and yet accurate low velocity calibration system to cover the range 1 m.s.\(^{-1}\) to 16 m.s.\(^{-1}\).

The heart of the system is a Regulated Air Supply (R.A.S.)
which is used as a velocity reference (see Figure 15), instead of a commercial unit or continual reference to an absolute device. The R.A.S. comprises three basic stages; filtration, regulation and control. Two filters (Dominic Hunter Ltd. types PF375 and B2A) together remove all particles down to a size of 0.01 μm in diameter. This precaution is taken to avoid damage to the 5 μm probes. The compressed air at a line pressure of 800 KPa is then reduced using a pressure release valve (Pressure Control Ltd., type 1501/2/RS) to 600 KPa. The purpose of this valve is to eliminate the variation in line pressure introduced by the compressor. A pressure regulator (Air Products type 34-1202) further reduces the pressure to 270 KPa. By increasing or decreasing this value the velocity range of the calibration system may be raised or lowered. Finally an 18-turn needle valve (Edwards Ltd, type LB2B) allows a very precise airflow setting to be made. The source of compressed air is provided by an electric compressor (Sperry Ltd., type SM/TV7/A1) which has a maximum line pressure of 1 MPa, and a flow rate of $3 \times 10^{-3} \text{m}^3\text{s}^{-1}$.

Before the R.A.S. may be used as the velocity reference for calibrating the hot-wire probes, it must be calibrated against a device capable of measuring velocity absolutely. In this instance a pitot tube is used. The R.A.S. is fed to one end of a small, circular brass wind tunnel 75mm in diameter and 0.65m in length. Two gauzes are placed at 0.25m from both ends to smooth the flow. At the other end of the wind tunnel a trombone mouthpiece is used to form the final nozzle section. During the calibration of the R.A.S. the pitot tube is placed at the exact point where the hot-wire probe resides during the impedance measurements. This point is at 2-19
the middle of the mouthpiece throat, where the cross-sectional area of the mouthpiece is a minimum. The differential pressure between the pitot tube positioned axially in line with the airflow at the throat, and a pressure normal to the flow at that plane is measured with an inclined tube tilting micromanometer (Combustion Instruments, no type number) with a resolution of 0.01 mm of water. The wind tunnel, pitot tube and micromanometer are shown in Figure 16. A close up of the mouthpiece and pitot tube is shown in Figure 17.

The differential pressure, \( \Delta P \), measured by a pitot tube in a stream of fluid moving with a velocity of \( w \) m.s\(^{-1}\) and density \( \rho \) is given by:

\[
\Delta P = \frac{1}{2} \rho w^2
\]

At each of the 18 turns of the needle valve the pressure is recorded, and hence the velocity may be calculated. For air at 21°C and 760 mm of Hg., the velocity is related to the height of a column of water by the expression:

\[
w = 4.03 \sqrt{h}
\]

A plot of the needle valve setting (N.V.S.) against velocity is shown in Figure 18. The calibration of the R.A.S. is checked regularly, and the repeatability has been found to be excellent. Changes in velocity for a given N.V.S. were typically ±1% over a two year period. These results demonstrate the suitability of the R.A.S. as a velocity reference. An additional feature of the R.A.S.
is the linearity of velocity with respect to the N.V.S., although such linearity is not a necessary requirement of any reference.

After the R.A.S. has been calibrated, the pitot tube is removed and a hot-wire probe inserted in its place. The anemometry system is now ready to be calibrated. For each N.V.S. the anemometer voltage is recorded, and since the velocity at each N.V.S. is known, the data may be fitted to an equation of the form [23]:

\[ w = A + BV^2 \]

where \( V \) is the output voltage from the hot-wire anemometer
\( w \) is the air velocity
\( A, B \) and \( p \) are constants

The original theoretical work of King [24] indicated that \( p = \frac{1}{2} \), but in practice the optimum value for \( p \) depends on many factors and may be considerably different. The value for \( p \) is optimised during calibration, and is found to lie in the range \( 0.35 < p < 0.45 \). Hardware linearisers may be used to assist the calibration procedure, but they are unnecessary in this case since the computer may be used to linearise the velocity signal. This is done by feeding the velocity signal to one channel of the A/D converters, and running a program (FKAL), which takes 1,000 samples and averages for each turn of the needle valve. Since the velocity characteristics of the needle valve are known, the constants \( A \) and \( B \) may be computed for a given value of \( p \). \( p \) is initially taken as 0.35 and is incremented in steps of 0.01 until the error of fit in the above equation is at a minimum. The corresponding value of \( A, B \) and \( p \) are then recorded for subsequent use.
2.13 Effect of the non-uniform velocity profile

The existence of a non-uniform velocity profile over the plane of measurement must be taken into consideration when calculating the volume velocity. It is not sufficient therefore to multiply the on-axis particle velocity by the cross-sectional area. It may be shown that, for a.c. signals, viscous resistance losses result in a laminar motion throughout the cross-section of the pipe with the velocity increasing rapidly from zero at the walls to nearly its maximum value at a distance given by [8]:

$$\delta = \left(\frac{2\eta}{\rho \omega}\right)^{\frac{1}{2}}$$

where $\eta = \text{viscosity}$
$\rho = \text{density}$
$\omega = \text{angular frequency}$

For air the boundary layer is approximately 1mm at 10 Hz., falling to 0.1mm at 1000 Hz.

The small physical size of the hot-wire probes makes them ideal for experimental measurements of boundary layer thickness, since the probe may be traversed across a given section. From such experiments conducted in the mouthpiece throat it was possible to verify that the velocity reached approximately 90% of its maximum value at the distance $\delta$ calculated from the equation above, over the frequency range 10-800 Hz. Precise measurements within the boundary layer proved difficult, due to the curvature of the mouthpiece throat section,
and the small discontinuities introduced by the palolin washer which locates the probes. Despite these limitations it was found that the velocity decreased rapidly as the probe approached the wall. The effective cross-sectional area, $S'$, was calculated from the expression:

$$S' = 2\pi(r-\delta/2)^2$$

where $r =$ radius of the mouthpiece throat

This has the effect of raising the first impedance maximum ($\approx 40$ Hz.) by about 10%, and the twelfth maximum ($\approx 740$ Hz.) by about 2%. An example of a traverse is shown in Figure 19.

2.14 Measurement accuracy

Errors introduced during the measurement of impedance may be separated into two groups, calibration errors and system errors.

2.14.1 Calibration errors

The calibration errors for the probe microphone supplied by the National Gas Turbine Establishment have an amplitude error of $\pm 0.5$ dB and a phase error of $\pm 2\%$. The probe microphone was calibrated with a pistonphone before each run, with a maximum error of 0.1 dB. The tilting micromanometer has a typical error of 0.25%, and the repeatability when testing the R.A.S. was typically $\pm 1\%$ over a period of nearly two years.
2.14.2 System errors

The repeatability for $|Z|$ is typically ±2% and for $\phi$ is ±1%, although these figures would be improved if a frequency step of 0.1 Hz. were used, since the Q's of the resonances are very high. The positions of the impedance maxima very rarely moved by more than 0.5% on successive trials. The temperature of the room was held at 21°C ±1°C.

2.15 Comparison with theory

A theoretical investigation of the acoustic impedance of ducts has been carried out by several authors, and their work is reviewed by Elliot [25]. In this paper he shows that the input impedance of a cylindrical tube is given by:

$$Z_i = Z_o \times \frac{(\alpha \beta + \beta \tan \beta')/(1 + \beta \alpha \beta \tan \beta')}{(1 + \beta \alpha \beta \tan \beta')}$$

where

$\alpha$ = the attenuation coefficient

$\beta$ = the wave number

$\beta'$ = the actual length

$\beta' = \beta +$ the end correction

Impedance maxima occur for frequencies at which $\beta \beta' = (n + \frac{1}{2})\pi$

where $|Z| = Z_o / \alpha \beta$ and $\phi = 0$.

Similarly impedance minima occur for frequencies at which $\beta \beta' = n \pi$ where $|Z| = Z_o \times \alpha \beta$ and $\phi = 0$. 

2-24
The turning points of the phase of the input impedance occur when:

\[ \beta z' = (n + \frac{1}{4})\pi \quad \text{or} \quad (n + \frac{3}{4})\pi \]

so \[ \phi = \pm \tan^{-1} \frac{1}{2\alpha L} \quad \text{and} \quad |Z| = Z_0 \]

A straight tube of length 1.42m and internal radius 5.45mm was measured using the apparatus, and these results are in reasonable agreement with the predicted values (see Figures 20-22). It will be noted that the experimental values for the impedance (both modulus and phase) are slightly greater than the predicted values at higher frequencies. It should be remembered that the tube is connected to the apparatus via a mouthpiece, and the impedance of the mouthpiece back-bore (which may be shown to be inductive, see Figure 23) is also included in the measurement.

All the impedance measurement systems described hitherto have used a high impedance acoustic source, but this condition is not mandatory. Although the absolute values for the pressure and volume velocity will be affected by the source impedance, their ratio depends only on the load impedance.

To confirm this result experimentally, the cross-sectional area of the brass tube connecting the loudspeaker to the instrument under test was reduced by 94% by inserting a tightly fitting aluminium plug, and a selected instrument was then re-measured. From the results shown in Figure 24, it may be seen that such a reduction has little
effect on the impedance measurements.

2.16 Summary

In this Chapter the concept of acoustic impedance has been introduced and defined. The distinction between Resonance and Impedance measurement systems was drawn, and experiments conducted using the former technique were briefly reviewed. It was noted that impedance measurements have the advantage of being independent of the room acoustics, and have consequently replaced the Resonance method.

The impedance systems of several workers were then reviewed, and their limitations described. All the systems were found to be variants of a method originally devised by Kent and fellow workers at Conn Co.

Early experiments carried out by the author using a hot-wire anemometer to measure particle velocity directly were described. The final Impedance system was then discussed in detail, including sections relating to transducer calibration and measurement accuracy.
CHAPTER 3 THE SUBJECTIVE ASSESSMENT OF TROMBONE QUALITY

3.1 Introduction

From the review of acoustic impedance measurement systems given in the last Chapter, it may be seen that several workers have attempted to develop an objective assessment technique for brass instruments based on an instrument's input impedance. Unfortunately the equally important task of developing subjective assessment techniques has received virtually no attention in comparison, and consequently the variations between the impedance curves of instruments of different quality remain totally unexplained. In this Chapter two subjective assessment procedures are described, and some previous studies concerning the assessment of timbre are reviewed. Finally, some experiments designed to investigate brass instrument quality are described. These experiments enable subjects to quantify the timbre, and also the "feel" or "responsiveness" of a range of trombones.

3.2 Test environment

Since the subjective characteristics of an instrument will vary according to the nature of the acoustic environment in which it is played, it is clearly desirable for all the experiments to be conducted in the same room. The acoustics laboratory of the Physics Department was used, since it well damped, and it is also reasonably well insulated from external noise. The dimensions of the room are 6m × 6m × 2.75m, and the reverberation time is approximately 0.4s at mid-frequencies.
3.3 Quantifying subjective characteristics

Timbre, unlike pitch or loudness, is a multidimensional quantity, and there is no single scale that may be used to describe it completely [26]. Therefore a measurement system reflecting the multidimensional nature of timbre must be used. Two methods which fulfil this condition are:
(a) Multidimensional Scaling
(b) Semantic Differential Scaling

An outline of these procedures is given in Figure 25.

3.4 Multidimensional Scaling (MDS)

3.4.1 MDS - data collection

MDS has been applied successfully to a variety of psycho-acoustical problems including the effect of phase on timbre [26] and the subjective assessment of concert hall acoustics [27]. Using this technique subjects are asked to rate the similarity between stimuli, and this may be accomplished using diadic or triadic comparisons. A diadic comparison requires the subject to assign a numerical value to the degree of similarity observed between a pair of stimuli. Alternatively, in triadic comparisons, the subject is presented with three stimuli, and requested to select the most similar and most dissimilar pair.

3.4.2 MDS - data reduction

The results from either method may be reduced to a single
data matrix $D(N \times N)$ where $N$ is the total number of stimuli, and the value of the element $D(i,j)$ is an estimate of the similarity between the stimuli $i$ and $j$ [28]. Techniques are available [29] for transforming this data matrix into a set of co-ordinates in a multidimensional space where the number of dimensions needed to represent a group of stimuli is minimised for a given level of error or "stress", and the distance between the co-ordinates is an estimate of their similarity (metric MDS). If the rank order only of this distance is used, this corresponds to non-metric MDS. The experimenter is then required to match intuitively the subjective dimensions to the physical characteristics of the stimuli.

3.5 Semantic Differential Scaling (SDS)

3.5.1 SDS - data collection

SDS is a technique formalised by Osgood and a number of co-workers, and a detailed account of their work may be found in reference [30]. The SD scale is essentially a condition of controlled judgemental and rating procedures. Subjects are presented with "concepts" to be rated, and a set of pairs of antonymous adjectives which lie at each end of a seven-point Semantic Scale. The authors then postulate a Semantic Space, Euclidean and multidimensional. Each SD scale is a straight line function whose mid-point passes through the origin of this space. An example of such a scale is given in Figure 26(a).
3.5.2 SDS - data reduction (Factor Analysis)

The data reduction process for SDS is most simply expressed as a "search for synonyms". The scores for each of the scales are correlated against each other thus providing an estimate of the similarity between a given pair of scales. A high correlation means that subjects regard the pair of scales as synonymous. A correlation matrix may be formed for all the pairs of scales, and then submitted to a Factor Analysis which yields a series of orthogonal factors which characterise groups of scales. A factor loading for each scale is also computed, and this gives an indication of the degree to which a given factor characterises any scale. In practice a variation of Factor Analysis, known as Component Analysis is almost universally used, since this procedure does not require any assumptions concerning the structure of the raw data to be made.

3.6 Comparisons of MDS and SDS

The MDS and SDS methods each have their own particular advantages and disadvantages. The suitability of either method is thus dependent on the nature of the problem under investigation. It should be remembered therefore that the following comments refer to the particular application of these techniques to the subjective assessment of trombone quality.

The advantage of MDS with respect to SDS is as follows:

subjects are freed from the restrictions imposed by verbal descriptors and rate only the similarity between instruments.
The disadvantages of MDS are:

(a) acoustic stimuli cannot be presented simultaneously, and hence experiments can become prohibitively long [27];

(b) the maximum number of subjective dimensions that may be extracted is limited to one less than the number of stimuli used in the experiment;

(c) a strong single difference between the stimuli can reduce the results to a single dimension, thus masking weaker differences [31];

(d) since subjects are free to form their own subjective space, it is difficult to compare their results.

The advantages of SDS with respect to MDS are as follows:

(a) subjects can indicate preference if suitable scales are included (e.g. Bad Intonation/Good Intonation, Unpleasant Timbre/Pleasant Timbre);

(b) the ability of subjects to discriminate between stimuli may easily be examined [32];

(c) since all subjects use the same semantic space, by comparing their ratings for any given stimulus an indication of the uniformity with which subjects rate the stimuli may be obtained.

The disadvantage of SDS is:

the success of the experiment is critically dependent on the choice of scales. Should a relevant scale be omitted, then subjects
do not have the opportunity to rate that attribute. The inclusion of an irrelevant scale will increase the time taken to perform the experiment without obtaining any useful data.

3.7 Requirements for a subjective rating procedure

Since the aim of this work is to derive a subjective rating procedure enabling a comparative study of trombones to be performed, such a procedure must satisfy the following requirements:

(a) subjects must be able to indicate preference;
(b) statistical tests to check the significance of any preference must be readily available;
(c) the experiments must be kept reasonably short, since the goodwill of the student players should not be exploited, and the services of professional players must be paid for.

For the above reasons it was decided to employ principally the SDS method. However one experiment was conducted using MDS, and provided useful, corroborative data.

3.8 Review of timbre assessment

Several studies using MDS or SDS have investigated the subjective dimensions of timbre, and related these dimensions to the physical composition of the experimental stimuli. Since timbre is itself multidimensional, many of the experimental and analytical procedures described in these studies are relevant to the more general problem of assessing trombone quality. Accordingly, certain selected papers are reviewed below.
3.8.1 Review of papers using MDS

Wedin and Goude [33] used MDS to investigate the minimum number of dimensions needed to describe satisfactorily the timbre of the following nine instruments: flute, bassoon, violin, oboe, French horn, trumpet, trombone, clarinet and 'cello. For each instrument an experienced musician was instructed to play the note A4 (440 Hz.) at a dynamic level corresponding approximately to mezzo-forte, and these notes were recorded. Subjects were then presented with a series of paired tones, where each instrument was paired with itself and every other instrument, and the order of the tones within a pair was also reversed. Subjects were asked to rate the subjective similarity of timbre between the tones in each pair using the method of dyads. A similarity matrix was derived and a three-dimensional solution obtained. These dimensions were found to represent the timbre of the following groups of instruments:

(a) dimension 1; violin, 'cello, clarinet;
(b) dimension 2; trombone, French horn, flute;
(c) dimension 3; trumpet, oboe, bassoon;

The authors note that the instruments within a given dimension may not always sound similar when played in their normal range. It should be remembered however that the note A4 is at the extreme of the normal playing range for some of the instruments, notably the bassoon and trombone. A spectral analysis was performed on the steady state portion of each of the tones, covering the frequency range 0-4 KHz. The resulting nine spectrum envelopes were then submitted to a component analysis, in order to investigate the degree of correspondence
between the physical composition of the stimuli, and the three factors derived from the subjective experiment. The analysis showed that three spectrum envelope profiles accounted for 95% of the variance. By examining the factor loadings for the spectra of the instruments with respect to the three profiles, it was found that the three factor profiles characterised the following instruments:

(a) Profile 1; 'cello and clarinet;
(b) Profile 2; trombone, French horn and flute;
(c) Profile 3; trumpet and oboe.

These three profiles correspond approximately to the three factors of instruments derived from the subjective experiment. The agreement is not perfect however, since the violin and bassoon spectra are negatively loaded with respect to Profiles 1 and 3. Thus, although an approximate relationship between subjective and objective factors exists, this relationship is not completely understood.

Two similar studies have been carried out using MDS to investigate timbre. Both studies used synthesized tones equalised for pitch and volume. Since their experimental techniques are very similar to those of Wedin and Goude, only a description of the stimuli used will be given, followed by a summary of the results.

Miller and Carterette [31] varied the composition of the stimuli as given below:

(a) number of harmonics (3, 5 or 7);
(b) attack/decay envelope shape for each harmonic (horn, strings, trapezoidal);
(c) attack time for the envelopes in (b).
This resulted in a three-dimensional solution where:
(a) dimension 1 separated tones into three groups, which comprised 3, 5 or 7 harmonics;
(b) dimension 2 separated tones into two groups, which comprised 5 or 3 and 7 harmonics;
(c) dimension 3 separated tones into three groups

It is interesting to note that one characteristic number of harmonics is capable of producing more than one dimension. The second dimension does not therefore give any additional information. Note also that the attack times do not appear in this solution.

Grey [34] used stimuli that were synthesized on the basis of data obtained from the analysis of sixteen instrumental notes. The synthesis procedure allowed the amplitude/time history of each harmonic to be controlled independently, and thus the physical characteristics that could be varied were very similar to those described in the last experiment. A three-dimensional solution was obtained where:
(a) dimension 1 separated tones with low harmonic content from those with high harmonic content;
(b) dimension 2 separated tones whose harmonics developed synchronously from those whose harmonics developed asynchronously;
(c) dimension 3 separated tones with small attack times for the higher harmonics, from those with no preceding high frequency energy.
3.8.2 Summary of MDS experiments

Although the data from the three experiments described in the last section could be expressed satisfactorily on each occasion in a three-dimensional solution, the nature of these solutions is very different. Furthermore the complexity of the solution seems to be related to sophistication of the analysis/synthesis techniques. For example Wedin and Goude analysed their notes to yield only the steady-state spectral energy, and were able to derive a solution using only envelope profiles. Both Miller and Carterette and Grey had more detailed information, namely the amplitude/time history of each harmonic, and their solutions include such factors as envelope shape and attack time. Despite the considerable similarity between the stimuli used for these two studies, only the first dimension (harmonic content) is the same. Miller and Carterette's second and third dimensions were related to harmonic content (on this occasion separating tones with 5 harmonics from those with 3 or 7), and envelope shape respectively, while Grey extracted two further dimensions related mainly to attack time. It is suggested that the subjective interpretation of MDS results by the experimenter is largely responsible for such discrepancies.

3.9 Review of papers using SDS

The most comprehensive SDS experiment on timbre has been carried out by von Bismarck [35]. In this study, which was originally carried out in Germany, sixteen subjects were presented with 35 synthesized sounds which they rated on 30 selected SD scales. All
except five of these sounds were complex tones with a fundamental frequency of 200 Hz. The remaining five sounds were band-limited noise. The results from the experiment were then used to form a correlation matrix, and a component analysis was performed, revealing that four factors, represented by Dull/Sharp, Compact/Scattered, Empty/Full, Colourless/Colourful, accounted for 90% of the variance. The factor Dull/Sharp, which accounted for 44% of the variance, was subsequently shown to correspond approximately to Low harmonic content/High harmonic content. The factor Compact/Scattered, which accounted for 26% of the variance represented the difference of timbre between complex tones and noise. Similar factorial studies of the suitability of selected SD scales to quantify timbre have been carried out by a number of authors. The factors emerging from such experiments will vary with the stimuli used (for example Jost [36] found that the two most important subjective dimensions of clarinet timbre were "volume" and "density"), but in general quite a small number of factors can satisfactorily account for most of the variance.

In another study by Pratt and Doak [32], a Subjective Rating Scale for timbre was devised comprising three SD scales; Dull/Brilliant, Cold/Warm and Pure/Rich. These scales were chosen by issuing a questionnaire containing a vocabulary of nineteen words used to describe timbre, to students in the Music Department at the University of Southampton. The questionnaire is reproduced in Figure 27. Subjects had to select six adjectives from the vocabulary which, in their opinion, they considered the most useful to describe the timbre of the following families of instruments; strings, woodwinds, brasses,
and a combination of all three families. The combined results for all the subjects are marked on the questionnaire and show a strong preference for certain words when describing the timbre of the "combination" group. The limit of just three scales was introduced in a somewhat arbitrary manner, as noted by the authors. This was done deliberately to see if subjects could use a small number of scales to discriminate between sounds, since an exhaustive evaluation of a large number of scales had already been carried out by von Bismarck. The experiment was carried out as follows: six synthesized sounds, differing only in harmonic content, were rated by 21 subjects. Each sound was repeated six times in a balanced Latin Square order, making a total of 36 presentations. Thus each subject rated each sound on six separate occasions, on the three SD scales. For a given subject the results for (say) sound 1 and sound 2 were then compared, and a t-test applied to determine whether the responses differed significantly at the 5% level for any of the three scales. If this was true for one or more scales, the subject was said to be able to "discriminate" between the two sounds. If all six sounds are compared with each other in this way, then each subject can make a maximum of 15 discriminations. The average number of discriminations made by the subjects was 11, indicating that the Subjective Rating Scale was reasonably successful at categorising a small vocabulary of sounds of different harmonic content.

The concept of using scales to discriminate between stimuli in this way is fundamental to the current investigation.
3.10 Factors Governing Trombone Quality

The success of any experiment involving SDS will depend on the selection of scales relevant to the attributes under investigation. In order to select such scales, the views of trombone players must be sought, and the features that determine the quality of an instrument established. Accordingly, trombone players in the Music Department at Surrey University were interviewed. These players were asked a number of questions in an attempt to establish the subjective dimensions of trombone quality. Such questions included: "what do you consider the important qualities of a trombone to be?", "what factors influenced you when contemplating buying a new instrument?", "what features of your instrument would you like to see improved?".

From their responses, and from more detailed interviews carried out by Edwards [37] on professional players, the following features were considered to be of critical importance for a high quality instrument. These features are, in order of importance:

(a) Slide quality
(b) Timbre
(c) Responsiveness

Four secondary features also emerged, the intonation, balance, comfort and weight. The players' comments on these features may be summarised as follows:

Slide quality: the slide should be light and run smoothly with the minimum of friction. It must also be made as airtight as possible.

Timbre: the requirements for timbre are governed by factors
in addition to the personal preference of the player. Examples of these are the type of music that is to be played (e.g. symphony, jazz or renaissance) and whether the instrument is played solo or in an ensemble. Presented with such conflicting requirements the player has two choices: either to buy a number of instruments, each one suited to a particular requirement, or to buy one instrument that enables him to vary the timbre to suit the style of music being played.

Certain makes of trombones are reputed to have greater flexibility of timbre than others, where the attribute of flexibility refers to the relative ease with which the player may vary the timbre of the note produced. This attribute is considered highly desirable by professional players.

Responsiveness: this word is used by players to describe the transient behaviour of the instrument. A responsive instrument allows the player to start and change a note easily and swiftly.

It might at first seem surprising that intonation is considered of only secondary importance. However it must be remembered that deficiencies in intonation may be corrected by experienced players owing to the continuous nature of the slide action. Finally the instrument should be made as light as possible, and the centre of gravity should lie at the handgrips to ensure a good balance. The handgrips should be comfortably spaced.

These original interviews were conducted amongst professional players most of whom performed in symphony orchestras. However, more recently a questionnaire has been sent to a broader sample of 320 professional trombone players, and the replies are in good agreement with findings of the interviews.
3.11 Experimental Procedure

Before describing the experiments in detail it should be noted that a small modification is made to Osgood's SD scale. Instead of a seven point scale (Figure 26(a)) the scale is drawn as a continuous 0.127m (5 inch) line and a cross may be placed anywhere along the line. The scale is divided into 100 units and the score is expressed as a number in the range 0-100 (Figure 26(b)). A continuous scale has two advantages: first it eliminates the need for verbal descriptions of the seven subdivisions, whose meaning might be interpreted differently by individual subjects, and secondly the data may be reduced to seven levels if required.

A preliminary experiment was conducted to examine how successfully listeners could use SD scales to rate the timbre of a range of trombones. Three different instruments were used, one of which was played on two occasions using a different mouthpiece each time. Thus a total of four instrument/mouthpiece combinations (referred to simply as instruments) were assessed, and each instrument was played by three players (two music students and one semi-professional player. The instruments used were:

(a) Boosey and Hawkes Sovereign B♭ tenor trombone with Dennis Wick 4AL mouthpiece (I1)
(b) Yamaha B♭ Bass trombone with 4AL mouthpiece (I2)
(c) Bach 42B B♭ tenor trombone with 4AL mouthpiece (I3)
(c) Boosey and Hawkes Sovereign B♭ tenor trombone with 6BL mouthpiece (I4).

The listeners who took part are referred to as L1-L4. The
players are referred to as P1-P3.

While one of the players was playing an instrument the remaining two players and a further non-playing subject formed a listening panel. The panel rated the timbre of the instrument on three scales: Dull/Bright, Compact/Scattered and Not Penetrating/Penetrating. The scales were selected on the basis of the interviews described in the last section, and from previous verbal studies of timbre [32,35].

3.11.1 Experiment 1

The experiment was conducted as follows: a player and an instrument were drawn by lot. The listening panel faced away from the player and could not see the instrument, but were aware of the identity of the player. The player was instructed to play the note B2b (121 Hz.) at a level of 85 dB(A). A Bruel and Kjaer Impulse Sound Level Meter (type 2204) positioned at a distance of 2m on-axis from the bell of the instrument was used to measure this level. This note was chosen since it contains a great number of harmonics, and is therefore the most likely one to elicit differences between instruments and between players. After the listening panel had rated the note, another player was selected to play an instrument, and the rating procedure was repeated until the three players had played all four instruments. The total experimental time was about two hours. The instructions to the listeners are shown in Figure 28. The scores of the listening panel were analysed using the analysis of variance technique. This technique is appropriate here, since it will give
a quantitative assessment of the relative importance of the three factors: instrument, mouthpiece and player.

From the results of this analysis it was found that the scores of the listeners were significantly different at the 1% level, and hence the scores of each listener must be analysed separately. The following facts emerged:

(a) Dull/Bright: using this scale two listeners could discriminate between instruments (L1 @ 1%, L2 @ 5%).

(b) Compact/Scattered: no discriminations were made by any listener.

(c) Not Penetrating/Penetrating: using this scale two listeners could discriminate between instruments (L1 @ 1%, L3 @ 5%) and two listeners could discriminate between players (L3 @ 1%, L4 @ 5%).

Since the scale Compact/Scattered did not yield any significant results it was not included in any subsequent experiments. It is interesting to note that this scale characterised the second factor in von Bismarck's study [35]. As Plomp has noted [26], the factors emerging from any particular experiment are highly dependent on the stimuli used.

The analysis of variance can only show that a listener has made discriminations within a factor. Having established this fact the scores must be examined more closely to elicit the precise nature of these differences. For example, a listener whose results showed that he was able to discriminate between instruments using a particular scale, may have been able to discriminate between all four instruments, or he may only have been able to discriminate one instrument from the
remaining three.

A more detailed examination may be performed easily using the analysis of variance program written by Edwards [38]. The means and standard deviations for each of the factors are both tabulated and plotted. An example of the printout from this program is shown in Figure 29. The means are represented by an asterisk, and a vertical bar denotes ±1 standard deviation. It follows that if the standard deviation bars for any two factors do not overlap, then the means are separated by at least two standard deviations. Therefore the hypothesis that the means are the same (i.e. the two factors are from the same population) may be rejected at least at the 5% level.

The results were analysed accordingly and the following findings emerged.

For the scale Dull/Bright.

Instruments: L1 rated I3 "brightest", followed by I1 and I4 (no discrimination was made between these two instruments) and finally I2. L2 rated I3 "brightest", followed by I1, I2 and I4. (No discrimination was made between these three instruments).

Players: no discriminations were made by any listeners.

For the scale Compact/Scattered.

No discriminations were made by listeners using this scale.

For the scale Not Penetrating/Penetrating.

Instruments: L1 rated I3 and I4 "most penetrating", (no discrimination was made between these two instruments) followed by I2, and finally I2. L3 rated I1, I3, I4 "most penetrating", followed by I2.
Players: L3 rated P1 "most penetrating", followed by P2 and finally P3. L4 rated P1 "most penetrating", followed by P2 and P3 (no discrimination was made between these two instruments).

Several important conclusions may be drawn:
(a) the scale Dull/Bright may be used to discriminate between instruments;
(b) the scale Not Penetrating/Penetrating may be used to discriminate between instruments and players;
(c) the order of the factors having the greatest influence on timbre is: instrument, player, mouthpiece;
(d) where listeners could make discriminations within a given factor, the rank order was always the same, thus demonstrating that the listeners were using the scales in a similar manner.

3.11.2 Experiment 2

It is clearly unrealistic to judge the timbre of an instrument on the basis of a single note, which was the case in the first experiment. To assess an instrument thoroughly it is necessary to hear it being played at several pitches and dynamic levels, thus enabling an assessment to be made over a range of conditions likely to be encountered during an actual performance. Such an experiment would take much longer to perform, and more importantly, the timbre of the instrument itself varies with changes in pitch and dynamic level. Clearly if these factors are to be included in future experiments then their influence on timbre must be well understood. For this reason an experiment was devised to investigate quantitatively
the effect of frequency, amplitude, player and instrument on timbre.

Pre-recorded trombone notes were used in this experiment since the
repeatability of a subject's scores when rating identical presentations
of a given note was to be investigated, and the use of tape ensures
that such repetitions are indeed identical. To prevent the experi­
ment from becoming excessively long just two examples of each of the
above four factors were used, selected to provide good contrast.

The pairs of factors used were as follows:
(a) 1 high pitch, D4 (288 Hz.) and 1 low pitch B2b (121 Hz.).
(b) 1 loud note corresponding approximately to f, and 1 quiet
note, p.
(c) 1 Tenor player and 1 Bass player.
(d) 1 professional model large bore trombone and 1 student
model medium bore trombone.

All 16 \(2^4\) possible combinations were used each repeated
7 times making a total of 112 presentations. For the recording the
instruments were played by two music students, and the Sound Level
Meter ensured that the sound levels were equal (i.e. same "A" weighted
level) where necessary. The recordings were made at one bell radius
on-axis [39]. A level of 105 dB(A) corresponds to f, and a level of
95 dB(A) corresponds to p. The players were instructed to play each
note for about 1.5s, and the edited tape used in the experiment
comprised the 112 notes arranged in a balanced Latin Square order.
During the actual experiment the tape ran continuously and the subjects
rated the sounds on two scales, Dull/Bright and Unpleasant Timbre/
Pleasant Timbre, during a 10s silence that followed each note. The
first scale was chosen since it has been used successfully to investigate the effect of pitch on timbre [35]. The second scale was included to examine listeners' preferences, and determine if any consensus of opinion exists. The tape was replayed to listeners on a Nagra IV tape recorder via Koss PRO 600A headphones at a comfortable listening level.

The results may be analysed using analysis of variance, and since only two examples of a given factor occur, this analysis alone is sufficient without having to use the t-tests. The scores of the 16 listeners differ significantly (0.1%) and so the scores of each listener must be analysed separately. This was done, and the results from the Dull/Bright scale are summarised below:

(a) Frequency: listeners judged the high frequency notes "brighter" than the low frequency notes (4 @ 1%, 5 @ 5%). 5 listeners judged the low frequency notes "brighter" than the high frequency notes (3 @ 1%, 2 @ 5%).

(b) Amplitude: all 16 subjects judged the loud notes "brighter" than the quiet notes (1%).

(c) Player: 7 listeners judged the Bass player's notes "brighter" than the Tenor player's notes (4 @ 1%, 3 @ 5%). 2 listeners judged the Tenor player's notes "brighter" than the Bass player's notes (2 @ 5%).

(d) Instruments: no discriminations made by any listeners.

Similarly, for the scale Unpleasant Timbre/Pleasant Timbre:

(a) Frequency: 12 listeners judged the low frequency notes "more pleasant" than the high frequency notes (11 @ 1%, 1 @ 5%). 1 listener judged the high frequency notes "more pleasant" than the
low frequency notes (1%).

(b) Amplitude: 8 listeners judged the quiet notes "more pleasant" than the loud notes (7 @ 1%, 1 @ 5%). One listener judged the loud notes "more pleasant" than the quiet notes (1 @ 1%).

(c) Player: 3 listeners judged the Tenor player's notes "more pleasant" than the Bass player's notes (2 @ 1%, 1 @ 5%). 2 listeners judged the Bass player's notes "more pleasant" than the Tenor player's notes (1 @ 1%, 1 @ 5%).

(d) Instrument: 2 listeners judged the professional instrument's notes "more pleasant" than the student instrument's notes (1 @ 1%, 1 @ 5%). 2 listeners judged the student instrument's notes "more pleasant" than the professional instrument's notes (1 @ 1%, 1 @ 5%).

These results show that the frequency and volume of a note have a much greater influence on the assessment of timbre than the player or the instrument. They also illustrate the problem of devising an experiment capable of enabling listeners to discriminate between instruments, when the instruments are played at a number of frequencies and amplitudes. It is also interesting to note that the listeners who were able to discriminate between instruments and between players using the scale Unpleasant Timbre/Pleasant Timbre are nearly equally divided in their preference of both instrument and player.

3.11.3 Experiment 3

In view of the difficulties experienced by listeners in discriminating between instruments and between players, and also since
listeners can only rate the timbre of the instruments, it was decided to concentrate on the use of players as subjects for the remaining experiments. The use of players to assess instrument quality has three important advantages:

(a) they can play the instrument over a range of frequencies and amplitudes, and thereby give an "averaged" score on any particular attribute;

(b) they can assess the responsiveness, in addition to the timbre;

(c) the views of the player on instrument quality are perhaps more important than those of the listener, since it is the player who buys the instrument, and whom the music manufacturers approach for opinions of a new model.

Again, drawing upon the results of the interviews with players, seven scales were selected on which to rate a range of instruments. These scales were:

(a) Small Dynamic Range/Large Dynamic Range
(b) Bad Intonation/Good Intonation
(c) Unresponsive/Responsive
(d) Heavy Resistance/Light Resistance
(e) Stuffy/Free Blowing
(f) Unpleasant Timbre/Pleasant Timbre
(g) Inflexible Timbre/Flexible Timbre

The first scale is a measure of the dynamic range of an instrument, since a common complaint about poor trombones is the feature referred to by players as "breaking up" or inability to play
notes at a high dynamic level. The second scale measures the player's subjective opinion concerning the relative intonation of the harmonics of the instrument.

The scales Unresponsive/Responsive, Heavy Resistance/Light Resistance and Stuffy/Free Blowing are the "feel" scales derived from the adjectives most frequently used by players. The scale Unpleasant Timbre/Pleasant Timbre is included so that a measure of different players' preferences may be sought, and finally the scale Inflexible Timbre/Flexible Timbre is a measure of how successfully the player feels able to influence the timbre of the sounds he produces.

The experiments were conducted in the acoustics laboratory, and the procedure was as follows. Players were blindfolded and wore thick gloves to disguise the instruments as much as possible. Three medium bore instruments adjusted to have approximately equal weight and balance were used, and each instrument was played with a large diameter mouthpiece rim and a small diameter mouthpiece rim, making a total of six instrument/mouthpiece combinations. The instruments used were a Boosey and Hawkes prototype (I1), a Conn 5H (I2), and a Bach 12 (I3). The mouthpieces used were a Dennis Wick 9BS (M1), which has a nominal rim diameter of 25.0mm, and a 6BS (M2) which has a nominal rim diameter of 25.4mm. Each instrument/mouthpiece combination was presented to the player a total of five times during the course of the experiment. Two student players (R.D'C and R.P.) and one semi-professional player (J.M.B.) took part. They were tested individually, and were handed the instruments to be rated by the experimenter. The slide lock was engaged so that only the first
slide position could be used. It is realised that this is a limitation for the players, but the results of the interviews suggested that the different qualities of the three slides would prejudice the outcome of the experiment. Since the players were blindfolded, they gave their scores verbally to the experimenter using the range 0-10 for each scale. The subjects were allowed to play each instrument for as long as they wished, and were encouraged to replay the instrument before giving a score for a particular scale if they felt this to be desirable. Each subject needed about three hours to complete this experiment. The scores of each player were submitted to an analysis of variance with the following results:

(a) Small Dynamic Range/Large Dynamic Range: R.D'C. rated I2 as having "Large Dynamic Range", followed by I1 and I3, using the mouthpiece M2 (1%);

(b) Stuffy/Free Blowing: J.M.B. rated I1 "stiffer" than I2 and I3 using either mouthpiece (5%);

(c) Unpleasant Timbre/Pleasant Timbre: J.M.B. rated I1 as having "less Pleasant Timbre", than I2 and I3 using either mouthpiece (5%).

These results indicate that the players were finding the task of discriminating between instruments a difficult one, although it would appear that J.M.B. was able to identify the Boosey and Hawkes prototype using two of the scales.

3.11.4 Experiment 4

To discover whether the difficulty lay in using SDS or in
the lack of experience of the players, a professional session player (C.S., who played a Vincent Bach 12) was invited to participate in a similar experiment. To reduce the experimental time still further, only the scales Bad Intonation/Good Intonation, Stuffy/Freeblowing, and Unresponsive/Responsive were used. Five medium bore trombones (three of which had been used in the last experiment, plus a King 2B (I4), and a Yamaha YSL 651 (I5) ) and one mouthpiece (Dennis Wick 10CS) were used. Each instrument was presented 5 times making a total of 25 presentations. The results obtained were very different from those of the previous experiment, and are produced in full in Figure 30. Analysing the results with the t-test, the following conclusions may be drawn (1% level of significance throughout):

(a) Bad Intonation/Good Intonation: I5 has worse intonation compared to the rest, which were indistinguishable on this scale.

(b) Stuffy/Freeblowing: I1 was more stuffy than the rest, again indistinguishable.

(c) Unpleasant Timbre/Pleasant Timbre: I4 had the most pleasant timbre followed by I2 and I3 (no significant difference between them) then I5 and finally I1.

These results demonstrate that this particular player had very little difficulty in using the scales consistently to quantify his assessment of the instrument. It is also interesting to note that his rank ordering of the instruments was very similar for the scales Stuffy/Freeblowing, Unpleasant Timbre/Pleasant Timbre.

An MDS experiment was also performed on this player using the same five instruments. Each instrument was presented with itself and
the other four, on two occasions (with the order of the pair reversed for the second presentation), as a series of dyadic comparisons. He was asked to state which instrument of the pair he preferred (using any criteria) and by how much, using a "preference scale" of 0-10. A score of 0 meant that he judged the instruments to be identical, and 10 meant the greatest possible preference. The results were analysed using MDSCAL and the data could be reduced to one dimension with very low stress (<1%). By comparing the results obtained in this way with the scores from the SD experiment using the scale Unpleasant Timbre/Pleasant Timbre (Figure 31), it may be seen that the single dimension corresponds very closely to the timbre of the instrument.

3.12 Summary of experimental results

The results from the first experiment where pitch and loudness were held constant, indicate that the order of the factors governing timbre is as follows:

(a) Instrument
(b) Player
(c) Mouthpiece

The second experiment investigated the influence of the five factors pitch, loudness, player, instrument and mouthpiece on timbre. The two factors pitch and loudness were found to have very much greater influence on subjects' ratings than the other three. Furthermore where subjects were able to make distinctions using the scale Dull/Bright there was good general agreement between subjects on the rank order in which the sounds were placed. Using the scale
Unpleasant Timbre/Pleasant Timbre subjects generally preferred the low pitch and low volume sounds but were equally divided in their preference between players and instruments. Five subjects were able to distinguish between players, and four subjects were able to distinguish between instruments over a range of pitches and loudness.

The third experiment investigated players' attitudes towards trombone quality. When prevented from identifying an instrument visually, the three players had great difficulty in distinguishing between instruments and between mouthpieces. After the tests were completed, players were invited to play the instruments informally with the gloves and blindfold removed. During this time all three players unhesitatingly gave firm opinions about the quality of the instruments they were playing.

A professional player was tested using a very similar experiment. He had little difficulty distinguishing between instruments, which indicates the importance of playing experience for a reliable assessment of instrument quality (it should be noted however that this player had the advantage of using his own mouthpiece during the test). He also took part in an MDS experiment, and the results clearly showed that the most important acoustical factor governing his preference of any particular instrument is the timbre. This result is in agreement with the findings of the interviews carried out by the author, and by Edwards [37].

3.13 Selection of subjects

In view of the difficulty experienced by the majority of
the subjects in making discriminations between instruments and between players, it would be very useful to establish a selection procedure to enable the more discerning subjects to be readily identified. To pursue this aim the subjects were asked to rate their musical imagery (i.e. the ability to recall musical sensations) using SD scales. This work is not directly related to the assessment of trombone quality, and is therefore presented in Appendix B.

3.14 Summary

In this Chapter the techniques of Semantic Differential Scaling and Multi-dimensional Scaling were described, and the advantages and disadvantages of each method discussed. Some papers using these techniques were then presented. The factors governing trombone quality (based on interviews with players) were introduced, and formed the basis of a series of experiments aimed at quantifying the subjective dimensions of trombone quality. Less experienced players found the task of discriminating between instruments very difficult, but a professional player tested was capable of performing this task with ease.
CHAPTER 4 THE OBJECTIVE ASSESSMENT OF TROMBONE QUALITY

4.1 Introduction

Having described the impedance measurement system and the subjective assessment procedures in detail, in this Chapter ways in which the acoustic impedance of a trombone may be used to predict its subjective quality will be examined.

4.2 Summary of the sound production mechanism of brass instruments

A brief review of the sound production mechanism of brass instruments is included at this stage since an understanding of this mechanism is needed to explain the selection of acoustic impedance as the primary objective measurement.

The first combined theoretical and experimental model of brass instrument behaviour was proposed by A.G. Webster [40] in 1918. The mechanism described is that of a valve controlled by a spring under tension, which admits a puff of air into the instrument. The pressure wave thus generated propagates down the length of the instrument, and reflected by the bell, arrives back at the valve at the appropriate phase to maintain oscillation. The arrangement is shown in Figure 32.

This model has been adopted by Benade [41] to explain the function of the lips when playing a brass instrument. This reference also includes a most illuminating discussion of the historical development of the model. In 1929 Bouasse [42] showed that the non-linear characteristics of the valve cannot in general be ignored. For stable oscillation an instrument must posses impedance maxima located near to
the harmonics of the note being played. It is interesting to note that this fact was known, at least empirically, by Barton [43] and Lamb [44] some twenty years previously. This arrangement whereby several impedance maxima combine to determine the playing frequency, is referred to by Benade as a "regime of oscillation". The above theories are discussed in a paper by Benade and Gans [45], and certain corollaries given which are reproduced below. For the non-linear case:

(a) "oscillation is favored at a frequency for which the air column input impedance is large (as in the linear case);"

(b) "oscillation is also favored if the impedance is large at some or all of the harmonics of this frequency".

Worman [16] has extended this work and gives an expression which may be used to predict the variation of the internal spectrum of a note with playing dynamic, if the impedance of the instrument is known. The pressure amplitude of the \( n \)th harmonic is given by:

\[
P_n = P_1^n \times Z(nf_1) \quad \text{for} \quad P_n \ll P_1
\]

where \( P_n \) is the pressure of the \( n \)th harmonic

\( Z(f,n) \) is the value of \( Z \) at \( n \times f_1 \)

4.3 The "Sum Function"

In Section 2.4 the terms impedance maxima and playing frequency were introduced. The relationship between these two sets of frequencies for a given instrument is not exact, due partly to the non-linear sound production mechanism. Wogram [16] has derived what he terms a "Sum Function" (Summenprinzip) which takes into account the fact that the
impedance values of an instrument at integral multiples of the fundamental frequency combine with the players lips to establish the playing frequency. He further argues that the playing frequency is directly related to the frequency at which maximum energy is transferred from the instrument to its surroundings, and that this occurs when the Sum Function is at a maximum. The Sum Function is therefore calculated by summing the real part of the impedance of an instrument at integral multiples of the fundamental frequency:

\[ S(\omega) = \frac{1}{n} \sum_{i=f_1}^{nf_1} R_i \]

where \( n \) is maximised such that \( nf_1 < f_{\text{max}} \), the highest frequency for which \( R \) is known.

where \( R_i = \) real part of the impedance at frequency \( i \) Hz.

\( f_1 = \) fundamental frequency

A computer program (FSUM) has been developed jointly by the author and Dr. J.M. Bowsher, which enables the Sum Function to be calculated from the disk files of instrument data. This program extends the Sum Function concept to incorporate the changes in playing frequency that occur with playing dynamic. This extended Sum Function is computed thus:

\[ SF(\omega) = \frac{1}{n} \sum_{i=f_1}^{nf_1} R_i \cdot n^{-k} \]

The case where \( k = 0 \) corresponds to fortissimo playing and the expression reduces to Wogram's Sum Function. However Worman has
shown that the contribution of the impedance maxima that amplify the harmonics of a given note diminishes as the playing dynamic is reduced. Thus when \( k = 1 \) for example the contribution of \( R_2 \) is halved, \( R_3 \) is divided by 3 and \( R_n \) is divided by \( n \). For increasing \( k \), the contribution of the higher frequency impedance maxima is further reduced until for very large \( k \) the impedance maximum at the fundamental is dominant. This corresponds to a decreasing of the playing dynamic until the note is being played as quietly as possible. In the diagrams depicting the Sum Function, a value of \( K = 0 \) is normally used, unless otherwise specified.

4.4 Hypotheses (a) and (b)

In this Section two simple hypotheses are advanced which attempt to relate the subjective quality of a trombone to its impedance. They are based on the corollaries of a non-linear sound production mechanism which were stated in Section 4.2. For an instrument possessing a stable regime of oscillation:

(a) the overall amplitude of the impedance maxima shall be high;
(b) the frequency location of these maxima shall lie at closely harmonic intervals.

It is assumed that a stable regime of oscillation results in a trombone that is easy to play and will also have a pleasant timbre [41], although the author is unaware of any direct evidence supporting this view.

One further facet of trombone quality that must be considered is that of intonation. The use of the equal temperament tuning
system means that the frequency location of the impedance maxima is necessarily a compromise between their use as fundamentals, and their use for the amplification of the harmonics of other notes [4]. It was decided at the outset of this work that the qualities of timbre and ease of playing were to be given a higher priority than intonation, and there were two reasons for this:

(a) Boosey and Hawkes already had a student working on the problem of intonation [1];

(b) the continuous nature of the slide action of a trombone enables players to make corrections to the intonation of an instrument.

4.5 Two case histories

Two case histories are now reported which relate directly to the two hypotheses given above.

4.5.1 A comparative study of two large bore tenor trombones

The instruments examined in this experiment were a Vincent Bach 42, and a Boosey and Hawkes Sovereign (lacrered). These instruments were chosen since it was believed that Boosey and Hawkes based their design on the Bach, and it was hoped to see what similarities existed between the instruments.

The instruments were measured with the impedance apparatus and the results are given in Figure 33. Note that the amplitudes of the impedance maxima are in general greater for the Bach, and that the frequencies of the maxima for the two instruments are typically within 2 Hz.

The instruments, together with a silver plated Boosey and
Hawkes Sovereign, were assessed subjectively by three players as part of a larger experiment which sought additionally to examine the effect of different finishes. The mouthpiece used was a Dennis Wick 4AL. Subjects were presented with twelve pairs of instruments, six of which comprised two different instruments, and six were repetitions of a given instrument. The twelve pairs were ordered in a random sequence and subjects were asked to state whether they thought that the instruments in each pair were the same or different. The complete results for all three subjects are shown in Figure 34. The results pertaining to the finish will be discussed at greater length in Section 4.9.5.

The group of three subjects consisted of one semi-professional player (J.M.B.), and two student players (R.P., and G.C.).

One feature of the results for J.M.B. and R.P., is that neither player was able to identify any of the repetitions. It may be concluded therefore that these players were not able to discriminate between the three instruments. However from the results of G.C., it is clear that he never confused the Bach with either of the Boosey and Hawkes Sovereigns.

All the players were aware of the identity of the instruments before the start of the experiment, but the experimental protocol used (i.e. gloves and blindfold) was devised especially to minimise the possibility of a player employing non-acoustical cues to discover the identity of a particular instrument. At the end of the formal trials each subject was invited to play the instruments with the gloves and blindfold removed. All three subjects were both firm and unanimous as to the subjective quality (in timbre and responsiveness) of the instruments. The Vincent Bach 42 was considered to be the best.
followed by the laquered Sovereign, and finally the silver plated Sovereign.

For the one subject capable of making consistent judgements, the results of this trial are in good agreement with Hypothesis (a).

4.5.2 Improving the timbre and responsiveness of a bass trombone

Bass trombones commonly employ one or more valves (in addition to the slide) to increase the length of the instrument, thereby reducing the playing frequency. The instrument used in this experiment possesses a G valve which lowers the pitch of a B♭ instrument by three semitones. It follows therefore that the note G2 (98 Hz.) may be played in two ways, either:

(a) the slide in 1st position and the valve depressed;
(b) the slide in 4th position and the valve released.

In both cases the overall length of the instrument is the same, but the extra tubing is introduced at different points. Dr. J.M. Bowsher noted that using the valve to play G2 resulted in a note that was difficult to sustain comfortably, and that this difficulty further manifested itself in a marked deterioration of the timbre.

The acoustic impedance of the instrument with all its tuning slides fully "in" was measured for both of the above cases, and the results are shown in Figure 35. The plots are similar, but the fundamental of G2 (which is the second maximum) is flatter by 6 Hz. when using the slide. There are also differences between the amplitudes of the maxima, but the present study will be confined to matching the frequencies of the fundamentals as closely as possible for the two cases.
The need to do so is explained by Benade[41]. When using the valve to play G2 the fundamental is too flat for a truly successful regime of oscillation. What is required then is to raise the frequency of the fundamental when the valve is used without altering the positions of the higher maxima.

A computer program (FSPECT) calculates, using Worman's equation, the internal spectrum for any playing frequency, in particular the ones predicted by the Sum Function (obtained by running FSUM). When the Sum Function is calculated for the bass trombone using the valve it is found that at high dynamic levels the playing frequency is 103 Hz., but at low levels it falls to 94 Hz. and the internal spectrum envelope deteriorates considerably (see Figure 36). Interestingly the change of playing frequency also occurs when 4th position is used, indicating that the possibility still remains of effecting further improvement to the whole instrument.

A perturbation theory exists to move the positions of the resonances of the trumpet [1] and a simple scaling procedure enables it to be used for a trombone. Clearly it is necessary to restrict the changes only to the G valve section so that the parts common to the Bb and G instruments are unaffected. Calculations [46] indicated that a 9% reduction in the cross-sectional area of the tube forming the G valve was required. A new section was therefore fitted by Boosey and Hawkes, and the impedance re-measured. The results indicate a considerable improvement although the fundamental is still 3 Hz too flat (see Figure 37).

To determine whether any real subjective improvement had been made, a professional bass trombone player (P.H.) was invited,
during the course of an extended subjective experiment, to compare this instrument with an unmodified one whose impedance was measured and found to be identical (within experimental error) to that of the original instrument before modification. The player wore a blindfold and heavy gloves during the experiment, and the slides of both instruments were cleaned and oiled so that they felt as similar as possible. This precaution is taken since it is known that musicians are strongly influenced by the slide quality [37]. The experiment was conducted by presenting the player with a pair of instruments sequentially. Each pair was either a repetition of a given instrument or the two different instruments. The player was then instructed to play the note G2 under both conditions (i.e. with and without the valve) on the instruments and then state whether he thought they were the same or different. If he thought they were different he was then asked which one of the pair he preferred. During extensive trials he was always able to distinguish between the two instruments, and always correctly identified the repetitions. He referred to the unmodified instrument as "stuffy", "dull", and "hard to play" when using the valve. He greatly preferred the modified instrument and stated that the two playing conditions were "as closely matched as possible".

This study has used the impedance of an instrument as a diagnostic tool, and has therefore successfully implemented the improved design procedure outlined in Figure 3. Additionally this result is in good agreement with Hypothesis (b).
4.6 A comparative study of seven medium bore trombones

The nature of the two preceding case histories has been illustrative rather than exhaustive. It could be argued, for example, that the differences in quality of the two tenor trombones were due to the small discrepancies in the location of the impedance maxima in the frequency domain. Alternatively, for the case of the bass trombone, the differences in quality might be related to the nature of the differences of the amplitudes of the impedance maxima (i.e. the envelope formed by a locus passing through the maxima).

An examination of the factors required for a stable regime of oscillation indicates that both the amplitude and the frequency location of the maxima are important in determining the overall quality of a trombone. For this reason it was decided to perform a more comprehensive study of instrument quality using a larger sample of instruments.

4.6.1 Hypothesis (c)

The Sum Function is essentially a combination of Hypotheses (a) and (b). If for a given instrument the peaks of the Sum Function are well defined and high in amplitude, then both of the corollaries given in Section 4.4 are (at least partially) satisfied, and the instrument might reasonably be expected to possess stable regimes of oscillation. This proposal will be referred to as Hypothesis (c).

4.6.2 Selection of the instruments

At the request of Boosey and Hawkes the study was carried out on a range of medium bore tenor trombones. The seven instruments
used are given below, together with their retail prices at 1/5/77 (including case):

(a) Boosey and Hawkes prototype

(b) Conn 5H

(c) Holton Collegiate

(d) King 2B

(e) Lafleur

(f) Vincent Bach 12

(g) Yamaha YSL 651

£315

N/A

£310

£140

£430

£290

The Holton belongs to the author, and the remaining instruments were kindly loaned by Boosey and Hawkes.

4.6.3 Objective measurement

The instruments were measured using the impedance measurement system, and the results are given in Figures 38 to 44. Also included are the frequencies and amplitudes at maximum and minimum values for $|Z|$, the Q's of the maxima, and a plot of the Sum Functions.

4.6.4 Subjective assessment

Three of the instruments (the Boosey and Hawkes prototype, the Conn 5H and the King 2B) were assessed by three players, and their results have been discussed in Section 3.11.3. Although the players had difficulty in distinguishing between instruments, the results, where statistically significant, did indicate that J.M.B. rated the Boosey and Hawkes prototype both "stuffier" and of "less pleasant timbre" than the other two instruments.

Five instruments were subsequently tested by a professional
session player (C.S.), whose results were presented in Figure 30. This player was in fact able to identify by make each instrument as it was presented to him by his blowing only one or two notes for just a few seconds. He made only one identification error in a total of 72 separate presentations. It follows therefore that when he used the rating scales the fact that he did not always discriminate between certain instruments does not imply that he was incapable of doing so, merely that he felt that those particular instruments were evenly matched with respect to that attribute.

The Lafleur and the Holton were not used at this stage for subjective assessment experiments, and there were two reasons for this:

(a) Time: the experimental time must be kept within reasonable limits to avoid player fatigue, and this precludes the assessment of all seven instruments by a single player;

(b) Distinguishing features: the large spacing of the handgrips of the Lafleur made it readily identifiable even when wearing gloves. The Holton had a rather distinctive odour (as a result of being kept in a somewhat musty case) which proved impossible to remove despite a thorough cleaning.

The Lafleur is the cheapest model available on the British market, and the Holton Collegiate is believed to have been discontinued.

4.6.5 Comparison with objective Hypotheses (a) to (c)

In this Section the results of the subjective trials carried out on C.S. will be compared with the three Hypotheses relating to
4.6.5.1 Hypothesis (a)

First consider the impedance curves for the Bach 12 and the Boosey and Hawkes prototype (shown together in Figure 45). These instruments were rated "best" and "worst" respectively for both timbre and ease of playing. However in this case the overall impedance level of the Bach is lower than for the Boosey and Hawkes prototype, in contradiction to Hypothesis (a). As further evidence of the breakdown of Hypothesis (a), compare the impedance of the King with that of the Boosey and Hawkes prototype (see Figure 46). The differences in level are very small indeed, but the subjective difference as judged by C.S. is very large.

4.6.5.2 Hypothesis (b)

The degree of harmonicity to which the impedance maxima are aligned is computed as part of an analysis program FPEAKS (see Section 4.7). If the frequency of the $n^{th}$ maxima is divided by $n$, a set of frequencies of approximately 60 Hz. is obtained (excluding the first maximum which is not "used" for playing). The standard deviation (S.D.) of this set of numbers represents the degree of harmonicity of the maxima, and the smaller the S.D. the greater the degree of harmonicity. The values for the S.D.'s of the seven instruments is given in Figure 47. When compared with the ratings of C.S. it will be seen that the result is not in agreement with Hypothesis (b).
4.6.5.3 Hypothesis (c)

The Sum Function for the Boosey and Hawkes prototype and the King are given in Figure 48. The degree of similarity is quite remarkable, yet C.S. greatly preferred the King. This result does not appear to lend support to hypothesis (c).

4.6.6 Comparison with straight tubes

To demonstrate conclusively the inadequacy of Hypotheses (a) to (c), it is helpful to consider the acoustical properties of straight tubes. The impedance of a tube 1.42m long and diameter 5.45mm has already been given in Figure 20. The overall amplitude level of the maxima is high and since the degree of the harmonicity of the maxima is reasonably high, the peaks of the Sum Function for the tube are comparable with those of a trombone (see Figure 49). However the ease of playing and the timbre of a straight tube are non-existent and appalling respectively. In addition it is possible to "play" the tube at frequencies where the Sum Function is far from its maximum value. Thus the most unplayable "instrument" comes out best using the objective Hypotheses: clearly these Hypotheses must be revised in the light of such evidence.

4.7 Search for alternative hypotheses

With the breakdown of the three Hypotheses for instrument quality, new hypotheses were sought. Features of the impedance curves that have not yet been incorporated in any of the above Hypotheses are the Q's of the maxima, and the envelope of the impedance curve. Benade [47] has stated that the Q's of the maxima are high
for instruments that are easy to play, and low for stuffy instruments. The Q's for the maxima of the seven instruments are given in Figure 47. These results, compared with the ratings of C.S., do not support Benade's assertion. A more formal analysis (i.e. rank order correlation is not possible since only the Boosey and Hawkes Prototype was rated stuffier than the remaining four instruments.

Attention was then turned to the envelope of the impedance curve. This is a sensible feature of the curves to study since it forms the basis of the formant theory for timbre. In addition the spectrum of a trombone note is related to the magnitude of the impedance at integral values of the playing frequency, and thus the envelope of the impedance curve plays an important part in determining the spectrum of a note.

Accordingly the impedance curves were submitted to a Profile Factor Analysis (PFA), similar to the analysis used by Medin and Goude [33]. The data required are the values of the impedance for the first twelve maxima. This information is used to form a correlation matrix which is then reduced to a specified number of factors. The results showed that the first factor accounted for 94% of the variance, and hence by multiplying the factor loadings for each instrument by the raw data (the values of the impedance maxima), a Factor Profile may be obtained (see Figure 50). The Factor Loadings for each instrument are given in Figure 47. Note that with the exception of the relatively high placing of the Boosey and Hawkes prototype, these results represent the best correlation to the subjective assessment of C.S. that has so far been obtained. A clearer picture is obtained if the nature of the envelopes is examined. From Figure 50
it may be seen that the Factor profile may be thought to consist of three sloping lines joining maxima 2 to 5, 6 to 8 and 9 to 12 respectively. From a purely visual inspection of the impedance curves for the seven instruments it appears that the steepness of the slopes and the magnitude of the impedance at the point of intercept on the impedance axis correlate to some degree with subjective quality. Although there is no appropriate formal analysis procedure to investigate this phenomenon, Dr. J. M. Bowsher has written a program (FPEAKS) which fits three straight lines to the impedance curve of an instrument, and calculates the three slope and intercept values. An instrument is then awarded points relating to the steepness of the slopes and the intercept amplitudes. If these points are then summed, the following rank order emerges: King 2B, Conn 5H, Holton Collegiate, Vincent Bach 12, Boosey and Hawkes prototype, Lafleur, Yamaha. It should be stressed however that this procedure is purely empirical, and the nature of a physical mechanism capable of relating subjective quality to the impedance envelope is at present unknown.

4.8 Further evidence supporting the subjective assessment results

The main weakness of the preceding analysis has been the use of the results of only one player (C.S.). This was necessary due to the poor discriminatory powers of the other players, who produced results of very little statistical significance. Since completing this experimental work a survey has been conducted [48] on the popularity of various trombones by issuing a questionnaire to professional trombone players in the London area. The results for the relevant medium bore instruments are reproduced, by kind permission of the
author, in Figure 51 and are not entirely in agreement with the opinions of C.S. It should be remembered however that other factors, for example cost, are involved in a player's selection of his own instrument. The results of the survey relate well to the rank order produced by the analysis program FPEAKS.

4.9 An examination of the effect of certain parameters on quality

During the course of this work, some eighty impedance curves have been measured for a variety of instruments under a series of different conditions. In the following Sections the effects, both objective and subjective, are described. In some cases the results are readily interpretable in terms of theories which are currently available. However the considerable amount of completely new impedance data created as a result of this study has given rise to a number of interesting observations which cannot, at present, be explained.

4.9.1 Internal bore cleanliness

Opinion is divided as to the ideal condition of the internal bore section. It might be argued that a clean, well polished section was desirable since it would introduce lower losses and hence lower the damping. Brass players in general do not favour brand-new instruments, and refer to a period of blowing-in that must be endured before the instrument performs to their satisfaction.

Subjective assessment of an instrument before and after cleaning cannot be performed in the usual way, since it is not possible to present a series of pairs for comparison. It is possible however
to measure the impedance of an instrument in these two conditions. The instruments used were a Boosey and Hawkes Sovereign (silver plated) and an alto trombone in Eb. The Sovereign had been on loan for two years (without being cleaned) at the time of the measurement. A modified version of the program used to control the apparatus was written which enabled the frequency at which an impedance measurement was to be taken to be entered manually via the keyboard. Using this program (FCOMP) the frequencies of the impedance maxima were quickly found, and their amplitudes recorded. The instrument was then cleaned in soapy water at room temperature \((21^\circ C)\), and the amplitudes of the maxima were re-measured (see Figure 52). Note that after cleaning the maxima increased in amplitude very slightly, with the exception of the fourth (240 Hz.) maximum which increased in value by approximately 20%.

The alto was tested in the same way, and the results are given in Figure 53. A similar trend emerges, but here the third harmonic (242 Hz.) is raised by 13%. It is impossible to draw any firm conclusions from these results since the distribution of dirt throughout the instrument was unknown at the start of the experiment. One might have expected such an effect to depend on the mode number, but it appears to be constant with frequency. This region at around 240 Hz. seems particularly sensitive to change of any description since the difference in amplitude with and without the valve for the maxima of a bass trombone is also of the order of 25% (see Section 4.5.2.).

4.9.2 The mouthpiece
4.9.2.1 Theoretical inclusion of the mouthpiece cup volume

In Section 2.3., it was mentioned that although the primary plane of measurement used is that of the mouthpiece throat, the contribution of the cup volume may be included theoretically. This is accomplished by terminating the mouthpiece throat with a series LCR circuit, as given by Backus [5].

A program (FMPIECE) has been written by S.J. Elliott which allows the user to enter values for the cup volume, throat diameter, backbore length and series resistance. The instrument data files may then be transformed accordingly, and the values for impedance thus obtained represent the input impedance seen at the mouthpiece rim. The results showing the effect of a typical mouthpiece cup (Dennis Wick 9BS), are compared with the raw data for the Boosey and Hawkes prototype in Figure 54. These results will be discussed more fully in Chapter 5.

4.9.2.2 Throat diameter

The availability of a range of Dennis Wick mouthpieces allowed a study of the effect of throat diameter on the impedance of an instrument to be performed. Two mouthpieces, a 6BS and a 9BS, whose diameters are 6.7 and 6.8mm respectively (at the plane of measurement), were fitted to the Boosey and Hawkes prototype and the resulting impedance curves are given in Figure 55. To determine whether such a small (but measurable) difference in impedance could be detected by players, a subjective assessment experiment was devised.
4.9.2.3 Subjective experiments

One professional bass trombone player (P.H.) and one semi-professional player (J.M.B.) took part in a subjective experiment to discover the subjective importance of both the mouthpiece cup-volume and the throat diameter. This experiment is facilitated by the Giardinelli range of mouthpieces. This manufacturer has adopted the sensible practice of making the mouthpiece rims detachable. Thus the player is able to select a rim that he finds comfortable, and then a suitable body may be chosen from a large range whose parameters (such as cup volume and throat diameter) have been systematically selected. Should the player require, for example, a larger cup-volume only, then it is possible to select a different body which has a larger cup-volume whilst maintaining the same throat diameter. This body is then used in conjunction with the selected rim.

Three different bodies were tested (the rim being the same in all cases) by the players using their own instruments; and in this test they were free to use the slide. A series of paired comparisons were made by the players who were blindfolded. As a further precaution against identification the mouthpiece bodies were kept in a water bath set at 37°C. The cup volumes and throat diameters of the test bodies are given, together with the results of the trials, in Figure 56. It may be seen that neither player was able to discriminate between any of the mouthpiece bodies reliably. Since the variations of the throat diameters of the bodies used in this experiment (4.3%) are considerably greater than the differences in diameter for those shown in Figure 55 (1.5%), it would appear that the apparatus is more sensitive than the players to changes in throat diameter.
4.9.3 The mouthpipe

The mouthpipe is a venturi-shaped section into which the mouthpiece fits (see Figure 1). The mouthpipe of the Boosey and Hawkes Sovereign is 200mm long, and the cross-sectional area is reduced by 8% at the narrowest part.

The magnitude of the variation in impedance introduced by the mouthpipe may be demonstrated by comparing the impedance of a Boosey and Hawkes Sovereign trombone with the slide removed, with that of a straight tube of same average diameter and identical length (see Figure 57). A perturbation theory has been developed that allows the intonation of a brass instrument to be altered by changing the mouthpipe section. A change of less than 0.2mm over a length of 0.9m is all that is needed to alter the position of a maximum by 5 cents (or approximately 1 Hz. at 240 Hz.) [4].

4.9.4 Gross distortion to the tuning slide

During the three years of experimental work only one accident has resulted in damage to an instrument; the author's Holton was knocked off a bench onto the floor. It landed on the tuning slide, squashing it considerably. The cross-sectional area was reduced by about 50% over a length of 20mm. This provided a good opportunity to examine an instrument with gross perturbations. The instrument was re-measured and no discernable change in impedance was observed (see Figure 58).

This result might at first seem surprising in the light of the remarks made in the last Section, but it should be remembered that the length over which perturbations are intentionally applied is
typically 200mm, the entire length of a mouthpipe. For maximum effect the perturbations should be applied over a distance of half a wavelength of the frequency in question [46]. Thus although pressure nodes exist near this point for the fifth, eighth and ninth modes, and anti-nodes exist for the third, seventh and tenth modes, for the damaged instrument the length of the perturbation is such that the maximum effect will occur at a frequency of 8.55 KHz, which is much higher than that of the impedance maxima. A perturbation of length 20mm would appear in practice to be negligible at the frequencies of interest.

4.9.5 Material finish

The results of a subjective assessment experiment which was partly concerned with finish have already been given in Figure 34. From these results it is clear that the players tested were unable to distinguish between laquered and silver-plated finishes.

A similar experiment was conducted on a professional bass trombone player (P.H.), using two identical laquered Sovereigns and the silver-plated Sovereign, but he also was unable to distinguish between any of the three instruments.

Using the program FCOMP it was possible to measure differences between all three instruments, and these results are given in Figure 59. Here again the impedance measurement system appears somewhat more sensitive than the players.

4.9.6 D.C. airflow

As Backus has noted, a d.c. airflow reduces the Q's of the
impedance maxima [14]. The impedance of the (undamaged) Holton was measured at the reference d.c. airflow setting of 2 m.s\(^{-1}\), and at the higher value of 10 m.s\(^{-1}\). The result is shown in Figure 60, and is in general agreement with those of Backus. Furthermore the reduction in amplitude that occurs predominantly at lower frequencies was predicted theoretically by Trimmer [49] in 1937. The magnitude of the airflow is such that the frequencies of the impedance maxima are not significantly affected. The reduction in frequency is just observable using the program FCOMP. If the frequency of a maximum is entered via the keyboard, and the airflow setting increased, then a slight increase in the phase angle will be observed indicating a lowering of the frequency of the maximum.

4.9.7 Slide position

The subjective experiments carried out on trombones required the slide to be locked since players might use the feel of the slide action to discriminate between instruments. Consequently the impedance measurements were also made with the slide in this position.

For two of the instruments, the Bach and the King, the impedance was measured in slide positions 1, 3, 5 and 7, and the results are shown in Figures 61 and 62. The amplitudes of the maxima are in general decreased as the instrument length (and hence the losses) increases. Note also that the combined envelope of the four slide positions is similar to the Factor Profile given in Figure 50.
4.10 Summary

A discussion of the sound production mechanism of brass instruments resulted in the formulation of three simple Hypotheses concerning instrument quality. Some preliminary experiments appeared to confirm these Hypotheses, but a more systematic study illustrated their limitations. Several other factors were considered, and a relationship between impedance envelope and subjective quality was discussed.

The effect of varying a range of parameters was investigated both subjectively and objectively. The sensitivity of the impedance measurement system was found in all cases to be greater than the discriminatory powers of the players participating in the subjective trials.
5.1 Improving the impedance measurement system

The accuracy of any measurement system becomes of critical importance when the differences between the variables to be measured is small. In this Section ways in which the accuracy of the impedance measurement system may be improved will be discussed.

Typical values for the repeatability of the system are given in Section 2.14.2. The frequency location of the impedance maxima for a repetition of a given instrument never differed from the original by more than 0.5%, and it may be shown that such changes in frequency correspond to a change in ambient room temperature of less than 1%. Thus either the room temperature must be controlled more closely than within two degrees (which is not possible in this instance), or the experimental time must be reduced in order that changes in ambient temperature become insignificant.

This reduction in experimental time may be accomplished if one of the alternative excitation methods described in Section 2.11 is used. The implementation of either the impulse or broadband excitation method would enable the experimental time to be reduced from the 4½ hours currently needed for the stepped sine wave method (see Section 2.11), to only a few minutes. By appropriate adjustment of the sampling rate and time, the upper frequency limit and the resolution may be increased. This would enable a more accurate value for the Q's of the impedance maxima to be calculated.

For a 2-port network the best estimate of the input impedance may be shown to be [50]:

5-1
\[ Z(f) = \frac{G_{pu}(f)}{G_{uu}(f)} \]

where \( G_{pu}(f) \) is the cross-spectral density of pressure and volume velocity;
and \( G_{uu}(f) \) is the auto spectral density of the volume velocity.

5. Plane of measurement

The selection of the mouthpiece throat as the primary measurement plane was discussed in Section 2.3, and a procedure for including the effect of the mouthpiece cup-volume theoretically was outlined in Section 4.9.2.1.

The apparatus was designed in such a way as to allow measurements in the plane of the mouthpiece rim to be made, but the reduced particle velocity resulted in a very noisy signal from the hot-wire anemometer. As a consequence only one instrument was measured in this way and the result (for the Boosey and Hawkes prototype) is given in Figure 63. Although the amplitude information is subject to increased error, the frequency location of the impedance maxima is thought to be relatively unaffected.

The Sum Function was computed for the Boosey and Hawkes prototype when measured under the following conditions:

(a) in the plane of the throat;
(b) in the plane of the rim;
(c) as (a), but including theoretically the cup volume.

The results, together with the playing frequencies obtained by the three players, are shown in Figure 64. The players consisted
of a semi-professional player (J.M.B.), a trumpet player (P.S.W.) and the author (R.L.P.). The reasons for including players unfamiliar with the type of instrument under study, and inexperienced players, is that they will probably perform less "lipping" and are thus more likely to play the "true centre" of a note [16].

There are two interesting facts that emerge from these results. Firstly, the agreement of the frequency location of the impedance maxima for the cases (b) and (c) above is good, which supports the theoretical circuit of Backus [5]. However the amplitudes are not in good agreement (compare Figures 54 and 63), due probably to the poor signal-to-noise ratio of the velocity signal. Secondly, the results of the playing frequencies are subject to large variations, and are bracketed by the Sum Function frequencies obtained from the throat and rim impedance measurements. The large deviation of playing frequencies that are observed between different players (and indeed between successive trials involving only one player) has been comprehensively studied by Wogram [16].

5.3 The time domain behaviour of a trombone

Since the modulus and phase of the input impedance have been measured, it is possible to compute (using the program FIMPULSE), for the first time, the pressure waveform as measured in the throat resulting from an impulse (delta function) of volume velocity, by performing an inverse Fourier Transform on an instrument data file.

This technique may be employed to examine Benade's theory that a stuffy instrument is one that suffers from premature reflections [47]. Figure 65 shows the pressure response of the Holton Collegiate
before and after it was damaged. The vertical lines indicate multiples of the throat-to-damaged section round trip times. The lack of an echo is due to the short length (20 mm) over which the damage occurred (despite the massive 50% reduction in cross-sectional area), although Benade states that "for a 10% reduction in the cross-sectional area over a length of 20 mm, the reflected wave is 7% at 330 Hz." [51].

5.4 Subjective assessment

An important question concerning the subjective assessment experiments remains unanswered, namely why was the professional session player (C.S.) much more competent at discriminating between instruments? Undoubtedly his greater experience was an important factor, but it must be remembered that the student players were not familiar with medium bore instruments, nor were they permitted to use their own mouthpieces.

Results of a subjective assessment experiment carried out on a brass band player (L.P.), using his own mouthpiece, are presented below. Five instruments were used, the Boosey and Hawkes prototype, King 2B, Holton Collegiate, Lafleur and Yamaha YSL 651. The scores are given together with their analysis in Figure 66. Not only was this player able to discriminate between instruments just as clearly as C.S., but also his assessment of the three instruments common to both players (Boosey and Hawkes prototype, King 2B and Yamaha YSL 651) is very similar to that of C.S. Both preferred the King 2B to the Boosey and Hawkes prototype, and L.P.'s preference of the Yamaha over the King is explained by the fact that he plays a
Yamaha YSL 651 and is therefore accustomed to its feel and timbre.

It is also interesting to note that the two instruments rated only by L.P., the Holton Collegiate and the Lafleur, had the "worst" and "best" harmonicity of the impedance maxima respectively (see Figure 47), and this fact appears to have had a strong influence on his judgement.

5.5 Conclusion

The work described in this thesis has been concerned with establishing a relationship between the subjective quality and the geometry of an instrument. During the course of this work a number of relationships proposed by other workers has been examined in detail, but none of them was found to be entirely satisfactory (see Sections 4.6.5.1 to 4.6.5.3). The experiment conducted on the player L.P. (see Section 5.4) appears to support the hypothesis that the harmonicity of the impedance maxima is important for a good instrument (Hypothesis (b)). However when a selection of instruments whose degree of harmonicity is comparable is made, then the results of C.S. (see Section 3.11.4) suggest that a quality criterion related to the impedance envelope is adopted (see Section 4.7).

The study of that humble acoustical system, the straight tube, has proved particularly rewarding. Theoretical estimations of its impedance have allowed a valuable check on the performance of the measurement system to be obtained. In addition the playing properties of the tube are not consistent with the non-linear regeneration theories of Benade and Gans [45], nor with the Sum Function concept of Wogram [16]. It is tempting to speculate on the outcome of
their researches had they considered the properties of the straight tube more fully.

Clearly much work remains to be done before the relationship between the subjective quality and the geometry of an instrument is understood, but with the completion of this thesis the first steps have been taken.
APPENDIX A  DISK FILE TITLES

All the instrument data files stored on disk have a six character title, e.g.

5BP91C

The first character denotes the bore size:

5 = Medium bore (typically 0.500 inch)
T = Tenor symphony bore (typically 0.547 inch)
B = Bass bore (typically 0.562 inch)

The second and third characters denote the make:

BP = Boosey and Hawkes prototype
CO = Conn
HO = Holton
KI = King
LF = Lafleur
VB = Vincent Bach
YM = Yamaha

The fourth character denotes the (Dennis Wick) mouthpiece type:

for medium bore instruments:

5 = 5BS
6 = 6BS
9 = 9BS

for large and bass bore instruments:

4 = 4AL
5 = 5AL
6 = 6BL

The fifth character denotes the slide position.

The sixth character denotes the repetition serial letter.
APPENDIX B MUSICAL IMAGERY

In Chapter 1 the subjective quality of an instrument was described as a "player's or listener's personal assessment of an instrument, including such factors as timbre, responsiveness and intonation." The methods used for assessing these factors quantitatively were given in Chapter 3. The ability of subjects to discriminate between stimuli is, a priori, likely to depend on various other aspects of the subject's "musicality", such as musical imagery and musical memory, which vary widely between individuals [52]. A questionnaire (see Figure 67) was therefore devised that would give quantitative measures (using SD scales) of certain aspects of musical imagery. This questionnaire was completed by subjects participating in Experiment 2, and by C.S., and L.P.

It was hoped that subjects who used the SD scales in Experiment 2 with the minimum of scatter when rating repetitions of a given sound would prove outstanding in one (or even all) of the aspects of musical imagery listed in the questionnaire, thus enabling future reliable raters to be selected on their performance on the questionnaire.

In order to discover whether such a relationship existed, a "Scatter Coefficient" (S.C.) was computed for each subject. The S.C. was formed by summing the standard deviations of the scores of the repetitions for each of the 16 sounds (for both SD scales) divided by the total range used by the subject when rating that sound. A low S.C. means that the subject was using the SD scales in a consistent manner when presented with repetitions of a given sound. If the
S.C. is high the subject was experiencing difficulty discriminating between the sounds.

This S.C. was correlated with subjects' scores on questions 1 to 5 of the questionnaire (0 - 100 measured from left to right), and in none of the five cases was the correlation significant. C.S. did not experience vivid musical imagery (his score for question 1 being zero), but L.P. scored 70.

Thus it would appear that the subjects who are most able to use SD scales to discriminate between stimuli are not necessarily those who consider themselves to possess a high degree of musical imagery.
APPENDIX C PROGRAM LISTINGS

The operation of FRUN, the program used to control the experiment and collect and analyse the data, has already been given in detail in Section 2.12.

A number of programs mentioned in this thesis have been written to perform various operations on the instrument data files created by FRUN. The function of each program is given, and then all the listings are presented. Finally the two subroutines written in Data General Assembler language that control the analogue-to-digital and digital-to-BCD converters are given.

FDRAW: draws an instrument data file in either Modulus/Phase or Real/Imaginary form, together with appropriate axes.

FIMPULSE: computes and plots the impulse behaviour of an instrument by performing an inverse Fourier Transform on the data file.

FIND: locates and displays the maximum and minimum values for $|Z|$, together with the appropriate frequencies (in Hz. and musical notation), and computes the Q's of the maxima from the real part.

FKAL: samples the A/D converters into which the velocity signal from the hot-wire anemometer is fed for each turn of the needle valve. It then finds an optimum value for $p$, and computes the constants $A$ and $B$.

FMPiece (author S.J. Elliott): computes the effect of the mouthpiece cup volume and modifies the instrument files accordingly.

FPEAKS (author J.M. Bowsher): forms a rank order of
instruments based on their impedance envelopes.

FRUN: see Section 2.11.

FSPECT: calculates the internal spectrum directly from the values of impedance (modulus or phase) of integral values of the (user specified) playing frequency.

FSUM: computes the Sum Function as defined in Section 4.3.

ACQUIRE: Assembler routine which acquires data from two channels of the A/D converters.

SEND: Assembler routine which allows the frequency of the programmable frequency oscillator to be set.
DIMENSION Z(768),P(768),IZ(768),IP(768),IR(768),IM(768),NAME(10)

IT=15

1

READ(11,1) NAME(1)

1 FORMATT(820)

CALL FOPEN(1,NAME)

CALL FTDISP

CALL FTENCLEAR

CALL FTDISP

CALL FTPENCLEAR

ACCEPT"MODULE/PHASE (0) OR REAL/IMAGINARY (1)?",IANS

CALL RDBLK(1,0,Z,6,IER)

CALL RDBLK(1,6,P,6,IER)

DO 90 I=1,768

IZ(I)=Z(I)*0.7E-5

IP(I)=P(I)*111.41+185

IR(I)=IZ(I)*COS(P(I))+420

IM(I)=IZ(I)*SINC(P(I))+185

90 CONTINUE

IF(IANS.EQ.1) GO TO 50

CALL FTAPLOTC(160,IZ(10),1)

DO 91 I=11,768

CALL FTAPLOTC(150+I,IZ(I),0)

CALL FTAPLOTC(160,IP(10),1)

DO 92 I=11,768

CALL FTAPLOTC(150+I,IP(I),0)

GO TO 51

50 CONTINUE

CALL FTAPLOTC(160,IR(10),1)

DO 93 I=11,768

CALL FTAPLOTC(150+I,IR(I),0)

CALL FTAPLOTC(160,IM(10),1)

DO 94 I=11,768

CALL FTAPLOTC(150+I,IM(I),0)

51 CONTINUE

CALL FTAPLOTC(150,770,1)

CALL FTAPLOTC(150,418,0)

CALL FTAPLOTC(150,360,1)

CALL FTAPLOTC(150,10,0)

CALL FTAPLOTC(150,420,1)

CALL FTAPLOTC(950,420,0)

CALL FTAPLOTC(150,185,1)

CALL FTAPLOTC(950,185,0)

DO 95 I=1,5

IY=770-70*(I-1)

CALL FTAPLOTC(150,IY,1)

95 CALL FTAPLOTC(150+IT,IY,0)

DO 96 I=1,8

IX=100*I+150

CALL FTAPLOTC(IX,420,1)

96 CALL FTAPLOTC(IX,420+IT,0)

CALL FTAPLOTC(150,360,1)

CALL FTAPLOTC(150+IT,360,0)

CALL FTAPLOTC(150,12,1)

CALL FTAPLOTC(150+IT,12,0)

CALL FTAPLOTC(150,300,1)

DO 97 I=1,8

C-3
IX = 100*I + 150
CALL FTAPLOT(IX, 185, 1)
CALL FTAPLOT(IX, 185+II, 0)
CALL ZEROD(129, 390)
CALL ZEROD(226, 390)
CALL ZEROD(244, 390)
CALL ZEROD(262, 390)
CALL TWO(326, 390)
CALL THREE(344, 390)
CALL ZEROD(426, 390)
CALL ZEROD(444, 390)
CALL ZEROD(462, 390)
CALL FOUR(526, 390)
CALL ZEROD(544, 390)
CALL ZEROD(562, 390)
CALL FIVE(626, 390)
CALL ZEROD(644, 390)
CALL ZEROD(662, 390)
CALL SIX(726, 390)
CALL ZEROD(744, 390)
CALL ZEROD(762, 390)
CALL SEVEN(826, 390)
CALL ZEROD(844, 390)
CALL ZEROD(862, 390)
CALL EIGHT(926, 390)
CALL ZEROD(944, 390)
CALL ZEROD(962, 390)
CALL FREQU(650, 350)
CALL MEGOHM(35, 595)
CALL FIVE(111, 759)
CALL ZEROD(129, 759)
CALL FOUR(111, 689)
CALL ZEROD(129, 689)
CALL SEVEN(111, 619)
CALL ZEROD(129, 619)
CALL TWO(111, 549)
CALL ZEROD(129, 549)
CALL ONE(111, 479)
CALL ZEROD(129, 479)
CALL FTAPLOT(100, 310, 1)
CALL FTAPLOT(100, 270, 0)
CALL FTAPLOT(80, 290, 1)
CALL FTAPLOT(120, 290, 0)
CALL FTAPLOT(80, 100, 1)
CALL FTAPLOT(120, 100, 0)
IF(ISANS.EQ.1) G0 T0 52
CALL MODZ(35, 595)
CALL HPI(81, 350)
CALL RADFIC(35, 155)
CALL HPI(81, 0)
CALL FTCLEAR
STOP
52
CALL BIGRC(35, 595)
CALL TWO(111, 349)
CALL FIVE(129, 349)
CALL MEGOHM(35, 145)
CALL BIGX(35, 145)
CALL TWO(111, 0)
CALL FIVE(129, 0)
DIMENSION Z(0:512), P(0:512), R(0:512), RI(0:512), NAME(10), ARRAY(2050)
JFLAG=1

TYPE 'FILE TO BE INVERSE F.T.'D ?
READ(11,1) NAME(1)

1
FFORMAT (S20)
CALL FOPEN(1, NAME)
CALL FOPEN(0, "$TT01")
CALL FOPEN(2, "SWAPA")
CALL RDRLK(1, 0, Z, 4, IER)
CALL RDRLK(1, 6, P, 4, IER)
PIB2=1.570796
ONEMEG=1E6
DO 999 I=1, 512
J=512-I
Z(K)=Z(J)
P(K)=P(J)
999 CONTINUE
Z(9)=ONEMEG*1.7
Z(8)=ONEMEG*1.6
Z(7)=ONEMEG*1.5
Z(6)=ONEMEG*1.4
Z(5)=ONEMEG*1.3
Z(4)=ONEMEG*1.2
Z(3)=ONEMEG*1.1
Z(2)=ONEMEG*1.0
Z(1)=ONEMEG*0.9
Z(0)=ONEMEG*0.8
P(9)=PIB2
P(8)=PIB2
P(7)=PIB2
P(6)=PIB2
P(5)=PIB2
P(4)=PIB2
P(3)=PIB2
P(2)=PIB2
P(1)=PIB2
P(0)=PIB2
DO 9 J=1, 513
I=J-1
R(I)=Z(I)*COS(P(I))
RI(I)=Z(I)*SIN(P(I))
9 CONTINUE
DO 99 I=1, 513
J=2*I-1
L=I-1
K=2051-J
ARRAY(K)=-RI(L)
ARRAY(K-1)=R(L)
ARRAY(J)=R(L)
ARRAY(J+1)=RI(L)
99 CONTINUE
ARRAY(1)=0.0
ARRAY(2)=0.0
ARRAY(1026)=0.0
CALL DFT4C(ARRAY, 1024, JFLAG)
IF(JFLAG, NE, 0) STOP UNDERFLOW/OVERFLOW ERROR OCCURED IN FPIDFT
CALL WRBLK(2, 0, ARRAY, 16, IER)
CALL FSWAP(*FAXES.SV*)
STOP
END
DIMENSION Z(768), P(768), R(768), NAME(10)
IFLAG=0
TYPE "FILE TO BE SCANNED?"
READ(11,1) NAME(1)
1 FORMAT(S20)
ACCEPT "UPPER BOUND = ", BU, "LOWER BOUND = ", BL
BU=BU*1E6
BL=BL*1E6
CALL FOPEN(0, "$TT01")
CALL FOPEN(1, NAME)
WRITE(0,3)
3 FORMAT(1H1)
WRITE(0,2) NAME(1)
WRITE(10,2) NAME(1)
2 FORMAT(1, S20/)
CALL RDBL(1, 0, Z, 6, IER)
CALL RDBL(1, 6, F, 6, IER)
DO 99 I=10, 768
99 R(I)=Z(I)*COS(F(I))
I=10
91 IF (I, GT, 768) STOP
I=I+1
J=I+1
IF (IFLAG-1) 100, 200, 200
100 IF (Z(J), LT, Z(I), AND, Z(I), GT, BU) GO TO 30
60 TO 91
200 IF (Z(J), GT, Z(I), AND, Z(I), LT, BL) GO TO 31
60 TO 91
30 CALL FSTYPE(IFLAG, I, Z(I), R(I), R(I-5), R(I+5))
IFLAG=1
I=I-1
60 TO 91
31 CALL FSTYPE(IFLAG, I, Z(I), R(I), R(I-5), R(I+5))
IFLAG=0
I=I-1
60 TO 91
STOP
END
DIMENSION V(20), SNV(20), VS(20), U(20), PU(20), H(20)

COMMON/H/H

DATA H/0.05, 0.22, 0.5, 0.89, 1.41, 2.08, 2.91, 3.92, 
15.08, 6.37, 7.82, 9.33, 10.93, 12.56, 14.22, 15.75/

CALL FOPEN(0, "$TT01")
WRITE(0,22)
22 FORMAT(1H1)

JF=0
JHI=0
LO=0
N=16
R=0.0

ACCEPT 'TEMPERATURE (OHMS)/(DEG.C) ?.............', T
ACCEPT 'PRESSURE (MM. OF H.G.) ?.............', P

IF(T.GE.75.0) T=(T-100.0)/38.5*100.0
RK=SQRT(19.579739*(T+273.0)/(0.46446*P))
WRITE(10,100) T, P, RK

100 FORMAT(' TEMPERATURE = ', F5.2, ' PRESSURE = ', F6.1, ' K = ', F5.2)

DO 99 I=1, N
SNV(I)=I+2
PAUSE
CALL KAL(JHI, LO)
TOT=(JHI*32768.0+LO)/1024.0
V(I)=TOT*10.0/16384.0
VS(I)=V(I)**2
U(I)=RK*SQRT(H(I))
WRITE(10, 2) SNV(I), V(I), U(I)
WRITE(0, 2) SNV(I), V(I), U(I),
2 FORMAT(' NVS = ', F4.1, ' VOLTS = ', F5.3, ' VEL = ', F6.3)
CONTINUE

P=0.34

1 FORMAT(1H0, 'A =', F10.6, ' B =', F10.6, ' R =', F10.6, ' CL =', F10.1, ' P =', F6.2)

15 RS=R
P=P+0.01
DO 999 I=1, 16
PU(I)=U(I)**2
999 CONTINUE
CALL FLSQF(N, A, B, R, CL, VS, PU)
WRITE(10, 1) A, B, R, CL, P
WRITE(0, 1) A, B, R, CL, P
IF(JF.EQ.1) GO TO 5
IF(R.GE.RS) GO TO 15
P=P-0.02
WRITE(10, 11)
WRITE(0, 11)

11 FORMAT('/** AN OPTIMUM VALUE FOR P, AND CORRESPONDING VALUES FOR A, B, AND R ARE AS FOLLOWS**/

JF=1
GO TO 15
5 WRITE(0, 4)
WRITE(10, 4)
6 FORMAT(1H0)
WRITE(0, 100)
WRITE(0, 22)
TYPE "RESET THE NEEDLE VALVE"
STOP

C-8
DIMENSION Z(768), P(768), TZ(768), TP(768), NAME(10)

TYPE 'PROGRAM TO TRANSFORM IMPEDANCES WITH MOUTHPIECE MODEL'
TYPE 'FILE TO BE TRANSFORMED ?'
READ(11,1) NAME(1)

1 FORMAT(S20)
CALL FOPEN(1, NAME)
TYPE 'LETTER ADDED TO FILENAME ?'
READ(11,2) J

2 FORMAT(S1)
ACCEPT 'VOLUME OF CUP (C.C.) = ', V
ACCEPT 'EFFECTIVE LENGTH OF THROAT (M.M.) = ', EL
ACCEPT 'DIAMETER OF THROAT (M.M.) = ', D
ACCEPT 'RESISTANCE OF THROAT (MEG.OHM) = ', R
CALL RDBLK(1, 0, Z, 6, IER)
CALL RDBLK(1, 6, P, 6, IER)
DO 100 I = 10, 768
ZR = Z(I) * COS(P(I))
ZI = Z(I) * SIN(P(I))
WL = 8.88E-3 * I * EL / (D**2)
WC = 4.57E-11 * I * V
A = ZI + WL
B = ZR + R * 1E6
DEN = (1 - WC**2) + (WC*B)**2
TZR = B / DEN
TZI = (A * (1 - WC) - WC*(B**2)) / DEN
TZ(I) = SQRT(TZI**2 + TZR**2)
TP(I) = ATAN(TZI/TZR)
100 CONTINUE
NAME(J) = J
CALL FOPEN(2, NAME)
CALL WRBLK(2, 0, TZ, 6, IER)
CALL WRBLK(2, 6, TP, 6, IER)
STOP
END
DIMENSION Z(768), F(768), TZ(768), TP(768), NAME(10)

TYPE 'PROGRAM TO TRANSFORM IMPEDANCES WITH MOUTHPIECE MODEL'
TYPE 'FILE TO BE TRANSFORMED ?'

READ(11,1) NAME(1)
1 FORMAT(S20)

CALL FOPEN(1, NAME)

TYPE 'LETTER ADDED TO FILENAME ?'

READ(11,2) J

2 FORMAT(S1)

ACCEPT 'VOLUME OF CUP (C.C.) = ', V
ACCEPT 'EFFECTIVE LENGTH OF THROAT (M.M.) = ', EL
ACCEPT 'DIAMETER OF THROAT (M.M.) = ', D
ACCEPT 'RESISTANCE OF THROAT (MEG. OHM) = ', R

CALL RDBLK(1, 0, Z, 6, IER)

DO 100 I=10, 768

ZR=Z(I)*COS(F(I))
ZI=Z(I)*SIN(F(I))
WC=4.57E-11*V
A=ZI+WC
B=ZR+R
DEN=(1-WC*A)**2+(WC*B)**2
TZR=B/DEN
TZI=(A*(1-WC*A)-WC*(B**2))/DEN
TP(I)=ATAN(TZI/TZR)

100 CONTINUE

NAME(4)=J

CALL FOPEN(2, NAME)

CALL WRBLK(2, 0, TZ, 6, IER)

STOP

END
BSE=0.0
AT=0.0
BT=0.0
FS=0.0
FSS=0.0
DO 98 K=2,KM
FS=FS+F(K)/K
FSS=FSS+(F(K)/K)**2
98 CONTINUE
FM=FS/(KM-1)
FSD=SQRT((FSS-(FS**2/(KM-1)))/(KM-1))
DO 99 K=2,KM
KS=K-1
IF(F(K),GT,FL1) GO TO 400
SA=SA+F(K)
SB=SB+F(K)
SC=SC+F(K)**2
SD=SD+F(K)**2
99 CONTINUE
400 D=(KS-1)*SC-SA*SA
A=(SC*SB-SA*SD)/D
B=((KS-1)*SD-SA*SB)/D
DO 999 J=2,KS
999 S=S+(M(J)-A-B*F(J)**2
SE=S/(KS-3)
AE=SQRT(SE*SC/D)
BE=SQRT((KS-1)*SE/D)
IA=A+0.5
IB=-1000.0*E+0.5
AS=AS+IA-AL1
BS=BS+1000.0*E+IB
AT=AT+K-AL1/SE
BT=BT+(E-1)*BE
IF(I TEST.EQ.1) WRITE(0,2) KS,A,AE,B,BE
WRITE(10,2) KS,A,AE,B,BE
2 FORMAT(" HIGHEST PEAK = ",F2.0," INTERCEPT = ",F5.2," INT.ERROR=1,/",SLOPE="F8.4," SLOPE ERROR="F8.5,/
S=0.0
SA=0.0
SB=0.0
SC=0.0
SD=0.0
KK=KS+1
DO 101 L=KK,KM
LS=L-1
IF(F(L),GT,FL2) GO TO 401
SA=SA+F(L)
SB=SB+F(L)
SC=SC+F(L)**2
SD=SD+F(L)**2
101 CONTINUE
401 D=(LS-KS)*SC-SA*SA
A=(SC*SB-SA*SD)/D
IA=A+0.5
B=((LS-KS)*SD-SA*SB)/D
IB=-1000.0*E+0.5
DO 1000 J=KK,LS
1000 S=S+(M(J)-A-B*F(J)**2
SE=S/(LS-KS-2)
AE=SQRT(SE*SC/D)
BE = SQRT((LS - KS) * SE / D)
AS = AS + IA - AL2
BS = BS + IB + 1000 * BL2
AT = AT + (A - AL2) / AE
BT = BT + (BL2 - B) / BE
IF (TEST.EQ.1) WRITE (0, 2) LS, A, AE, B, BE
WRITE (10, 2) LS, A, AE, B, BE
S = 0, 0
SA = 0, 0
SB = 0, 0
SC = 0, 0
SD = 0, 0
LL = LS + 1
DO 102 N = LL, KM
SA = SA + FC(N)
SB = SB + MC(N)
SC = SC + FC(N) * MC(N)
SD = SD + FC(N) * MC(N)
102 CONTINUE
D = (KM - LS) * SC - SA * SA
A = (SC * SB - SA * SD) / D
IA = A + 0.5
B = (KM - LS) * SC - SA * SB / D
IB = B + 1000 * B + 0.5
DO 1001 J = LL, KM
1001 S = S + (M(J) - A - B * FC(J)) ** 2
SE = S / (KM - LS - 2)
AE = SQRT(SE * SC / D)
BE = SQRT((KM - LS) * SE / D)
AS = AS + IA - AL3
BS = BS + IB + 1000 * BL3
AT = AT + (A - AL3) / AE
BT = BT + (BL3 - B) / BE
IF (TEST.EQ.1) WRITE (0, 2) KM, A, AE, B, BE
WRITE (10, 2) KM, A, AE, B, BE
WRITE (10, 4) AS, BS, AT, BT, FM, FSD
IF (TEST.EQ.1) WRITE (0, 4) AS, BS, AT, BT, FM, FSD
CALL FCLOSE (1, NAME)
IF (0, EQ. 0) GO TO 5
IF (TEST.EQ.1) WRITE (0) "<14;" 0 = 0
GO TO 50
STOP
END
DIMENSION IDATAC(5000), VP(50), VU(50), U(50), NAME(20)
DIMENSION PASCC(768), VOLU(768), Z(768), PHASE(768)
PI=3.1415926535
N=12
NBLN=0
CALL SENDC(10)
TYPE*FILENAME ?
READ(11,1) NAME(1)
1 FORMAT(S20)
CALL FOPEN(1, NAME)
IF(LEV. EQ. 130) CONST=31.7/0.05
IF(LEV. EQ. 140) CONST=31.7/0.268
IF(LEV. EQ. 150) CONST=31.7/0.085
PAUSE MOUTHPIECE
DO 9 L=10,768
PRESS=0.0
CPRESS=0.0
US=0.0
ZMEG=0.0
PH=0.0
PHM=0.0
CALL SENDC(L)
CALL FDELYC(3000)
SAM=50000.0/L
ISAM=SAM
DO 19 IFR=1,N
199 ISTEP=2
ISTEP=ISTEP/2
CALL ACQUIRE(ISAM, IDATAC(1))
2 IF (INUM.LT.50) GO TO 3
INUM=INUM/2
ISTEP=ISTEP*2
GO TO 2
3 CONTINUE
DO 29 I=1, INUM
J=(I-1)*ISTEP+1
K=J+1
VP(I)=IDATAC(J)/1638.4
VU(I)=IDATAC(K)/1638.4
U(I)=(B*VU(I)*VU(I)+A)**(1.0/F)
29 CONTINUE
CALL FUND(INUM, VP, PRMS, PPH)
CALL FUND(INUM, U, URMS, UPH)
CALL FPCALC(L, AM, PE)
P1=CONST*PRMS
DE1=20.0*ALOG10(P1/0.00002)+AM
CF1=0.00002*10.0**(DE1/20.0)
US1=URMS*PI*DO/4E6
IF(US1.LE.1.0E-6) GO TO 199
ZMEG1=CF1/(US1*1E6)
PRESS=PRESS+P1
CPRESS=CPRESS+P1
US=US+US1
ZMEG=ZMEG+ZMEG1
PH1=(FPH-UPH)*(-1.0)+PE+PI
7 IF(PH1.GT.PI) PH1=PH1-2.0*PI
IF(PHI.LT.-PI) PHI=PHI+2.0*PI
IF(PHI.GT.PI.OR.PHI.LE.-PI) GO TO 7

PH=PH+PI
WRITE(10,50) ZMEG1, DB1, PHI, US1


CONTINUE
PASC(L)=CPRESS/N
Z(L)=ZMEG6/N*1E6
ZED=ZMEG6/N
PDB=20.0*ALOG10(PASC(L)/0.00002)
VOLU(L)=US/N
PHASE(L)=PH/N

77 IF(PHASE(L).GT.PI) PHASE(L)=PHASE(L)-2.0*PI
IF(PHASE(L).GT.PI) GO TO 77

WRITE(10,10) L, ZED, PHASE(L), PDB, VOLU(L)


CONTINUE
CALL WRBLK(1, IBLN, Z, 6, IER)
JBLN=IBLN+6
CALL WRBLK(1, JBLN, PHASE, 6, IER)
KBLN=JBLN+6
CALL WRBLK(1, KBLN, PASC, 6, IER)
LBLN=KBLN+6
CALL WRBLK(1, LBLN, VOLU, 6, IER)
CALL FSTAT(1, 3, IER)
CALL FCLOS(1)
CALL SEND(10)
STOP
END
DIMENSION Z(768), P(768), SR(768), SM(768), NAME(10)

Type 'File to obtain spectrum?'

READ(11,1) NAME(1)

1 FORMAT(S20)

CALL FOPEN(1,NAME)

ACCEPT 'Playing frequency = ', IFR

ACCEPT 'Real (0) OR Modulus (1) ', IANS

CALL RDBLK(1,0,Z,6,IER)

CALL RDBLK(1,6,P,6,IER)

DO 99 I=IFR,768,IFR

SM(I)=Z(I)

SR(I)=Z(I)*COS(F(I))

99 CONTINUE

NAME(4)="F"

CALL FOPEN(2,NAME)

IF(IANS.EQ.0) CALL WRBLK(2,0,SR,6,IER)

IF(IANS.EQ.1) CALL WRBLK(2,0,SM,6,IER)

STOP

END
DIMENSION Z(768), P(768), R(768), RF(768), NAME(10)

TYPE 'FILE TO BE SUMMED ?'
READ (11, 1) NAME(1)

1 FORMAT (S20)
ACCEPT 'INDEX OF WEIGHTING FUNCTION? ', RK

CALL FOPEN (1, NAME)
CALL RDBLK (1, 0, Z, 6, IER)
CALL RDBLK (1, 6, P, 6, IER)
DO 9 I = 10, 768
   R(I) = Z(I) * COS (P(I))
9 CONTINUE

DO 99 I = 10, 768
   P(I) = 0, 0
   N1 = 768/I
   RS = 0, 0
   DO 999 J = 1, N1
      RS = RS + (J**K)**R(J*I)
999 CONTINUE
   RF(I) = 2, 0 * RS / N1
99 CONTINUE

IF ((NAME(4), AND. 177400K), GT. 35000K) GO TO 980
   NAME(4) = 'S'
980 GO TO 981

981 CALL FOPEN (2, NAME)
CALL WRBLK (2, 0, RF, 6, IER)
CALL WRBLK (2, 6, P, 6, IER)
STOP
END
.TITLE ACQUIRE
.EXTN FRET
.EXTD ACQUIRE
 .CPYL
 .NREL
WCT: 0
MODE: 4001
STOP: 400
STAD: 10000
FSMCS: 15401
DISP=-167

ACQUIRE:JSR @CPYL
LDA 1, @DISP, 3
NEG 1, 1
STA 1, WCT
LDA 1, DISP+1, 3
DOA 1, 61
LDA 1, WCT
DOE 1, 61
LDA 1, MODE
DOC 1, 61
LDA 1, STAD
DOC 1, 61
LDA 1, FSMCS
DOC 1, 61
SKPBZ 61
JMP -.1
LDA 1, STOP
DOCC 1, 61
FRET .END
.TITLE SEND
.EXTN FRET
.ENT SEND
.EXTD CPYL
.NREL
.OPBF: IFED
IFED: 0
WCT1: 177777
BDC: 100167
DISP=-167

SEND: JSR 0.CPYL
LDA 0,@DISP,3 ; GET IFED
STA 0,IFED ;
LDA 1,OPBF ; FEED
DOAC 1,61 ; CURRENT
LDA 1,WCT1 ; VALUE
DOB 1,61 ;
LDA 1,BDC ;
DOCS 1,61 ;
SKPBZ 61 ;
JMP .-1 ;
FRET
.END

C-18
Figure 1 Construction of a trombone and mouthpiece.
Figure 2: Flowchart of design procedure used by Boosey and Hawkes.
Construct prototypes

Measure prototypes complex acoustic impedance

Submit prototypes to a panel of players for subjective assessment using SDS and MDS

Players satisfied with quality?

NO

Modify instrument using Perturbation Theory

YES

Enter next stage

Figure 3 Flowchart of improved design procedure. Instruments are modified using Perturbation Theory on the basis of a thorough understanding of the relationship between the subjective dimensions of an instrument and its acoustic impedance. This understanding is obtained by comparing the results of subjective assessment experiment performed by a panel of players on a range of instruments of differing quality, with the measured impedance curves of those instruments.
Figure 4. Block diagram of experimental apparatus devised by Earle Kent.
Figure 5  The mouthpiece modified to accept the hot-wire and microphone probes
Figure 6  The hot-wire probe positioned in the mouthpiece throat
Figure 7  The Mark 1 excitation system
Figure 8  Impedance curve obtained using the Mark 1 system
Figure 9  Block diagram of experimental apparatus. The R.M.S. Meters (dotted) were omitted for Mark 3 version.
Figure 10  A brass instrument as a 2-port network

\[ Z(f) = \frac{P_i(f)}{U_i(f)} \]

\[ TF(f) = \frac{P_o(f)}{P_i(f)} \]
Figure 11  The complete Mark 3 system
Start

Input $A, B, p$

Set P.F.O. to 10 Hz

Sample 1 cycle of pressure & velocity waveforms simultaneously

Calibrate velocity waveform

Filter pressure & calibrated velocity waveform

Calibrate pressure waveform

Compute $l \neq 1, \phi$

Test loop done 12 times

YES

Average results for $1 \pm 1, \phi$

Increment frequency

NO

Test frequency $> 768$

YES

Store data on disk file

F-12

Stop

Figure 12. Flowchart of FRUN.
Figure 13  Circuit diagram of the Automatic Level Controller
Figure 15  Block diagram of the Regulated Air Supply.
Figure 16. The wind tunnel, pitot-tube and micromanometer.
Figure 18 Characteristics of the Regulated Air Supply.
Figure 20  Impedance of a straight tube
Figure 2 | The turning points of the amplitude of the impedance for the straight tube

- Experimental
- Theoretical

F-21
Figure 22. The turning point of the phase of the impedance for the straight tube.

- - - Experimental

--- Theoretical
Figure 23 Impedance of a mouthpiece backbore (Dennis Wick 9BS)
Figure 24

5YM91C

5YM910 cross-sectional area at rim
reduced by 94%
Figure 2.5 Diagram of the process of subjective assessment
Level 1 gives the names of the experimental techniques. Levels 2 and 3 describe the data collection and reduction procedures respectively. Solutions may be found for a given number of dimensions, and the accuracy of such solutions may be deduced from the data reduction procedures.
(a) Osgood’s 7 point Discrete scale.
(b) Continuous scale used by Pratt and Doak.
The aim of this questionnaire is to discover whether the timbre of musical instruments can be adequately described by using a limited number of adjectives (six in this case) with a subjective rating scale for each adjective.

Below are listed some words commonly used to describe timbre. For each family of instruments indicated below, and for the combination of all three families, select the six words that you feel would be most useful for describing the timbre by ticking the word in the appropriate column. (Thus each column should contain six ticks.) Please fill in the table first and then answer the questions overleaf.

<table>
<thead>
<tr>
<th></th>
<th>Strings</th>
<th>Woodwind</th>
<th>Brass</th>
<th>Combination of all three</th>
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<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
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<td>7</td>
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<td>8</td>
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<td>Mellow</td>
<td>6</td>
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<td>Rough</td>
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<td>Sharp</td>
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<td>0</td>
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<td>1</td>
</tr>
<tr>
<td>Colourful</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Harsh</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Dull</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Brilliant</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Nasal</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Clear</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Sweet</td>
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<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Smooth</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Bright</td>
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<td>3</td>
<td>7</td>
<td>7</td>
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<td>Hollow</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
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</tbody>
</table>

(1) What is your definition of the word timbre?

(2) Do you think that six adjectives are:
   (a) too few? [ ]
   (b) too many? [ ]

(3) Can you suggest any other useful adjectives for describing timbre?

THANK YOU FOR YOUR HELP

Figure 27 The questionnaire
INSTRUCTIONS TO LISTENERS

You are going to hear various trombone notes whose tone quality (timbre) you are asked to assess using a Subjective Rating Scale.

What is a Subjective Rating Scale?

A subjective rating scale comprises a pair of antonymic (opposite in meaning) adjectives which lie at each end of a line which represents the gradual transition between the two extremes. To indicate your choice simply mark with a cross at the appropriate position on the scale, for example:

Bright | X | | Dull

It is important that you use the entire range of the scale, don't cramp your results in a limited range.
### MEANS.RE

**********

**WHICH FILE ? L01**

R1S1.RP

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>LEVEL</th>
<th>NUMBER</th>
<th>MEAN</th>
<th>DEVIATION</th>
<th>STAND. ERROR</th>
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<td>3.814</td>
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<td>12.517</td>
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<td>6.164</td>
<td>3.559</td>
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<td>3</td>
<td>31.000</td>
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**GRAND MEAN = 27.583333**

### MEANS +/- 1 STANDARD ERROR

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<td>4.22</td>
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<tr>
<td>4</td>
<td>30.00</td>
<td>0.82</td>
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<td>5</td>
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**Figure 29 ANOVA printout**
<table>
<thead>
<tr>
<th>Scale 1</th>
<th>Bad Intonation (0) - Good Intonation (10)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>7 9 9 9 9 9</td>
<td>8.6</td>
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<tr>
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<td>8 8 8 9 8</td>
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</tr>
<tr>
<td>I3</td>
<td>9 10 9 9 8</td>
<td>9.0</td>
</tr>
<tr>
<td>I4</td>
<td>9 9 8 8 7</td>
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<td>I5</td>
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<table>
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<th>Scale 2</th>
<th>Stuffy (0) - Free blowing (10)</th>
<th>Average</th>
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<tbody>
<tr>
<td>I1</td>
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<tr>
<td>I2</td>
<td>9 9 9 9 9 9</td>
<td>9.0</td>
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<tr>
<td>I3</td>
<td>9 9 10 10 9</td>
<td>9.4</td>
</tr>
<tr>
<td>I4</td>
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<td>9.0</td>
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<tr>
<td>I5</td>
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<td>8.8</td>
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<table>
<thead>
<tr>
<th>Scale 3</th>
<th>Unpleasant Timbre (0) - Pleasant Timbre (10)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0</td>
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<td>I2</td>
<td>9 8 8 9 9 9</td>
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<td>I4</td>
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<td>9.8</td>
</tr>
<tr>
<td>I5</td>
<td>6 7 7 7 7 7</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Figure 30  The complete results for C.S.
Figure 3 | (a) Average ratings by the professional player for instrument II to I5 using the scale Unpleasant Timbre/Pleasant Timbre.
(b) 1 dimensional solution of the response made by the professional player during the MDS experiment.
Figure 32. A.G. Webster's theoretical and experimental model of the sound production mechanism of brass instruments first proposed in 1919.
Figure 33

Vincent Bach

Boosey and Hawkes Sovereign
### PREFERENCE

<table>
<thead>
<tr>
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<th>J.M.B.</th>
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<th>G.C.</th>
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<td>2</td>
<td>1</td>
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<tr>
<td>CC</td>
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<td>2</td>
<td>Same</td>
</tr>
<tr>
<td>BC</td>
<td>1</td>
<td>1</td>
<td>Same</td>
</tr>
<tr>
<td>CA</td>
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<td>2</td>
<td>2</td>
</tr>
<tr>
<td>BB</td>
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<td>1</td>
<td>Same</td>
</tr>
<tr>
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<td>1</td>
<td>Same</td>
</tr>
<tr>
<td>BA</td>
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<td>BB</td>
<td>2</td>
<td>1</td>
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<tr>
<td>AC</td>
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<td>2</td>
<td>1</td>
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</table>

**Figure 34** Assessment of the Vincent Bach (A), laquered Boosey and Hawkes Sovereign (B), silver plated Boosey and Hawkes Sovereign(C). When subjects rated the instruments different, they were asked to state which of the pair the preferred.
Figure 35 The acoustic impedance of the Bass Trombone before modification.

---

Using the valve

Not using the valve
Figure 36  Internal spectra of Boosey and Hawkes bass trombone, when played.
(a) ff
(b) pp
Figure 37 The acoustic impedance of the Bass Trombone after modification.

Using the valve

Not using the valve

F-37
Figure 38  5BP9IC  (1 of 3)
<table>
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<th>Mode</th>
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<th>Deviation</th>
<th>Resistance</th>
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<td>49 cents</td>
<td>45.61 MΩ</td>
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<td>MIN</td>
<td>74 Hz</td>
<td>14 cents</td>
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<td>141 Hz</td>
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Figure 38  5BP91C  (2 of 3)
Figure 38  5BP91C  (3 of 3)
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Figure 39 5C091C (2 of 3)
<table>
<thead>
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<th>Note</th>
<th>Cents</th>
<th>Resistance</th>
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<td>D</td>
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<tr>
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<td>F</td>
<td>4</td>
<td>24.42 MΩ</td>
</tr>
<tr>
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<td>G</td>
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<td>23.68 MΩ</td>
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<td>C</td>
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<td>1.12 MΩ</td>
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<td>1.62 MΩ</td>
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<td>-4</td>
<td>2.06 MΩ</td>
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<td>B</td>
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<td>3.21 MΩ</td>
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Figure 40  5H091C (2 of 3)
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<th>Cent</th>
<th>Impedance</th>
</tr>
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</tr>
<tr>
<td>MIN</td>
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<td>42 Cent</td>
<td>0.73 MΩ</td>
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<table>
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<th>Impedance</th>
</tr>
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<td>MIN</td>
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<td>-39 Cent</td>
<td>0.81 MΩ</td>
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<tr>
<td>MIN</td>
<td>264 Hz</td>
<td>16 Cent</td>
<td>1.02 MΩ</td>
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<th>Impedance</th>
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</tr>
<tr>
<td>MIN</td>
<td>325 Hz</td>
<td>-24 Cent</td>
<td>1.58 MΩ</td>
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<table>
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<th>Impedance</th>
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<tr>
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<th>Impedance</th>
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<tr>
<td>MIN</td>
<td>450 Hz</td>
<td>39 Cent</td>
<td>1.66 MΩ</td>
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<table>
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<th>Impedance</th>
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<table>
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<th>Impedance</th>
</tr>
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<tbody>
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<tr>
<td>MIN</td>
<td>583 Hz</td>
<td>-13 Cent</td>
<td>3.02 MΩ</td>
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<table>
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<th>Cent</th>
<th>Impedance</th>
</tr>
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<tbody>
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<td>MAX</td>
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<td>19.00 MΩ</td>
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<tr>
<td>MIN</td>
<td>643 Hz</td>
<td>-43 Cent</td>
<td>3.13 MΩ</td>
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<table>
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<th>Impedance</th>
</tr>
</thead>
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<tr>
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<tr>
<td>MIN</td>
<td>695 Hz</td>
<td>-9 Cent</td>
<td>2.91 MΩ</td>
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<table>
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<th>Impedance</th>
</tr>
</thead>
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<td>MAX</td>
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Figure 41  5KI91C (2 of 3)
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<th>Note</th>
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<th>Change</th>
<th>Resistance</th>
<th>Q</th>
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<td>0.32 MEG. OHMS</td>
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<td>119 Hz</td>
<td>A#</td>
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<td>23.49 MEG. OHMS</td>
<td>34</td>
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<td>0.83 MEG. OHMS</td>
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<td>262 Hz</td>
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<tr>
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<td>583 Hz</td>
<td>D</td>
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<td>3.22 MEG. OHMS</td>
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**Figure 42  5LF91C (2 of 3)**
Figure 43 5VB91C (1 of 3)
Figure 43  5VB91C  (2 of 3)
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Pitch</th>
<th>Cent</th>
<th>Resistance (MΩ)</th>
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<tr>
<td>MAX 177 Hz</td>
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<tr>
<td>MIN 201 Hz</td>
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<td>0.82</td>
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<td>E 4</td>
<td>-35</td>
<td>1.73</td>
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</tr>
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<tr>
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<tr>
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</tr>
<tr>
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<td>MIN 690 Hz</td>
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<td>MIN 761 Hz</td>
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Figure 44  5YM91C  (2 of 3)
Figure 45

- 5BP91C
- 5VB91C
Figure 46

5BP91C

5KI91C

F-60
<table>
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<td>38</td>
<td>52</td>
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<td>63</td>
<td>68</td>
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<td>33</td>
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</tr>
</tbody>
</table>

Figure 47 The Standard Deviations, Factor Loadings and Q's for the seven medium bore instruments
Figure 49

--- Straight tube

--- 5C091C

F-63
Figure 50  The profile corresponding to Factor 1, which accounted for 93% of the variance.
Figure 51  The distribution of trombones used by a sample of professional players (from reference [48])
Boosey and Hawkes Sovereign (silver-plated)

<table>
<thead>
<tr>
<th>Frequency (Hz.)</th>
<th>Impedance (MΩ)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>29.2</td>
<td></td>
<td>30.1</td>
</tr>
<tr>
<td>116</td>
<td>24.0</td>
<td></td>
<td>24.9</td>
</tr>
<tr>
<td>178</td>
<td>18.3</td>
<td></td>
<td>19.1</td>
</tr>
<tr>
<td>240</td>
<td>16.4</td>
<td></td>
<td>20.1</td>
</tr>
<tr>
<td>305</td>
<td>14.0</td>
<td></td>
<td>15.3</td>
</tr>
<tr>
<td>368</td>
<td>19.5</td>
<td></td>
<td>19.7</td>
</tr>
<tr>
<td>424</td>
<td>16.1</td>
<td></td>
<td>16.6</td>
</tr>
<tr>
<td>491</td>
<td>13.6</td>
<td></td>
<td>13.8</td>
</tr>
<tr>
<td>561</td>
<td>14.1</td>
<td></td>
<td>14.9</td>
</tr>
<tr>
<td>616</td>
<td>13.9</td>
<td></td>
<td>14.3</td>
</tr>
</tbody>
</table>

Figure 52 The magnitudes of the impedance maxima of the Boosey and Hawkes Sovereign (silver-plated) before and after internal cleaning
**Latzsch Eb Alto Trombone**

<table>
<thead>
<tr>
<th>Frequency (Hz.)</th>
<th>Impedance (Mn) Before</th>
<th>Impedance (Mn) After</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>54.1</td>
<td>53.9</td>
</tr>
<tr>
<td>158</td>
<td>35.1</td>
<td>36.3</td>
</tr>
<tr>
<td>241</td>
<td>27.5</td>
<td>31.0</td>
</tr>
<tr>
<td>320</td>
<td>25.1</td>
<td>25.3</td>
</tr>
<tr>
<td>410</td>
<td>24.5</td>
<td>24.6</td>
</tr>
<tr>
<td>491</td>
<td>31.5</td>
<td>31.1</td>
</tr>
<tr>
<td>570</td>
<td>22.4</td>
<td>23.1</td>
</tr>
<tr>
<td>650</td>
<td>19.0</td>
<td>19.5</td>
</tr>
<tr>
<td>736</td>
<td>22.9</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Figure 53  The magnitudes of the impedance maxima of the alto trombone before and after internal cleaning
Figure 54  
--- Boosey and Hawkes prototype

----- As above, but including theoretically
the mouthpiece cup volume
<table>
<thead>
<tr>
<th>J.M.B.</th>
<th>P.H.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1</td>
</tr>
<tr>
<td>BA</td>
<td>2</td>
</tr>
<tr>
<td>BB</td>
<td>2</td>
</tr>
<tr>
<td>CA</td>
<td>2</td>
</tr>
<tr>
<td>AA</td>
<td>2</td>
</tr>
<tr>
<td>CB</td>
<td>1</td>
</tr>
<tr>
<td>AC</td>
<td>Same</td>
</tr>
<tr>
<td>AB</td>
<td>1</td>
</tr>
<tr>
<td>BC</td>
<td>Same</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Throat diameter (mm)</th>
<th>Cup volume (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouthpiece body A</td>
<td>7.35</td>
</tr>
<tr>
<td>Mouthpiece body B</td>
<td>7.10</td>
</tr>
<tr>
<td>Mouthpiece body C</td>
<td>7.10</td>
</tr>
</tbody>
</table>

Figure 56 The subjective assessment of three different Giardinelli mouthpiece bodies
Figure 57  --- Straight tube: length equal to 1st slide section of a Boosey and Hawkes Sovereign
            ------ Boosey and Hawkes Sovereign with slide removed
Figure 58  Holton Collegiate

Before damage occurred

After damage occurred

F-72
<table>
<thead>
<tr>
<th>Mode</th>
<th>Laquered (1)</th>
<th>Laquered (2)</th>
<th>Silver-plated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>38.1</td>
<td>36.1</td>
<td>30.8</td>
</tr>
<tr>
<td>3</td>
<td>24.8</td>
<td>24.3</td>
<td>24.1</td>
</tr>
<tr>
<td>4</td>
<td>20.5</td>
<td>19.7</td>
<td>18.4</td>
</tr>
<tr>
<td>5</td>
<td>24.3</td>
<td>23.6</td>
<td>19.7</td>
</tr>
<tr>
<td>6</td>
<td>15.5</td>
<td>15.7</td>
<td>14.7</td>
</tr>
<tr>
<td>7</td>
<td>20.8</td>
<td>21.5</td>
<td>19.3</td>
</tr>
<tr>
<td>8</td>
<td>16.9</td>
<td>18.3</td>
<td>16.2</td>
</tr>
<tr>
<td>9</td>
<td>14.5</td>
<td>15.0</td>
<td>14.2</td>
</tr>
<tr>
<td>10</td>
<td>16.1</td>
<td>16.6</td>
<td>14.8</td>
</tr>
<tr>
<td>11</td>
<td>14.9</td>
<td>14.1</td>
<td>14.3</td>
</tr>
<tr>
<td>12</td>
<td>9.4</td>
<td>9.7</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Figure 59  The magnitudes (in MΩ) of the impedance maxima for the two laquered and the one silver-plated Sovereigns
Figure 60  Holton Collegiate

--- d.c. airflow 2m.s\(^{-1}\).

--- d.c. airflow 10m.s\(^{-1}\).

F-74
Figure 61  5VB91C, 5VB93C, 5VB95C, 5VB97C
Figure 62  5KI91C, 5KI93C, 5KI95C, 5KI97C
Figure 63  Boosey and Hawkes prototype

- - - Measured at the throat
-- -- Measured at the rim
Boosey and Hawkes prototype

<table>
<thead>
<tr>
<th>Predicted Playing Frequencies (Sum Function maxima)</th>
<th>Playing Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition (a)</td>
<td>Condition (b)</td>
</tr>
<tr>
<td>117</td>
<td>117</td>
</tr>
<tr>
<td>179</td>
<td>176</td>
</tr>
<tr>
<td>244</td>
<td>235</td>
</tr>
<tr>
<td>308</td>
<td>295</td>
</tr>
<tr>
<td>369</td>
<td>352</td>
</tr>
<tr>
<td>Condition (c)</td>
<td>JMB     PSW RLP</td>
</tr>
<tr>
<td>118</td>
<td>118</td>
</tr>
<tr>
<td>177</td>
<td>177</td>
</tr>
<tr>
<td>236</td>
<td>236</td>
</tr>
<tr>
<td>296</td>
<td>296</td>
</tr>
<tr>
<td>354</td>
<td>354</td>
</tr>
</tbody>
</table>

Condition (a) Sum Function computed from measurements taken in the throat
Condition (b) As (a), but including theoretically the cup volume
Condition (c) Sum Function computed from measurements taken at the rim

Figure 64 The Sum Function frequencies computed for Conditions (a) to (c), and the playing frequencies obtained by three players.
Figure 65 Impulse response of the Holton

--- Before damage occurred

--- After damage occurred

F-79
<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>Stuffy (0) - Freeblowing (10)</th>
<th>Unpleasant Timbre (0) - Pleasant Timbre (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B&amp;H prototype</td>
<td>7 7 5 5 6</td>
<td>6.0</td>
</tr>
<tr>
<td>Holton</td>
<td>3 4 3 5 4</td>
<td>3.8</td>
</tr>
<tr>
<td>King 2B</td>
<td>6 6 6 7 6</td>
<td>6.2</td>
</tr>
<tr>
<td>Lafleur</td>
<td>9 9 9 7 8</td>
<td>8.4</td>
</tr>
<tr>
<td>Yamaha YSL 651</td>
<td>8 7 6 5 6</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 66 Scores and analysis for the player L.P. In the two lines immediately above, a space indicates a discrimination between instruments at the 1% level. No discrimination is indicated by vertical placement.
You are probably already familiar with the concept of a "photographic memory", the ability to recall visual sensations. In this questionnaire the questions are related to audio imagery or the ability to recall audio sensations. Before addressing yourself to the questions below, try to recall (or "play over") a favourite or familiar piece of music (preferably ensemble).

(1) How close to reality does the piece sound (i.e., is the experience as vivid as going to a concert?)

Not at all close to reality --- As vivid as reality

(2) How well can you adjust the volume of the piece?

Not at all --- Perfectly well

(3) How well can you pick out the various instruments (or voices) playing?

Not at all --- Perfectly well

(4) How well can you shift the piece to a different pitch?

Not at all --- Perfectly well

(5) How well can you change the solo instrument in a piece (i.e., could you change the horn in a Mozart horn concerto to a flute, for example?)

Not at all --- Perfectly well

Please also answer the following two questions:

(1) Sex: Male () Female ()

(2) Approximate Age:

11-15 () 41-45 ()
16-20 () 46-50 ()
21-25 () 51-55 ()
26-30 () 56-60 ()
31-35 () 61-65 ()
36-40 () over 65 ()
REFERENCES


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