Investigation into factors affecting the acoustics and playability of the horn, and the effect of auditory feedback on horn playing.

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Abstract

The acoustic impedance ($Z$) spectra of different horns with different mouthpieces, players’ hands, mutes, fingerings and the combinations of these were studied, as were the effects on the output sound of the horn of filtering the auditory feedback provided via headphones to players ranging from professionals to students. Accurate replicas of horn players’ hands in playing position were used for extensive and precisely repeatable measurements of the impedance spectra at the horn input. Differences in impedance spectra due to hand size, shape and position in bell were greatest for resonances above the cutoff frequency of the bell (about 500 Hz). Mutes affected the frequency of the resonance peaks, especially around 350 to 400 Hz (corresponding to the horn’s middle register). For practice mutes, resonances were up to 100 cents flatter than with hand in bell.

Players’ reports of the playability with different hands and mutes are qualitatively explained in terms of differences measured in the impedance spectra. Statistically significant correlations were found with players’ perceptions of quality of sound for the different hands and ease of playing for different practice mutes. No statistical differences were found between players’ ratings of playability for three different stopping mutes, which showed relatively similar impedance spectra. Practice mutes decreased the sound level by 10 dB without a large change in the spectral centroid. Stopping mutes increased the spectral centroid from less than 1 kHz to more than 3 kHz without affecting the sound level.

The horn radiates high frequencies better behind the player. Consequently, the presence and type of reflecting surfaces affect the sound received by the player. Horn players are sometimes concerned by such changes and how this affects their playing. When spectrally altered auditory feedback was provided to horn players, relatively little change in output spectra was measured. The wearing of headphones resulted in changes to the sound for some players, independent of the auditory feedback received. Players’ hand movements in the bell were video recorded and different types of movement were identified: movement in response to changes in auditory feedback, extra-musical movements, and movements associated with intonation.
At the beginning

In the middle

By the end
Acknowledgments

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In memory of Junior
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Introduction

The research that forms the basis of this thesis originated from a personal interest in the horn. The topics, experiments, analysis and findings were all approached first and foremost through the eyes of a musician, namely a horn player, who also has a passionate interest in the physics and acoustics of the instrument and how it is played. The various interrelated research questions addressed in this thesis were all motivated by various aspects of being a horn player. For example:

- The horn is played with the hand in the bell and the hand is used by the player to change the sound and to adjust intonation. However, every player’s hand is a different size and shape and is positioned slightly differently in the bell of the horn. How does the size, shape and position of the hand affect the acoustics of the horn and also the playability of the instrument?

- There are several types of mutes at the horn player’s disposal, but there are numerous different brands, materials, and styles from which to choose. What makes one mute easier to play than another?

- The bell of the horn points behind the player, so a proportion of the horn sound heard by the player is reflected sound. As different acoustic environments will change the reflected component of the sound, does the auditory feedback received by the player affect the way they play?

The results and findings of the research undertaken into the above three questions are reported in this thesis. It is my intention, in the near future to make this information available, in a more accessible form, to fellow horn players.

This thesis reports and analyses the results of three sets of experiments. Following this brief introduction, an introduction to horn acoustics (Chapter 1) and a review of methodologies (Chapter 2), these experiments are reported in chapters 3 to 5, each of which has its own background, methods, results and discussion. An overview of findings, implications for horn players, suggestions for future work and final conclusions are presented (Chapter 6) and the appendices contain extra material relevant to the experiments, such as frequency charts, surveys, graphs, etc.
Chapter 1

The horn: General acoustics and relevant literature

In order to investigate specific acoustic properties of the horn, it is necessary to describe the general acoustic properties of the horn and outline previous research that has been undertaken in the area of horn and brass instrument acoustics. Thus, this chapter begins with a general introduction to the geometry and mechanics of the horn. This is followed by an overview of the production of sound on the horn (including both the generating and radiating properties of the instrument) and the sound produced by the horn (including the starting transient, sound spectrum and ending transient). The effects of various factors on the acoustics of the horn are then introduced. Factors considered are the mouthpiece, bell, player’s hand in bell, instrument, player, and mutes. Relevant research in the above mentioned areas are referred to throughout the chapter.

1.1 General acoustics of the horn

The horn is a member of the brass instrument family and is thus a lip reed instrument, whose principal means of changing note is by “overblowing” to the next note of the harmonic series (Figure 1.1). The horn has a playing range of more than three and a half octaves and often plays up to the 16th harmonic and occasionally even higher. The easiest range to play is from the 4th to 12th harmonics and it is this

![Harmonic series with fundamental Bb1](image)

Figure 1.1: Harmonic series with fundamental Bb1. The black notes indicate pitches that are very out of tune on the horn in comparison to the nearest notes in equal temperament.
register that gives the horn its characteristic colourful, mellow tone. Consequently the horn is considered an alto/tenor instrument, even though it is able to play both higher and lower. The horn is also classified as a transposing instrument (in F) and consequently its music is written a perfect fourth higher than the desired pitch (see Appendix A).

1.1.1 Geometry and mechanics of the horn

The horn consists of a funnel-shaped mouthpiece, leadpipe, length of tubing (mixture of conical and cylindrical) including valves, and a widely flaring bell (Figure 1.2). The tubing is looped with the bell bending back to form an angle of approximately 60 degrees with the leadpipe. The horn is played with the left hand operating the valves and the right hand placed in the bell of the instrument. The tubing, valves and bell are usually made of brass (approximately 70% copper and 30% zinc) and can be lacquered, unlacquered or silver plated.

The modern double horn (ca. 1900) has three valves which, when used separately, decrease the fundamental by 2, 1, and 3 semitones respectively by adding in extra lengths of cylindrical tubing. This enables the horn to be fully chromatic. A fourth valve, operated by the thumb, switches between a horn in F (length ≈ 3.75 m) and one a fourth higher in B flat (length ≈ 2.8 m). The full double horn (used in this research) has completely independent sets of valve tubing for each of the F and B flat sides. However, there also exists a compensating horn which has a primary set tuned for the B flat horn and a secondary set tuned so that the lengths when added to the primary set, are correct for the F horn. Apart from the Vienna horn, which has piston valves similar to those on a trumpet, the valves on a horn are rotary valves.

Although the use of valves enables the horn to be fully chromatic, the extra tubing causes two important acoustical problems for the instrument. Firstly, the added valve tubing must be cylindrical which reduces the average taper of the instrument. This causes a greater percentage change in the frequencies of low resonances than high resonances (Benade, 1976). Secondly, to lower a note by a semitone involves lowering the frequency by about 6%. Thus, when used in conjunction with another valve, the length of tubing on the semitone valve would need to be longer (than if used by itself) to lower a note by a semitone. So that if the first two valves are tuned to lower the open horn by a tone and semitone respectively, then used together they will be much too short. This problem increases when all three valves are used together. In 1931, Redfield (1931) suggested a tuning system for the valve slides based on a trial and error method and Young (1967) proposed an optimal

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1It is important to note that horn players commonly use the term ‘harmonic’ when referring to a resonance of the instrument. The resonances of the instrument strongly influence the playing regime and the resulting sound consists of a fundamental frequency and harmonics.
tuning system based on a mathematical (least squares) model. Generally though, to compensate, the tubing of all three valves are made slightly longer so that when used separately they are too long and when used together they are only a little too short. The intonation is then able to be fixed by adjustment of the player's lips or right hand in the bell.

1.1.2 Production of sound on the horn

1.1.2.1 Generation of sound

The player's lips act as a nonlinear valve that, cooperating with one or more resonances in the bore, produce autonomous oscillations by regeneration, setting up standing waves in the bore. A small fraction of the energy stored in these standing waves is radiated each cycle from the bell. The player begins by blowing air through a small aperture between the lips, forcing the lips to vibrate at roughly the correct frequency for the required note. Waves, especially standing waves in the air column, exert forces on the lips and the air passing between them. If the natural frequency of the lips is at approximately the right frequency, the vibrations of the lips will be 'pulled' to the frequency close to that of a nearby resonance. If this note is naturally out of tune on the instrument, properties of the lips must be adjusted so as to achieve a playing regime at the desired frequency, which may be substantially displaced from that of the resonance – this is called 'bending' or 'pulling' the note into tune.

Starting a note (especially in the high register) is difficult as the time taken for the wave to travel from the mouthpiece to the bell and back is determined only by the length of tubing and not by the individual note played. Thus, the lips may have to excite up to sixteen oscillation cycles unaided, before they are stabilised by the reflected wave (Fletcher and Rossing, 1991). Skilled muscular control is needed to
vibrate the lips at roughly the correct frequency as the high resonances are separated by as little as a semitone.

Once a standing wave has been set up in the instrument, the lips must restore between one and five percent of the amplitude of the air flow in each cycle of oscillation (Benade, 1960) in order to maintain it, as energy is lost at the walls through friction and as radiated sound. To sustain oscillation, air must be supplied when the mouthpiece pressure is at a maximum. A steady flow of air will not sustain oscillation, as energy added during half the cycle would be removed in the other half. It would be impossible to synchronise the opening of the lips by muscular action alone, hence the lips act like an automatically controlled valve where the pressure pulses reflected back, force the lips open at the right time (Rossing, 1990). The air pressure in the mouth is higher than atmospheric pressure which forces the lips open and air to flow out. This causes the air pressure in the mouth to fall, creating suction between the lips. The resulting Bernoulli force causes the lips to close, allowing the air pressure in the mouth to build up again.

The lips are very adaptable due to the change of shape, size and muscle tension that can be achieved. The embouchure\(^2\) is critical to tone production, flexibility of playing and correction of intonation. With the correct embouchure, the pitch can be altered in four ways: by applying slight pressure (with the left hand) on the lips from the mouthpiece and horn; by changing the size and shape of the lip opening; by changing the degree of tension in the lip muscles, and; by changing the angle at which air is directed into the mouthpiece. The latter three methods are achieved by a movement (moderate and in proportion to the change in pitch) of the jaw, lower teeth and/or lip muscles. When changing notes, a combination of these methods is employed (Schuller, 1962).

Since Helmholtz’s *On the Sensations of Tone* (Helmholtz, 1954) was first published in the 1860s, the lips have generally been considered an outward-striking reed, as opposed to an inner-striking reed such as that of the oboe. This is due to the fact that the lips (reed) are generally considered to open with increasing blowing pressure, whereas an oboe reed closes with increasing blowing pressure (a detailed mathematical explanation is given in Fletcher (1979)). However, Fletcher (1993) shows that two types of reed motion are capable of producing sound on a brass instrument: outward-striking (+,−) and sideways-striking (+,+). Many studies of the lip reed have been undertaken in the following three main areas: observations and measurements of brass players’ lips *in vivo*; experiments with artificial lips; and modelling and simulation of the lip-reed.

Martin (1942b) was the first to photograph vibrating lips whilst playing a brass instrument. Using a modified mouthpiece and stroboscopic photography, he was

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\(^{2}\)Defined as “the lip technique involved in producing and controlling the... tone, together with the effect of such contributing factors as breath pressure, tongue and jaw setting, the operation of the facial muscles, etc.” (Henderson (1942)).
able to study the movement of the lips from both the front and the side. Although
this study was ground breaking, Martin did not draw any conclusions on the motion
of the lip-reed, instead suggesting that further research was necessary. However, he
did state that the differences in lip vibrations between low and high notes were very
small compared to the differences in spectral content between the same notes and
hence it was unlikely that differences in spectra were caused by lip vibration.

The contribution of each lip to the production of sound on the trumpet was
investigated by Henderson (1942) who studied players “buzzing” on the rim of a
trumpet mouthpiece (with the rest of the mouthpiece removed) and playing notes
on a trumpet with a modified mouthpiece, so that only the upper or lower lip could
contribute to the production of the sound. He found that when the top lip was
damped or unable to vibrate, sound could not be produced. However, when the
bottom lip was damped or unable to vibrate this had very little effect on the sound
produced. Henderson concluded that the upper lip essentially acts as a single reed
and that although the lower lip may contribute to the quality of the sound, its main
purpose is to provide a structure for the upper lip to vibrate against and to control
the frequency of vibration.

Yoshikawa (1995) used a strain gauge mounted to the player’s top lip to inves-
tigate the motion of the lips whilst playing the trumpet and horn. He noted that if
the lip opening impedance is negligible compared with the input impedance at the
mouthpiece, then outward-striking (or longitudinal) oscillation is favoured, but if
the lip opening impedance is comparable to the input impedance (more so as blow-
ing pressure is increased), upward-striking (or transverse) oscillation is favoured.
For the horn, Yoshikawa (1995) found that the lips exhibited outward-striking (+,–)
oscillation for only the lowest harmonic and that for notes above this, the oscillation
was predominantly upward-striking (+,+) where the upper lip oscillates perpendicu-
larly to the air flow. However, he also suggested that it may be necessary to consider
more complex two-dimensional models to characterise the lip-reed rather than the
one-dimensional outward- and upward-striking models employed in this study.

Using essentially a Helmholtz resonator with a modified trumpet mouthpiece,
Chen and Weinreich (1996) studied the lips’ vibration. They compared the recorded
playing frequency with the frequency of the resonating system and found that in
general, the playing frequencies were higher than the resonance frequencies which
corresponds to the outward-striking reed model. They also noted that players were
able to easily pull the playing frequency both higher and lower, indicating that the
model is insufficient to fully describe the lip motion and that the player’s oral cavity
may also need to be considered.

Copley and Strong (1996) followed on from Martin (1942b) with their photo-
graphic study of lip vibrations. They used a trombone mouthpiece inserted with a
small fiber optic probe stroboscope. Their aim was to produce detailed photographic
evidence of the lip reed in motion to aid in the study of lip reed models. Six different notes were recorded at two different dynamic levels and results showed that the lips opened at a much faster rate for loud notes than for soft notes. Similar to Henderson (1942), Copley and Strong found that the upper lip vibrates much more than the lower lip. They also confirmed the results of Yoshikawa (1995) which indicated that longitudinal oscillations are favoured at lower frequencies and transverse at higher frequencies.

A further stroboscopic study of lip motion was undertaken by Yoshikawa and Muto (2003) using a natural horn and a transparent horn mouthpiece. They found that lip motion is actually three-dimensional, rather than two-dimensional. That is, the upper lip moves upwards (opens), inwards (into the mouthpiece), and laterally (sideways). The amplitude of the lateral movement was found to depend on the player’s proficiency, with the most advanced players’ lips exhibiting almost two-dimensional behaviour. They also found that the amplitude of the lip vibration tended to decrease as higher notes were played. Yoshikawa and Muto also provided a detailed analysis of lip motion from the side view and attempted to estimate the elasticity of the upper lip tissue from the measured surface wave visible on the upper lip. Correlations were made between different players’ lip movements and their corresponding sound spectra. They concluded that differences in the spectra could be attributed to differences in the lips’ vibrations. Yoshikawa and Muto suggested that their measurements and findings should be able to contribute to the development of more biomechanically realistic artificial lip systems.

Since the 1990s, researchers have been developing artificial mouths or lip systems for use with brass instruments. Several studies have looked at using an artificial mouth to compare instruments without player interference (see section 1.5) however, the primary focus of experiments has been to enable a more thorough understanding of the lip reed and the production of sound on a brass instrument without the difficulties associated with including actual players. Eliminating the need for a human player allows for extensive and repetitive measurements without the variation that is inherent in actual playing and also allows the researcher to vary parameters individually.

Vergez and Rodet (1997) used an artificial mouth, first implemented by Govignon (1997), to study the nonlinear effects at the lip opening with the aim of improving the modelling of the entire brass instrument. The artificial mouth consisted of water filled latex lips placed in a steel mouth with a compressed air supply. Experiments were carried out using a plexiglass replica of a real trumpet mouthpiece and measurements were made of the lips’ opening and pressure inside the mouth. By subtly varying the tension in the lips, the angle between the mouthpiece and lips, and the supplied air pressure, they were able to produce sound for the first eight harmonics on a trumpet.
A similar artificial mouth device (with only an upper latex lip) was used by Gilbert et al. (1998) to study the relationship between the differing frequencies of the resonance tube, the lips, and the produced sound spectra on a trombone. Similar to experiments using actual players, results showed that it was possible to generate sound at frequencies both above and below the resonance frequency. They also found that as the lip frequency increased, the sounding frequency also increased, but the playing frequency was always higher than the lip frequency. Results obtained using only the mouthpiece coupled to the artificial mouth, showed two separate frequency regions which Gilbert et al. suggested may be due to a second lip vibration. They concluded from these results that a two-dimensional (two-mass) model of the lip reed is more suitable for characterising the motion of the lips.

The use of an artificial mouth to collect data for comparison with simulated data from a two-mass model was undertaken by Neal et al. (2002). They found that the lips vibrate in three different oscillating regimes depending on the frequency of the resonance: outward-striking (playing frequency is lower than the resonance frequency); inward-striking (playing frequency is higher than the resonance frequency); and a combination of the two (playing frequency is close to the resonance frequency). They suggest that by varying the lip resonances to favour one or the other of the lip oscillating regimes, the player can “lip” the note both above and below the resonance frequency. They also show that this behaviour is supported by the use of a two-mass model of the lip reed. Richards et al. (2002) used a slightly modified artificial mouth which allowed for a greater number of control parameters. Although their experiments were similar to those of Neal et al. (2002), their focus was on collecting data for specific lip model parameters. Due to the simplified nature of the two-mass model, they found that the measurements were useful only as first approximations in the model.

The artificial mouth used by Lopez et al. (2006) incorporated an artificial vocal tract and lung area to allow for a two-mass lip model which includes lung pressure (similar to that used for vocal fold models). They compared measured results with both a one-mass model and the two-mass vocal fold model of Lous et al. (1998) and found that the two-mass model was no better at predicting the lip behaviour than the one-mass model. They also found that the upstream acoustics (i.e. the inclusion of vocal tract and lungs) was of little importance to the lip vibration behaviour. Interestingly, Van Hirtum et al. (2007) combined experimental studies of the lip reed and vocal folds using a setup of water filled latex tubes designed to artificially replicate both the lip vibration and the vocal fold vibration. Again, the experiment was designed to obtain data for use in extending models of the lip reed and vocal folds. They investigated the lip opening area and how it is affected by the height of the initial opening, then incorporated the data into various one-dimensional and two-dimensional models.
Much effort has been spent trying to model the vibration of the lip reed and although many advances have been made in this area, any model still remains a simplified system compared to actual players’ lips. However, as more experiments have been carried out in vivo and with artificial lip systems, an increasing number of parameters have been included in the models. A brief overview of various models that have been proposed for the lip reed are presented in Table 1.1.

Although these models have contributed to the understanding of how the lip reed operates, their major limitations appear to stem from the simplification of what is essentially a very complex system with many parameters. Although the number of parameters included in the modelling has increased, with more realistic results obtained, the main difficulty currently experienced by researchers is that experimental measurements suggest that the lip motion is three-dimensional. This suggests that to accurately model the lip reed, a three-dimensional model will need to be developed. Of course, if the player is added into the model (rather than just the player’s lips), the number of additional parameters needed would increase dramatically (see section 1.6).

1.1.2.2 Radiation of sound

Radiation of the sound occurs at the bell of the horn. Details of the bell’s effect on various aspects of the horn sound is given in section 1.3. The maximum acoustical efficiency of the horn (amount of energy radiated as sound) is no more than a few percent for loud playing and the average efficiency may be as low as 0.1% (Fletcher and Rossing, 1991). The horn is highly directional, however, the directivity of the radiation from the bell varies with frequency. Thus the harmonic component of the radiated sound varies depending on the distance and position of the receiver relative to the bell.

Several researchers have studied the directivity and radiation patterns of the horn. Martin (1942a) investigated the directional characteristics of the horn by measuring the effect of azimuth angle on the sound pressure of the horn in an approximately free field. The horn was mechanically driven to produce several different frequencies and measurements were made every ten degrees over almost a full 360 degrees. He found that the directionality of the horn over its full frequency range (including the highest audible harmonics of the high notes) could be divided into three ranges: low frequencies (below 200 Hz) which are almost non-directional; high frequencies (above 500 Hz) which are largely directional along the axis; and intermediate frequencies (between 200 and 500 Hz) which do not produce regular equal loudness curves.
Table 1.1: Brief overview of proposed models of the lip reed.

<table>
<thead>
<tr>
<th>Author</th>
<th>Degrees of freedom</th>
<th>Parameters included</th>
<th>Accuracy in predicting lip vibration and producing brass instrument sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saneyoshi et al. (1987)</td>
<td>1</td>
<td>- Mass of lips&lt;br&gt;- Stiffness of lips&lt;br&gt;- Vibrating area of lips&lt;br&gt;- Area between lips&lt;br&gt;- Air flow</td>
<td>- Able to reproduce jump in frequency through the harmonic series with a constant increase in blowing pressure and reed (lip) frequency</td>
</tr>
<tr>
<td>Rodet (1995)</td>
<td>1</td>
<td>- Geometry of lips&lt;br&gt;- Elastic properties of lips&lt;br&gt;- Idealised air flow&lt;br&gt;- Pressure difference between mouth and mouthpiece&lt;br&gt;- Properties of the resonating tube (cylindrical tube)</td>
<td>- Behaviour related to brass instrument playing&lt;br&gt;- Produced sound contains typical characteristics of brass instrument sound especially in the transient&lt;br&gt;- Able to produce sound at several resonance frequencies</td>
</tr>
<tr>
<td>Adachi and Sato (1995)</td>
<td>1</td>
<td>- Area of mouthpiece opening&lt;br&gt;- Geometry of lips&lt;br&gt;- Lip mass and elastic properties&lt;br&gt;- Blowing pressure&lt;br&gt;- Properties of the resonating tube (trumpet)</td>
<td>- Able to produce sound for first 8 resonance frequencies (using different 1D models for lower and higher resonance frequencies)&lt;br&gt;- Similar shape sound spectra to actual trumpet spectra, but with a general lacking in harmonics&lt;br&gt;- Realistic changes in sound spectra with varying sound level&lt;br&gt;- Occasional aperiodic oscillations</td>
</tr>
<tr>
<td>Author</td>
<td>Degrees of freedom</td>
<td>Parameters included</td>
<td>Accuracy in predicting lip vibration and producing brass instrument sound</td>
</tr>
<tr>
<td>---------------------</td>
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<td>----------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Adachi and Sato (1996) | 2                  | - Area of mouthpiece opening  
- Geometry of lips  
- Lip opening area  
- Lip mass and elastic properties  
- Blowing pressure  
- Properties of the resonating tube (trumpet) | - Lip motion transitions between swinging motion for lower resonance frequencies and stretching motion for higher resonance frequencies, as in actual trumpet playing  
- Simulates production of sound on trumpet for first 6 resonance frequencies |
| Cullen et al. (2000)  | 1                  | - Mass of lips  
- Natural frequency and quality factor of lips  
- Distance between lips  
- Mouth pressure  
- Volume flow | - Good agreement with measured behaviour at oscillation threshold  
- Unable to accurately predict trombone slide and embouchure positions at transition points between different regimes |
| Richards et al. (2003) | 2                  | - Geometry of lips  
- Lip mass and elastic properties  
- Displacement of each lip  
- Air flow | - Simulates lip frequency response  
- Replicates lip opening area during oscillation |
### Table 1.1 continued

<table>
<thead>
<tr>
<th>Author</th>
<th>Degrees of freedom</th>
<th>Parameters included</th>
<th>Accuracy in predicting lip vibration and producing brass instrument sound</th>
</tr>
</thead>
</table>
| Kausel (2003)           | 2                  | - Geometry of lips  
- Air flow  
- Mouth, mouthpiece and Bernoulli pressures  
- Surface wave on lips  
- Lip displacement  
- Throat impedance and mouth capacitance | - Production of a whole harmonic series through increase in lip tension                                                                   |
| Lopez et al. (2006)     | 2                  | - Geometry of lips  
- Lip mass and elastic properties  
- Air flow  
- Properties of the resonating tube (cylindrical tube)  
- Properties of the throat/lungs reservoir | - No improvement from the one-mass model used by Cullen, et al. (Cullen et al. (2000))                                                      |
| Van Hirtum et al. (2007)| 1 and 2            | - Geometry of lips  
- Lip mass and elastic properties  
- Lip opening area and height of initial opening  
- Air flow | - Qualitative prediction of oscillation thresholds and frequencies                                                                       |
Meyer (1967) undertook a detailed study into the directional characteristics of the horn in three dimensions. Meyer noted that the directional characteristics of the horn were influenced by the player’s hand in the bell and also by the diffraction of sound around the player, as the instrument was held close to the body. An added complication was that of the horn’s oblique orientation. For these reasons, he considered the instrument and player as one unit. Recordings were made in an anechoic chamber using a microphone placed at ten degree intervals in the horizontal and vertical planes. As expected, results showed that the area of least radiation was to the player’s left and the maximum radiation was in the direction of the bell axis, with a secondary area of maximum radiation directly upwards (especially for high frequencies). The higher the frequency, the more narrow the concentration of radiation around these maximum directions. Below 100 Hz, the horn (including the player) essentially behaved as a spherical radiator. Meyer observed that the overall sound on the right side of the player was richer in harmonics than in front and the dynamic range was also greater. The difference in sound level radiated backwards compared to forwards was as high as 20 dB. Meyer’s diagrams showing the averaged directivity of the horn over various frequency bands are given in Figures 1.3 and 1.4.

Unlike Meyer’s use of directivity data averaged over the entire playing range of the horn, Otondo et al. (2002) investigated how the directivity of the horn changed with different played notes over the range of the horn. They used thirteen microphones to capture the horizontal and vertical directional characteristics of the instrument and recordings were made in an anechoic chamber of short notes played on the horn over its full playing range. Otondo et al. compared the measured directivities of certain notes with the averaged directivity for that frequency range and found that the directivity varied considerably from note to note. Individual note differences were also found to be greater for the vertical plane than the horizontal plane and hence, the averaged directivity was generally not representative of individual notes. Using these data, they undertook room simulations to investigate the effect of the directivity of the horn on the sound field of a room and found that the differences in directivity for different notes had a profound effect on various aspects of the simulated sound field. They concluded that the use of averaged directivity data for application in room acoustic simulations and auralisations is not ideal.

It is important to note that the bell of the horn generally faces in the opposite direction from where the sound is heard. Therefore, rear wall reflections are very important and play a large role in, not only the loudness, but most importantly the tone quality of the heard sound (both by the player and the audience). Thus, the sound heard when standing directly behind the bell of a horn, is not the same as that normally associated with the ‘sound’ of the horn (although it is generally this ‘direct’ sound from the bell of the horn that is referred to in musical acoustics as
1.1. GENERAL ACOUSTICS OF THE HORN

Figure 1.3: Diagrams showing the direction of radiation of horn sound at different frequencies in two vertical planes (left) and horizontal plane (right). The shaded area encompasses nearly all of the sound within 3 dB of the maximum amplitude. (Meyer, 1978)

Figure 1.4: Three dimensional directional characteristics of the horn and player (including screening of player). Range of amplitudes is 30 dB from the maximum value to the inner edge of the model. (Meyer, 1978)
the sound produced by the horn; see section 1.1.3.2).

1.1.3 Sound produced on the horn

1.1.3.1 Starting transient

The starting transient is the beginning section of a note, from the time the lips start to vibrate until the standing wave builds up in the instrument (see section 1.1.3.2). It plays an important role in an instrument’s sound as demonstrated by Clark et al. (1963) and Elliott (1975) who found that it was very difficult for listeners to identify the source instrument of sounds when the beginning of the note was removed. Although crucial to the sound, the starting transient is very difficult to accurately study as it generally has a very short duration, which itself is not easily defined.

In order to study the durations of starting transients, Luce and Clark (1965) defined the duration of a starting transient as the time from the beginning of the signal to the point at which the sound pressure level reaches 3 dB below that of the steady state. They investigated the effect of pitch, dynamic level, length of note and player on the durations of the starting transients of various instruments. They found that the average (over different pitches, dynamic levels and players) duration of the starting transient on the horn was 45 ms, but ranged from 20 ms to 70 ms. The duration generally decreased as pitch increased (although results showed that the durations began to increase again above G4) and also slightly decreased as the dynamic level increased. Also, there were significant differences in duration between different players.

A further study by Luce and Clark (1967) analysed the frequency components of the starting transients of horn notes. They found that the amplitudes of the high frequency components increased at a slower rate than the low frequency components and that the starting transient contained a series of rapid amplitude modulations which lasted for 15 to 30 ms. These modulations affected the higher frequency components to a greater extent than the lower frequency components. Melka (1970) found a similar effect to Luce and Clark (1965) for variation of starting transient duration with increasing pitch. Melka measured the durations of starting transients for soft and hard attacks and found that the soft attack had an average duration of more than twice that for a hard attack (106 ms versus 48 ms). This was significantly different to the results obtained by Luce and Clark (1965) which showed no significant differences between starting transient durations for notes of different length attacks (all around 45 ms). Melka (1970) attributes this difference to the player, which they consider to be the second most determining factor on the starting transient duration after the type of instrument. Meyer (1978) states that the starting
transient of the horn usually consists of harmonic\textsuperscript{3} frequency components below 1 kHz, but as the duration of the starting transient is so short, it is very difficult to measure accurately the frequency components present.

### 1.1.3.2 Quasi-steady state and sound spectrum

Once all of the harmonics have built up in the instrument, a standing wave is produced in the air column and an approximately steady state (or quasi-steady state) is achieved. This state is not entirely steady, as the air flow is not perfectly constant and low levels of broad band noise (due to the player’s production of sound) are also present. It is important to note that although the resonances of the horn are not harmonic, the partials of the horn sound are harmonic. In order to analyse the sound produced during this quasi-steady state period, a recorded sound must be transformed into the frequency domain, generally through the use of Fourier transforms. The resulting frequency information is referred to as the sound spectrum. Sound spectra for the horn have been analysed in several different studies which are described below.

Seashore (1938) made some early measurements of the sound spectra of various instruments including the horn. He noted that the recordings were made in a room in which the low frequencies were amplified due to reverberation and no information is given as to the microphone placement. Thus, Seashore acknowledges that the sound spectra are of the instrument and the room. Results were analysed to determine the percentage energy of the first ten harmonics of various notes played on the horn at both piano and forte dynamic levels (Table 1.2). The results showed that the amplitudes of harmonics were strongest between 200 and 600 Hz and that for notes below 150 Hz, the amplitude of the first harmonic (fundamental) was very small. He also found that differences in dynamic level did not correspond with a consistent change in distribution of the energy.

Meyer (1967) analysed the spectra of horn sounds recorded at a distance of 2.5 m in front of the player. He found that for notes above C4, the first harmonic had the highest amplitude. For notes below C4, the strongest harmonic stayed at approximately the same frequency (around 340 Hz) so that the fourth or fifth harmonic was strongest for the lowest notes (Figure 1.5). For these notes, the amplitudes of the harmonics below the strongest fall very rapidly. Thus for Bb1, the first harmonic is about 25 dB weaker than the strongest harmonic. Meyer attributed much of the horn’s sonorous tone to a main formant around 340 Hz.

Meyer (1967) also investigated the effect of a range of other factors on the sound spectra of the horn and found the following: the F horn has slightly more colour (especially in the middle register) than the B flat horn, due to the stronger harmonics.

\textsuperscript{3}Here the term ‘harmonic’ is used in its formal sense as a frequency component present in the sound produced.
Figure 1.5: Sound spectra for notes in a chromatic scale played on F horn, showing
the presence of a main formant region around 340 Hz in notes below C4 and the
maximum amplitude of the first harmonic in notes above C4. Note c’ = C4. (Meyer
(1967))
1.1. GENERAL ACOUSTICS OF THE HORN

Table 1.2: Percentage of energy in the first ten harmonics for various notes played on the horn. (Seashore, 1967)

<table>
<thead>
<tr>
<th>Note</th>
<th>f:</th>
<th>p:</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-466</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>A-440</td>
<td>86</td>
<td>12</td>
</tr>
<tr>
<td>F-440</td>
<td>66</td>
<td>1</td>
</tr>
<tr>
<td>A-435</td>
<td>94</td>
<td>6</td>
</tr>
<tr>
<td>F-435</td>
<td>26</td>
<td>8</td>
</tr>
<tr>
<td>C-435</td>
<td>77</td>
<td>2</td>
</tr>
<tr>
<td>F-430</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>C-430</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>A-415</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>F-397</td>
<td>1</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partial</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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</table>

on the F horn; the more valves that are employed, the weaker the harmonics become (Figure 1.6); and the dynamic level greatly influences the sound spectra. For example, for note F4 played at mezzoforte, the spectrum has significant harmonics up to about 1500 Hz, whereas at fortissimo, the higher frequency components become more important and the loudest harmonic shifts from the first to the second harmonic (Figure 1.7).

Several hundred horn notes recorded in an anechoic chamber, were analysed by Luce and Clark (1967) to determine the spectral envelope of the horn. Their results showed that the intensity levels of the frequency components present in the spectral envelope above 500 to 600 Hz drop off at a rate of about 15 dB per octave. However, for very loud playing levels, the intensity of the high frequencies increases relative to the lower frequencies, resulting in a decrease in spectral slope with increasing sound level (Figure 1.8) which is normal for sounds produced by musical instruments. Miśkiewicz and Rakowski (1994) investigated the effect of dynamic level on the shape of the spectral envelope. Recordings of scales, played at pp and ff by various instruments, were made in a reverberant room with the microphone placed one metre in front of the player. They found that for brass instruments (including the horn), the shape of the spectral envelope changed greatly with the dynamic level.

Although several of the above studies note that the sound spectra of the horn will be affected by the acoustic properties of the room, the particular instrument played, the individual player and the position of the microphone relative to the horn, only the study by Luce and Clark (1967) attempts to control for any of these parameters (by recording in an anechoic chamber, including two players on two different instruments and averaging over hundreds of recorded notes). Thus, in general, the above results cannot necessarily be referred to as characteristic of the sound spectra of the horn.
Figure 1.6: Sound spectra for A4 played on the F and Bb horns with various valve combinations. *Ventil* refers to the valves used and *Naturton* refers to the corresponding resonance number for that valve combination. (Meyer, 1967)
1.1. GENERAL ACOUSTICS OF THE HORN

Figure 1.7: Sound spectra for F4 played on the horn at pianissimo (bottom), mezzoforte (middle) and fortissimo (top). (Meyer, 1967)

Figure 1.8: Rate of rolloff for the horn spectral envelope versus the average intensity level of the scale. (Luce and Clark (1967))
1.1.3.3 Ending transient

The ending transient is the time taken for the note to decay once the lips have ceased vibrating. The air column is unable to store much energy and thus its duration is relatively short, generally about 150 ms for the horn (Meyer, 1978) and is usually not audible. This is independent of the room reverberation time which determines how long the sound remains audible. The spectral content of the ending transient differs from that of the quasi-steady state as each resonant frequency will be damped at a greater or lesser rate to the others.

1.2 Effect of mouthpiece

As the lips are a relatively large vibrator, a mouthpiece is necessary in order to couple them to the air column of the instrument. Without the increase in input impedance peaks of the resonances due to the mouthpiece, the lips would be less influenced by the air column and consequently it would be harder to produce notes with frequencies corresponding to the resonances of the instrument (Benade, 1976). Unlike the trumpet and trombone bores, which require the mouthpiece to aid in correcting the intonation of the instrument, the horn bore is designed so that the high resonances are mainly in tune (Campbell and Greated, 1987). Consequently, the resonance frequency of the horn mouthpiece (the Helmholtz resonance or ‘popping’ frequency which can be determined by slapping the mouth of the cup against the palm of the hand) is usually high to correspond to the upper end of the playing range as high frequency components of the sound are then favoured, making it easier to play high notes (Fletcher and Rossing, 1991). Whereas the trumpet mouthpiece increases the impedance peaks close to the mouthpiece resonance frequency, the horn mouthpiece amplifies the lowest frequency resonance peaks on the horn, which would otherwise be very difficult to play (Campbell and Greated, 1987).

The mouthpiece consists of a rim, cup, throat, bore, and backbore (Figure 1.9) and differences in shape and size of these components vary the tone and the ease of playing. Many studies have investigated the effect that changing various mouthpiece parameters has on the playability of the instrument, the sound produced and listeners’ ability to hear these differences in sound. However, the majority of this research has been carried out on either trumpet or trombone mouthpieces (e.g. Pratt and Bowsher, 1979, Carral and Campbell, 2002, Petiot et al., 2003 and Poirson et al., 2005). Whilst it is possible to generalise findings between these two different instruments due to the similarities in mouthpiece shape, the horn mouthpiece is very different and is more conical in nature than the cup shape of the trumpet and trombone mouthpieces. Thus, specific findings from these studies cannot be generalised to the case of the horn and will not be discussed here.

A detailed study of the horn mouthpiece was undertaken by Plitnik and Law-
1.3. Effect of bell

The bell is of great importance to the sound of the horn as well as enabling efficient radiation of the sound. It changes the frequency and height of impedance peaks, the radiation pattern (making it more directional at higher frequencies), the spectrum of radiated sound, and allows for more efficient radiation of sound (Rossing, 1990). Different bell shapes emphasise different harmonics and thus produce differences in the sound spectrum of the instrument. The greater the cross-sectional area of the bell, the greater the efficiency of radiation. A gradual flaring bell, such as that on the horn, minimises the reflection of energy and so maximises radiation. A flaring bell also imposes a transition barrier that is greater for low than high frequencies.

Figure 1.9: Horn mouthpiece.
As a result, low frequencies are reflected before reaching the mouth of the bell and thus the effective length of the horn increases with frequency. This causes the sharpening effect on low notes which makes them more in tune with the harmonic series (Fletcher and Rossing, 1991). Wachter (2008) measured the input impedance of a horn with and without a bell (Figure 1.10) and showed that without the bell, the resonance peaks are significantly higher than for the horn with bell (especially above 600 Hz), essentially raising the cut-off frequency of the instrument. This is not surprising, as the bell is designed to radiate the sound.

The effect of the bell material on the sound of the horn has been investigated by Pyle (1981) and Lawson and Lawson (1985). Pyle (1981) used a horn with a bare nickel silver bell and with the same bell lacquered or silver-plated. Recordings were made, in an anechoic chamber, of the horn played without the player’s hand in the bell. Results showed that silver-plating did not affect the sound pressure levels of the horn compared to the bare nickel silver bell. However, the presence of lacquer on the bell reduced the sound output of the horn, especially above 500 Hz. Pyle suggests that this is due to damping of the metal by the lacquer and thus, hypothesises that the presence of lacquer can darken the tone quality of the horn by decreasing the amplitudes of the high frequency components in comparison to the low frequency components. He also acknowledges that the effect is small and would likely be reduced with the hand placed in the bell in normal playing position.

Lawson and Lawson (1985) investigated the effect that bell hardness has on the sound of the horn. Using seven detachable horn bells of the same shape and size, they controlled for hardness by annealing the bells at different temperatures and for different lengths of time. Two different materials were also used – yellow brass and nickel-silver. Recordings were made without the player’s right hand in the bell so that hand position did not have to be controlled. Significant results were obtained showing that the bell made of the softest yellow brass radiated more energy around 250 Hz and less energy for frequencies between 1 and 3.5 kHz, compared with the bell

Figure 1.10: Impedance spectra for the open F horn without bell (blue), with bell (red), and with hand in bell (green). (Wachter, 2008)
made of hard yellow brass. However, the opposite was found for the nickel-silver bells, where the softest bell radiated less energy around 250 Hz and more energy above 1 kHz.

Several studies have also looked at the bell vibrations and their possible effect on the sound produced. Watkinson and Bowsher (1982) modelled the vibrations of trombone bells and found that the natural resonant frequencies of the bell were within the playing range of the trombone and thus could potentially contribute to the sound radiated. They also found that the geometry, wall thickness and material type affected the natural resonant frequencies of the bell. Results from modelling undertaken by Watkinson and Bowsher showed that generally, the resonances of the thicker walled bells had higher frequencies, but were less strongly excited than for thinner walled bells.

Moore et al. (2005) measured the sound spectrum of a trumpet played using an artificial mouth with and without damping of the bell. Damping was achieved through the placement of sandbags around the bell and the physical amplitude of the bell vibration was measured to be one tenth that of the undamped bell. They found that there were significant differences in the sound spectra between the damped and undamped bell conditions. Damping of the bell resulted in an increase in energy in the first harmonic and a decrease in one or more of the higher harmonics. However, they concluded that the differences in the radiated sound were not directly due to the radiation from the bell, but rather that the bell vibrations (or lack thereof) affected the feedback to the lips resulting in a change in sound produced. Moore et al. suggested that the bell vibrations could be affecting the impedance properties of the instrument (i.e. a change in the air column due to bell vibrations provides feedback to the lips and thus changes the sound spectra produced). However, they were unable to find any experimental evidence to support this idea. Instead, they hypothesised that the feedback to the lips occurs via the metal tubing to the mouthpiece at which point the vibrations of the mouthpiece interact with the lips’ vibrations to change the sound produced. Measurement of the amplitude of vibrations of the mouthpiece whilst playing with a damped and undamped bell, confirmed that when the bell is damped, the vibrations in the mouthpiece are considerably decreased.

A similar experiment was conducted by Nachtmann et al. (2007) with a Viennese horn (see section 1.1.1). However, in order to disprove the claim of Moore et al. (2005) that the change in the sound spectra was caused by mouthpiece vibrations, the mouthpiece was connected to the horn via a short length of flexible rubber tubing. The horn was driven using an artificial mouth and the bell was damped using sand. The horn was placed in a box with a hole in the side for the rim of the bell. Damping was achieved by burying the horn in sand (filling the box with sand). Recordings were made starting with an undamped bell (no sand in box) and gradually damped (box slowly filled with sand). Nachtmann et al. found that there
were large differences in the sound spectra produced as the bell was progressively damped and the sound produced with a fully damped bell was easily distinguishable (by listeners) from that of the undamped bell. Analysis of the sound spectra showed that damping the bell caused the amplitude of the first harmonic to increase and the higher harmonics to decrease. Generally, the higher the harmonic frequency, the greater the decrease in amplitude. They concluded that the differences in radiated sound due to damping of the bell was caused by a change in the instrument’s impedance due to changes in the boundary conditions of the bell, rather than from mechanical feedback to the lips via the mouthpiece as hypothesised by Moore et al.

1.4 Effect of hand in the bell

The horn is played with the player’s right hand placed in the bell of the horn (Figure 1.11). The hand is placed in the bell for several reasons. Firstly, the practice has been carried over from classical horn playing before valves were invented. At this time, changing the position of the hand in the bell was used to obtain notes that were not part of the harmonic series of the instrument. Secondly, high notes are made easier to play by increasing the reflection of high frequencies allowing standing waves to build up in the instrument. Thirdly, the quality of sound is changed, making it more mellow, and finally, intonation can be finely tuned by making small changes to the hand position. Placing the hand in the bell restricts the area of the bell, which increases the acoustic mass and hence, decreases the frequencies of resonances in the air column. Consequently, the horn will play sharp if the hand is not placed in the bell.

The effect that the hand has on the impedance spectra of the horn (Figure 1.12) has been illustrated by many researchers (e.g. Benade, 1976, Backus, 1976 and Benoit and Chick, 2006). As Figure 1.12 shows, the frequencies of the resonances are slightly lower with the hand placed in the bell and the amplitudes of the resonance peaks are considerably higher above 400 Hz. Without the hand in the bell, resonances cease to exist above approximately 700 Hz. The frequency at which the open bell fails to provide strong reflections (i.e. resonances) is called the cutoff frequency of the bell. Without the hand in the bell, notes with frequencies above the cutoff frequency of the bell (approximately 450 to 550 Hz on the horn) are almost impossible to play as there are no strong resonances in the instrument. The presence of the hand in the bell increases these resonances and allows high frequency notes to be played more easily.
1.4. EFFECT OF HAND IN THE BELL

Figure 1.11: Player’s right hand in bell in playing position. (Farkas (1956))

Figure 1.12: Impedance curves for the natural horn in Bb with hand in bell (top) and without hand in bell (bottom). (Benade, 1976)
1.5 Effect of the instrument

Since the development of an artificial mouth which is able to ‘play’ a brass instrument, much of the research investigating the effect of various parameters on the sound of an instrument has adopted this method so as to remove individual player effects from consideration. Of course, in order to achieve this, the artificial mouth must exhibit a very high level of reproducibility (difficulties of which are discussed in Bromage et al. (2003)) and be able to play a reasonable range of notes. Petiot et al. (2003b) built an artificial mouth specifically for the purposes of studying and comparing different instruments. Their aim was to make the artificial mouth more compact and easier to use so that it could be operated by instrument makers for testing and comparing instruments. They successfully carried out preliminary comparison measurements on two different trumpets.

It is obvious that different shaped instruments will sound different as the sound produced is related to the resonant properties of the instrument. For example, qualitatively, a narrow bore horn (commonly used in Europe) produces an audibly different sound to a large bore horn (commonly used in North America). However, the instrument also has the potential to influence the playability and sound produced in several other ways: material from which the horn is made; wall vibrations in the instrument; and inserts placed in the instrument. It is also interesting to compare the differences in playability and sound produced on student versus professional models, although little research has been conducted in this area.

As previously discussed in section 1.3, Pyle (1981) and Lawson and Lawson (1985) found that the material and hardness of annealing of the bell had a significant effect on the sound produced on the instrument. Lawson and Lawson hypothesised that the bell was the only section of the horn that would be affected by material type, as the rest of the instrument mainly consists of unyielding cylindrical tubing. Although players and other musicians claim to be able to hear differences between instruments made out of yellow brass, rose brass and nickel-silver, no qualitative experiments have been undertaken (other than the two mentioned above which focused on the bell).

The effect of different materials on the sound of the flute was investigated by Coltman (1971) and Widholm et al. (2001). Coltman used keyless flutes made from silver, copper, and wood and found that in blind tests, neither players nor listeners could significantly correlate the flute sounds with the different materials. Similarly, Widholm et al. (2001) used the same model of flute made from different materials (silver coated, silver, gold (9, 14, and 24 karat), platinum coated and platinum) and again found that in blind tests, neither players nor listeners could distinguish between the sound or dynamic range of the different flutes. Just measurable differences were found to exist in the sound produced due to the different materials, but these were very small compared to the differences produced by any one player
1.5. **EFFECT OF THE INSTRUMENT**

(intraplayer differences). Interestingly, instrument makers have experimented with trombones made of wood (Wooden trombone 2009 and Wooden trombone bell 2010), glass (Glass trombone 2010), and plastic (jiggspbone n.d.), however, no quantitative measurements have been made on these instruments.

The wall vibrations of the instrument’s tubing (see section 1.3 for effect of bell vibrations) and their effect on the radiated sound of brass instruments has also been researched by Knauss and Yeager (1941), Whitehouse et al. (2002) and Whitehouse et al. (2003). Knauss and Yeager measured the vibrations of the walls of a cornet at various positions throughout the instrument. They found that the sound level produced when the walls were artificially forced to vibrate at frequencies corresponding to particular playing frequencies (at the same level as that measured in actual playing), was insignificant to the sound level produced by actual playing of the instrument. They concluded that the sound produced by the wall vibrations would be completely masked by the sound due to the vibrating air column.

The studies by Whitehouse et al. (2002) and Whitehouse et al. (2003) used an artificial mouth coupled to a trombone mouthpiece and length of cylindrical tubing in order to measure the vibrations in the walls of the tubing. They first determined the structural modes (i.e. the natural resonances of the wall of the pipe) of the instrument by rigidly clamping the ends and mechanically driving the tubing, close to the mouthpiece, over a range of frequencies. Results showed that playing the instrument using the artificial mouth caused the walls of the cylindrical tubing to vibrate at frequencies similar to those of the air column (rather than the structural modes of the instrument’s tubing). Whitehouse et al. (2002 and 2003) also investigated the method of excitation of these vibrations and found that the wall vibrations were predominantly due to the direct coupling of the tubing with the mouthpiece and the vibrating lips, rather than from the vibrating air column. They also noted that the amplitude of the wall vibrations depended on the closeness in frequency of the structural resonances and the air column resonances produced when playing. From their measurements, Whitehouse et al. did not draw any conclusions as to whether or not the magnitude of the wall vibrations were large enough to affect the produced sound.

The most dramatic way of affecting the playability and sound of a brass instrument is to place a mute in the bell. There are many different types of mute available and each has a different effect on the sound. A detailed discussion on horn mutes is presented in section 1.7. Another more subtle and less common method of changing the playability and sound of the horn is that of placing various inserts in the actual tubing of the instrument. This practice of adding various objects (e.g. part of a matchstick or paperclip through a small piece of eraser) across various sections of valve tubing, is outlined by Leuba (2000). The addition of these inserts improved the playability of specific notes which would otherwise have very poor response (i.e.
difficult to centre). Leuba hypothesised that poor response of a particular note was due to turbulence at a nodal point for that resonance due to a sharp bend in the tubing or proximity to a valve. He proposed that the insert works by creating turbulence at another point, thus alleviating the turbulence at the nearby nodal point. However, Leuba suggested that further investigation into the phenomenon was required before a detailed and accurate explanation could be given. Although the addition of an insert was found to improve the response of particular notes on particular instruments, not surprisingly, it was also found to negatively affect the response of other notes on the instrument.

1.6 Effect of player

There are many factors that influence the musician during the playing of a brass instrument. Bouhuys (1969) approached this topic from a physiological standpoint and suggested that the following factors influence the player of a brass instrument: memory, coordination, motor pathways, respiratory muscles, face, arm and finger muscles, and auditory feedback. The approach of Bertsch (1997) is much more comprehensive. He splits the player’s influences into three categories, which he then breaks down into further influences (Table 1.3). As can be seen from this exhaustive list proposed by Bertsch, a player is influenced by an extremely complex array of factors whenever a sound is produced on the instrument. Thus, it is obvious that different players will produce different sounds even when playing on the same instrument (referred to as interplayer differences).

Research into several of the above influences, such as vocal tract, hand in the bell, and player experience will be discussed briefly. The effect of the player’s vocal tract on sound produced on the trombone was investigated by Wolfe et al. (2003). The trombone was ‘played’ by an artificial mouth coupled to two cavities which together represented the vocal tract, vocal folds and lungs. Two vocal tract configurations were used corresponding to playing with the tongue tip high in the mouth and with the tongue placed low in the mouth. They found that the different vocal tract configurations affected the sound spectra produced on the trombone by changing the intonation. The frequencies of the partials present in the sound were sharper with the high tongue tract (by approximately 20 cents) than for the low tongue tract. Thus, results showed that the vocal tract of the player does affect the sound produced on the trombone and that the player can vary the resonances of the vocal tract (and hence the entire instrument) by raising or lowering the tongue position in the mouth.

However, the study by Wolfe et al. (2003) occurred before measurements of the impedance in brass players’ mouths had been made and thus, the models used may have overestimated the effect of the player’s tract. A more recent study by Chen et
Table 1.3: Factors influencing the player. (Bertsch, 1997)

<table>
<thead>
<tr>
<th>Intention of the player</th>
<th>Ability of the player</th>
<th>Realisations of the played note</th>
</tr>
</thead>
<tbody>
<tr>
<td>- musical background</td>
<td>- talent</td>
<td>- motivation</td>
</tr>
<tr>
<td>- general music style</td>
<td>- age</td>
<td>- concentration</td>
</tr>
<tr>
<td>- specific context of the next note</td>
<td>- I.Q.</td>
<td>- situation</td>
</tr>
<tr>
<td></td>
<td>- education level</td>
<td>- psychological constitution</td>
</tr>
<tr>
<td></td>
<td>- educational style of teacher</td>
<td>- frame of mind</td>
</tr>
<tr>
<td></td>
<td>- experience</td>
<td>- health</td>
</tr>
<tr>
<td></td>
<td>- regional influence</td>
<td>- playing technique</td>
</tr>
<tr>
<td></td>
<td>- familiarity with instrument</td>
<td>- air flow</td>
</tr>
<tr>
<td></td>
<td>- physiological constitution</td>
<td>- lip oscillation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- embouchure pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- tongue position</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- instrument placement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- actual muscle control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- fingering</td>
</tr>
</tbody>
</table>

al. (in press) measured the mouth impedance of trumpeters whilst they played very high notes, notes with pitch bending and notes over a normal range. They found that the mouth impedances varied from player to player, but no player showed systematic changes in mouth impedance due to the frequency of the note played.

As the horn is played with the player’s right hand placed in the bell (see section 1.4), this is an obvious area in which the player can affect the sound produced. Every horn player’s hand is a different size and geometry, and is placed in the bell in a slightly different shape and position. The effect of these different variables has not been reported in the literature. Impedance measurements that have included the hand in the bell, have used a variety of ‘hands’. For example, Backus (1976) used a lump of plasticine to simulate a hand and Widholm (1988) used an unspecified artificial hand. Benoit and Chick (2006) measured the impedance of the horn with two different player’s hands in the bell. Considerable differences in both the frequencies and amplitudes of impedance peaks were clear between the two, however, no reference was made to this.

The effect of the player’s experience on various aspects of brass instrument playing has been commented on in various studies. In order to sound high notes on the trumpet, Henderson (1942) found that a less advanced player used approximately twice as much mouthpiece pressure as a professional player. Webster (1949) found that experienced trumpet players compensate for poor intonation, whereas less experienced players simply allow the instrument to dictate the frequency placement of the note. Basmajian and White (1973) investigated the facial muscles of
trumpeters and showed that, for advanced players, there was more neuromuscular activity in the muscles around the lips than those in the lips. However, for less advanced players, there was no difference in activity between the muscles around the lips and those in the lips. Yoshikawa and Muto (2003) observed the motion of horn player’s lips and found differences between advanced and less advanced players. The three-dimensional motion of the lips was reduced to almost two-dimensional motion in advanced horn players and this was accompanied by a change in the produced sound spectra. It was also found that less advanced players were unable to produce a distinct surface wave on the upper lip, unlike the advanced players.

Apart from expected differences between players, there can be quite large differences in sound produced by any individual player. This is perhaps not surprising when considering the large number of variables proposed by Bertsch (1997) that influence an individual player at any given time. These intraplayer differences are often as large, or almost as large, as any measurable interplayer differences, making it difficult to accurately compare the sounds produced by different players or indeed the same player. For example, in his study on Bassoon sound, Lehman (1964) found that the intraplayer differences were as much as 75% of interplayer differences.

1.7 Mutes

Brass instrument mutes fall into two different categories – those which are designed primarily to change the timbre of the sound and those which are designed primarily to reduce the sound level. There are many different types of mutes (more so for the trumpet and trombone than for the horn) and for each type there exist many different makes and models which are made of different materials and have different geometries. The majority of research on brass instrument mutes has focused on trumpet mutes and their effect on the impedance and sound spectra. For example: Ancell (1960) compared the sound spectra of a cornet played normally (open bell) with those of the cornet played with a straight, cup, harmon, and solotone mute placed in the bell; Bertsch (1995) investigated the effect of various different types of trumpet mute (straight, cup, harmon, plunger, wah-wah and velvet) on the sound level range, sound spectra, radiation of sound and responsiveness of the instrument; and Kühtreiber (2004) measured the impedance and sound spectra of a trumpet with thirteen different models of straight mute.

There are only three different types of horn mutes commonly used – straight, stopping, and practice mutes.\(^4\) By far, the most researched of these three is the effect of the stopping mute on the horn impedance and sound spectra (see section 1.7.2). However, Kurka (1961) compared the sound spectra of the horn with and without two different types of mutes and Smith (1980) investigated the geometric and

\(^4\)Denis Wick’s mute catalogue has, in the past, also included a cup mute for the horn.
acoustic properties of straight mutes (see section 1.7.1) and provided a review of the geometries, materials and sound qualities of fourteen different straight mutes commercially available at that time.

Horn mutes were also included in the study by Sluchin and Caussé (1991) which investigated the acoustic properties of various brass instrument mutes along with their effects on the impedance spectra and radiated sound (including the length of the starting transient and directivity of the sound). They also discuss the effect of the material on the sound of the mute. Interestingly, it is mentioned that horn mutes have to be more complex than those for other brass instruments, as there is the difficulty of having to remove the hand from the bell (and hence the effects of the hand on the acoustics of the horn) in order to insert a mute. Sluchin and Caussé (1991) also proposed and designed a waa-waa mute for horn.

1.7.1 Straight mutes

The straight mute is a non-transposing mute (i.e. the mute does not change the pitch of the note played) which is designed to change the timbre of the horn sound and also damp the sound slightly. There are two different geometric designs commonly used for the straight mute (Figure 1.13) with some models having an adjustable inner shaft to enable the mute to be tuned. Straight mutes can be made from many different materials, such as wood, fibreboard or cardboard, composite (plastic), fibreglass, or aluminium. Essentially, the straight mute acts as a Helmholtz resonator with an aperture, enclosure and neck. However, the neck is inverted and is contained within the enclosure so that the mute appears smaller in volume. According to Smith (1980), the Helmholtz resonance of horn straight mutes generally fall between 110 and 165 Hz.

There is great variation among straight mutes in regards to their intonation, quality of sound, sound attenuation, and ease of playing (as shown in the review by Smith (1980) of fourteen different straight mutes in which he included comments on the intonation and sound quality of each mute). Indeed, some players own more than one straight mute for use in different playing contexts. In his analysis of the

Figure 1.13: Two different designs of straight mute for horn. The model on the right has an adjustable inner tube.
sound spectra of the horn with and without a straight mute in the bell, Kurka (1961) found that the straight mute adds higher harmonics to the sound whilst reducing the amplitude of the fundamental, making the horn sound brighter. It also lowers the pitch in the middle register and increases the pitch in the low and high registers.

1.7.2 Stopping mutes

Playing stopped notes on the horn can be achieved either with a stopping mute (Figure 1.14a) or by covering the throat of the bell with the hand (Figure 1.14b). Both methods result in a distinct change in the timbre of the sound, making it more ‘nasal’ in quality. This is due to the change in distribution of energy in the harmonics which extend above 10 kHz for the stopped sound. The difference in sound spectrum between a normally played note and a stopped note is shown in Figure 1.15. Stopping produces a shift in pitch of the played note (approximately one semitone higher for notes in the middle register of the F horn) and thus the stopping mute is referred to as a transposing mute. Originally stopping was part of the hand horn technique used on the natural horn to obtain the 7th note in the diatonic scale. However, composers tended to avoid including this note in horn parts due to the distinctly different sound produced. Since the development of the modern horn, stopped notes have been included in horn pieces specifically to utilise this change in timbre.

In general the hand is used for stopping, as it enables quick changing between normal sound and stopped sound. However, this requires that the player be experienced in hand stopping as slight changes from the optimal hand position and shape will result in a muffled, unsteady, and out of tune sound. Hence, the use of a stopping mute is more reliable, but also more cumbersome. A stopping mute must be used when notes below C4 (written horn pitch) are stopped, as the hand is unable to produce a stopped sound for low notes.

There has been much debate as to why stopping produces a pitch increase, when a gradual covering over of the bell by the hand produces a gradual decrease in pitch.

Figure 1.14: (a) Stopping mute in bell of horn and (b) position of hand in bell for playing stopped notes.
However, experiments by Backus (1976) have shown that the increase in pitch is caused by the ‘jumping’ up of the note to the resonance above. That is, stopping causes the pitch of the note to decrease to a point where the pitch of the next highest resonance is approximately a semitone above that of the original note. Although it is commonly considered that the pitch increases by a semitone (and thus, the player must use the fingering corresponding to the note a semitone lower in order to produce the written pitch), the exact increase depends on the frequency of the note being played and thus, horn players tend to use a variety of alternative fingerings to produce the required pitched note, especially in the high register.

Luce and Clark (1967) recorded stopped notes played on a horn and analysed the resulting spectral envelope. They found that the amplitudes of the high frequency components decreased at approximately twice the rate of the open horn for both soft and loud playing. Kurka (1961) also recorded the horn playing with a stopping mute and found that the amplitudes of the high frequency components were greatly increased which would result in a ‘sharper’ sound than for the horn played normally.

Backus (1976) demonstrated the effect of a stopping mute on the input impedance spectra of the horn. He also hypothesised that the change of sound quality when the horn is stopped (using the hand) is due to small spaces between the fingers acting as high-pass filters, resulting in an increase in the ratio of the amplitudes of high frequency components to low frequency components. Backus also concluded that with the stopping mute in the bell of the horn, the second resonance in the impedance spectra almost disappeared (Figure 1.16). However, with advances in impedance measuring equipment, Wachter (2008) showed that although the second resonance has a much smaller peak than any of the other resonances, it nevertheless has a well defined peak shape (Figure 1.17).

Wachter (2008) undertook a detailed study of the effect of the stopping mute on
the acoustics of the horn with the aim of developing a simplified simulation model for the stopped horn. He measured the impulse response, transfer function and input impedance of the stopped and open horn. Wachter confirmed the findings of Backus (1976) and demonstrated that there is a continuous transition in the impedance spectra (and thus, pitch) between the open and stopped horn (Figure 1.18). He also found that removing the bell of the horn (Figure 1.19) does not affect the impedance spectra of the horn with stopping mute (Figure 1.20).

### 1.7.3 Practice mutes

The practice mute is only used whilst practising, rather than during a performance. There are many different models of practice mutes available (e.g. see Figure 3.10), each having a different design and made from a different material (similar to those
Figure 1.18: Impedance spectra for the open F horn with stopping mute at various amounts of insertion in bell, showing transition of resonance peaks from stopped horn to open horn. (a) stopping mute placed at 0 mm (fully inserted) to 5 mm out from throat of bell. (b) stopping mute placed at 0 mm (fully inserted) to 25 mm out from throat of bell. (Wachter, 2008)

Figure 1.19: Horn with stopping mute, bell detached. (Wachter, 2008)
for the straight mute; see section 1.7.1). Unlike the straight and stopping mutes which are designed to change the quality of the sound output of the horn, the sole purpose of the practice mute is to decrease the amplitude of the output sound. Sluchin and Caussé (1991) mention the practice mute for brass instruments, but do not discuss its effect on the instrument. Dishman (2005) produced a detailed evaluation of sixteen different models of trumpet practice mute. Each mute was subjectively rated on its intonation, sound quality, volume, and openness or ease of playing. Results showed that there were large differences between mutes in all categories and no correlations were observed across categories for any one mute. The effect that practice mutes have on the input impedance of the instrument as well as correlations with the playability of the mute do not appear to have been researched.

1.8 Concluding remarks

The purpose of this chapter has been to introduce the horn – its geometry, acoustics and sound – and provide an outline of the various factors which affect the acoustics and sound of the horn. At the same time, a background to the previous research that has been carried out in the area of brass acoustics and, more specifically, horn acoustics, has been examined. As can be seen, research relating specifically to the horn lags far behind that of the trumpet and trombone and there are large gaps in certain areas of the literature (especially the effect of mutes on the acoustics and playability of the horn, and detailed studies on the effect of the horn player’s hand in the bell).

In order to obtain much of the data and information that have been presented in this chapter, researchers have employed various methodologies which are commonly used in the field of musical acoustics research. These methodologies pertain to the collection of acoustic input impedance data, the production of sound recordings and
their analysis, and the collection of data relating to subjective perceptions of instruments and the sounds produced. Details of some of these methodologies relevant to the studies in this thesis are presented in the next chapter.
Chapter 2

Experimental methods in musical instrument research: Review of relevant literature

This thesis is concerned with various aspects relating to the acoustics and playability of the horn, and research relating to this area was presented in the previous chapter. However, in order to collect and analyse data, various different methodologies must be employed. Thus, this chapter outlines several of the main methodologies used in musical instrument research which are pertinent to this thesis, along with examples of their uses in the literature. The methodologies are divided into three main sections: objective measurements (including input acoustic impedance and analysis of recorded sound); subjective responses (including those of the player and listener); and the objective measurement of essentially subjective experiences, such as the effect on the player of auditory and non-auditory feedback. This is followed by a detailed description of the aims and objectives for this research.

2.1 Objective measurements in musical instrument research

2.1.1 Input acoustic impedance

Input acoustic impedance \((Z)\) is defined as the ratio of acoustic pressure \((p)\) to acoustic volume flow \((u)\):

\[
Z = \frac{p}{u}
\]  

(2.1)

It can be used to characterise and compare the resonance properties of wind instruments as it is an objectively measured property specific to a particular instrument and is completely independent of the player. Informally, one could say that the
impedance spectrum is the frequency response of the instrument over the frequency range measured. For musical instruments, the spectrum consists of several (or more) large impedance peaks (or troughs in the case of the flute). The frequency, height and width of these peaks has some correlation with the quality of the instrument and the ease of playing the corresponding notes (see sections 2.1.1.2 and 2.1.1.3).

2.1.1.1 Measurement of input acoustic impedance

In very simple terms, $Z$ is measured by inputting sound waves of many frequencies to the instrument, where the mouth would normally be placed, and recording the sound or sound pressure that is reflected back. Many $Z$ measurement techniques have been developed over the past eighty-five years and detailed reviews of the various techniques have been published by Benade and Ibisi (1987), Dalmont (2001) and Dickens et al. (2007). In general, measuring $Z$ involves the use of a loudspeaker coupled to an impedance head (consisting of one or more microphones or transducers mounted in a short cylindrical duct) which is then coupled to the instrument to be measured. The impedance head must be calibrated otherwise large errors will be present in the $Z$ data (see Dalmont (2001) and Dickens et al. (2007) for a review of calibration methods).

The three microphone, two calibration technique developed by Dickens et al. (2007) provides accuracy in $Z$ over a broad frequency range due to the use of three microphones and precision because of the choice of only non-resonant calibration loads. One of the experimental setups is shown in Figure 2.1. The input signal, consisting of the sum of components of all sampled frequencies, is generated by a computer and fed into the impedance head through a loudspeaker (via a truncated cone to match impedances). The frequency range that can be measured using this apparatus is very large (e.g. 25 Hz to 4 kHz). However, the smaller the range, the more energy can be used for each frequency, which improves the signal to noise ratio. The high frequency limit is imposed by the smallest microphone separation. The impedance head is not one dimensional and consists of a brass tube in which three non-identical condenser microphones are mounted (for specific details, see Dickens et al. 2007). The following two non-resonant calibrations are used: 1. Quasi-infinite impedance – thick brass plate; and 2. Almost purely resistive impedance – ‘infinitely’ long narrow pipe (142 m) which provides wall losses of 80 dB.

The output signal (from the loudspeaker) has an equal distribution of energy. However, this does not result in an equal distribution of errors and the error is greater for the impedance peaks (and troughs) which are the regions of interest when measuring wind instruments. Dickens et al. (2007) found that changing the distribution of energy in the output signal significantly reduced the error in the produced $Z$ spectrum. By estimating the error from a first measurement, the output signal can be changed to minimise these errors by supplying more power at
2.1. OBJECTIVE ANALYSIS

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Figure 2.1: Setup of a three microphone, two calibration impedance measurement apparatus used by Dickens et al. (2007).

particular frequencies. This is done over two or three iterations so that the final error is distributed evenly over the full frequency range and the errors at the maxima/minima are greatly reduced. Thus, using this three microphone, two calibration technique for measuring the $Z$ of wind instruments provides very accurate data on the resonances of the instrument.

2.1.1.2 Use of input acoustic impedance to characterise musical instruments

As explained in section 2.1.1, the input acoustic impedance can be used to characterise and compare different musical wind instruments. Many of the studies discussed in Chapter 1 made use of the impedance spectra for the following: to generally determine the effect that the mouthpiece and bell have on the resonant behaviour of the horn (Campbell and Greated, 1987, Rossing, 1990 and Fletcher and Rossing, 1991); to compare different mouthpieces (Plitnik and Lawson, 1999); to compare the horn with an open bell and hand placed in the bell (Benade, 1976, Backus, 1976, Widholm, 1988 and Benoit and Chick, 2006); and to examine the effect of mutes on the resonant properties of the instrument (Backus, 1976, Kühtreiber, 2004 and Wachter, 2008).

Other studies that have measured the input acoustic impedance of wind instruments can be placed into the following categories based on the aim of the research: to elucidate the general resonant properties of various wind instruments (e.g. Backus, 1974 and 1976); to compare properties of different instruments (e.g. Wolfe et al., 2001); to obtain data for the purposes of simulation or bore reconstruction (e.g. van Walstijn et al., 2002, Kausel, 2004 and Benoit and Chick, 2006); to correlate features of the impedance spectra with various objectively measured features of the sound spectra (see section 2.1.1.3); and to correlate the impedance spectra with subjective
parameters, such as sound quality and playability (see section 2.2.1).

Backus (1974) and Backus (1976) produced representative impedance spectra for various notes (fingerings) on the clarinet, oboe, bassoon, saxophone, trumpet, trombone and horn. These studies were limited to the measurement of only one of each type of instrument and thus, the results are of a general nature. Wolfe et al. (2001) compared the impedance spectra of a classical and modern flute and found that there were significant differences in the high frequency resonances. They also used the impedance spectra to compare the same classical flute with different foot joints.

Input impedance data were collected by van Walstijn et al. (2002) and Kausel (2004) for the purposes of reconstructing the geometrical shape of the acoustic bore. The aim of this procedure was to enable comparisons of the geometry of a bore (or musical instrument) with its acoustic response, without previously knowing the geometry of the bore or having to measure its geometrical shape. Similarly, Benoit and Chick (2006) measured the input impedance of the horn with hand in the bell for the purposes of developing a computer simulation for the instrument and hand combination.

2.1.1.3 Relationship between impedance peaks and playing frequencies

Although the playing frequencies on a brass instrument are related to the resonances of the instrument, they are not exactly the same as the impedance peak frequencies. This is due to the coupling of the players lips with the resonating air column. The relationship between the impedance peaks and playing frequency has been investigated by Fletcher (1993) through the use of simplified models. He showed that the playing frequency is close to the impedance peak as long as the acoustic load has a sharp resonance with large acoustic impedance. The acoustic load refers to the load across the reed due to the combination of both the upstream (player’s mouth, vocal tract, airway and lungs) and downstream (bore of instrument) pressure and flow components.

Benade (1985) used a simple model of the load on an autonomous valve to show that the impedance loading the oscillation generator ($Z_{\text{load}}$) is:

$$Z_{\text{load}} = (Z_{\text{tract}} + Z_{\text{bore}}) \parallel Z_{\text{reed}}$$  \hspace{1cm} (2.2)

The following approximations are also commonly made: the impedance of the reed ($Z_{\text{reed}}$) is very much larger than the impedances of the vocal tract ($Z_{\text{tract}}$) and the bore ($Z_{\text{bore}}$) resulting in the acoustic load approximating that of $Z_{\text{tract}} + Z_{\text{bore}}$; and the vocal tract impedance ($Z_{\text{tract}}$) is very much smaller than the bore impedance ($Z_{\text{bore}}$) which gives the simplest model of $Z_{\text{load}} = Z_{\text{bore}}$. Thus, based on a simple model for autonomous valves, Fletcher (1993) shows that the playing frequency is determined by the impedance of the acoustic load, the valve’s geometry and natural
2.1. OBJECTIVE ANALYSIS

Several studies have investigated the impedance of the vocal tract for clarinet and saxophone playing (e.g. Fritz et al., 2003, Fritz and Wolfe, 2005, Fritz et al., 2005, Chen et al., 2009 and Chen et al., 2011), but the impedance of the lip-reed player’s vocal tract has not been widely investigated. The majority of research in this area, for lip reed instruments, has focused on the didjeridu (e.g. Wolfe et al., 2003, Tarnopolsky et al., 2005 and Tarnopolsky et al., 2006). However, a study by Wolfe et al. (2003) included the trombone and the trumpet player’s mouth impedance has been investigated by Chen et al. (in press; see section 1.6). Results from these two studies indicate that the effect of the vocal tract impedance on brass instrument playing is much smaller than on the clarinet, saxophone or didjeridu. Wolfe et al. (2009) explains that this is due to the cross section of the bore at the mouthpiece being much smaller than that of the vocal tract.

As the lip reed is generally considered to act as an outward-striking reed for low notes and a sideways-striking reed for higher notes (see section 1.1.2.1), theory states that the playing frequency should be higher than both the frequency of the reed (lips) and the frequency of the bore (Fletcher, 1979). Studies by Petiot et al. (2003b) and Petiot et al. (2005) have shown that this is the case for the trumpet when it is played normally with warm air (37° from the player). When an artificial mouth was used, the air was colder (20°) and the playing frequencies were lower than the corresponding resonances for some notes.

2.1.2 Analysis of recorded sound

In order to analyse the sound produced by a musical instrument, the instrument must firstly be played, the sound recorded, and then the sound data analysed. However, for each of these stages there are various considerations which must be taken into account, as they can affect the final results. Possible considerations for each of the stages are shown in Table 2.1. Of course the final choices made will depend on many factors, such as the instrument, availability of players and equipment, and the aim of the study. The analysis of recorded sounds is further complicated by the lack of repeatable data when humans are involved in playing the instrument (see section 1.6).

2.1.2.1 Objectively measurable differences

The analysis of sound data is limited by various factors relating to the repeatability of measurements and the error due to digitisation. Any differences in the data that are measurable (outside of any error present) are referred to as objectively measurable differences. Often the measurements are averaged over time, either over a whole note or over many notes. Several objectively measurable quantities commonly used
Table 2.1: Examples of choices that may affect results when analysing musical instrument sounds.

<table>
<thead>
<tr>
<th>Playing of sound</th>
<th>Recording of sound</th>
<th>Analysis of sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>- representative or multiple instrument/s</td>
<td>- anechoic chamber or reverberant room</td>
<td>- time or frequency domain</td>
</tr>
<tr>
<td>- artificial or real player</td>
<td>- placement of microphone(s)</td>
<td>- averaged data or single measurements</td>
</tr>
<tr>
<td>- one or multiple player/s</td>
<td>- type of microphone and recording equipment</td>
<td>- FFT parameters (e.g. sampling size, windowing)</td>
</tr>
<tr>
<td>- experience level of player(s)</td>
<td>- sampling and bit rate</td>
<td>- features to analyse (e.g. spectral envelope, spectral centroid, harmonicity, formants)</td>
</tr>
<tr>
<td>- musical excerpt(s) to be played</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- number of repetitions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- style of playing (e.g. articulation, dynamic level, register)</td>
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</table>

in the analysis, characterisation, and comparison of musical instrument sounds are: spectral envelope; spectral centroid; harmonicity; and formant regions.

2.1.2.2 Spectral envelope

The spectral envelope is obtained by interpolating over frequency, the combined amplitudes of the frequency components over a range of notes (Figure 2.2). The notes chosen are usually consecutive notes in a chromatic scale, played at the same sound level. Any range may be chosen so that the full frequency range of interest is represented in the frequencies of the partials. For example an octave chromatic scale could be used, although the octave note should not be duplicated as this would load the amplitudes of those frequency components. The spectral envelope has been used by many researchers for the characterisation and comparison of various musical instrument sounds (e.g. Luce and Clark, 1967, Benade and Lutgen, 1988, Miśkiewicz and Rakowski, 1994, Fletcher and Tarnopolsky, 1999, Carral and Campbell, 2002, Fritz et al., 2005 and Tarnopolsky et al., 2006). It is also considered an important and easily manipulated parameter in the synthesis of realistic musical instrument sounds (e.g. Strong and Clark, 1967, McAdams et al., 1999 and Horner et al., 2004).

2.1.2.3 Spectral centroid

The spectral centroid \( S_c \) indicates the ‘centre of mass’ of the frequency spectrum. That is, the amplitude weighted mean of the frequencies present in the spectrum. It is calculated using the following formula:

\[
S_c = \frac{\sum_{n=0}^{n-1} f(n)x(n)}{\sum_{n=0}^{n-1} x(n)} \tag{2.3}
\]

where \( x(n) \) is the magnitude for the frequency corresponding to bin number \( n \) and \( f(n) \) is the centre frequency of that bin, with both \( x(n) \) and \( n \) being linear. Spec-
2.1. OBJECTIVE ANALYSIS

Figure 2.2: Waveform of two octave chromatic scale (bottom) and resulting sound spectra (top; black) and spectral envelope (top; red). (Magnitude with arbitrary units.)

The spectral centroid has been found to correlate well with the psychoacoustic parameter of brightness (see section 2.2.1). For musical instruments, the spectral centroid generally increases with increasing sound level intensity, as found by Beauchamp (1982) for trumpet and saxophone notes. This occurs because more energy is present in the higher harmonics of the sound when played more loudly.

2.1.2.4 Harmonicity

Harmonicity refers to the ratio of the frequencies of each partial to the frequency of the fundamental. For a sound to be perfectly harmonic, each partial frequency will be an integer multiple of the fundamental frequency ($f_1$):

$$f_n = nf_1$$  \hspace{1cm} (2.4)

Some musical instruments produce inharmonic sounds, such as those belonging to the tuned percussion family and it has long been known that some plucked or struck string instrument sounds deviate from harmonicity (Fletcher, 1964). Brass, wind and bowed string instrument sounds are harmonic due to the periodic excitation of the sound, as measured by Brown (1996). The term ‘harmonicity’ can also be applied to the resonances of an instrument, through an investigation of the peaks (or troughs) in the impedance spectrum.
2.1.2.5 Formant regions

In this context, formants refer to frequency regions in which the amplitudes of partials are increased relative to those of other frequencies. These frequency regions may or may not correspond to speech formants which are due to the shape of the mouth used to produce various vowel sounds (Fant, 1960). Formant regions have been used to characterise the sound produced by various musical instruments. According to Meyer (1978), for musical instrument sounds, the formant regions generally stay constant over a range of notes played (e.g. see Figure 1.5). The main formant region also tends to increase in frequency with increasing dynamic level. An example of the horn formants observed by Meyer (1978) are shown in Figure 2.3.

![Figure 2.3: Formant positions for various different types of horn. (Meyer (1978))](image)

2.2 Subjective responses in musical instrument research

Subjective responses to musical instruments encompass both player responses to playing the instrument and listener responses to the produced sound. In collecting and analysing subjective data, there are many difficulties inherent in the subjectivity and reliability of responses such as, the use of appropriate terminology, reliable data collection techniques and the correlation of qualitative (subjective) parameters with quantitatively (objectively) measured parameters. The use of appropriate terminology is important as musicians and acousticians usually have different terms
for the same parameter. Even amongst musicians, there are a wide variety of terms in common usage which may refer to the same psychoacoustic property and which may or may not have identical meaning.

This section will present some of this terminology through a look at some of the research into correlations of various subjective parameters with objectively measurable differences, with a specific focus on brass instruments. This is followed by an introduction to the two main methodologies used to collect subjective data (multidimensional and semantic differential scales) and an overview of the use of player and listener responses in the literature.

### 2.2.1 Correlations with objectively measurable differences

Many studies have attempted to relate either players’ or listeners’ subjective responses to an instrument, to the objectively measurable parameters responsible for these judgments. However, this process is quite complex for several reasons: a player is able to determine very subtle differences between different instruments and responses may not be the same from one player to another; both players’ and listeners’ responses will be influenced by their own preferences for an instrument or sound; the human ear is very sensitive to sound; differences may be smaller than objectively measurable differences; and a particular subjective parameter does not simply correlate to an objectively measured parameter. Not all subjective parameters are necessarily relevant to every type of instrument. Some common subjective parameters used by players and listeners to analyse an instrument or its sound are listed in Table 2.2 along with their possible objective parameter correlates.

Objective correlates to selected subjective parameters used in response to brass instruments have been investigated in several studies (Pratt and Powsher, 1979, Widholm, 1999, Bertsch et al., 2005b and Poirson et al., 2005). Pratt and Bowsher (1979) use the term ‘objective quality’ to refer to the physical characteristics (e.g. geometry, material and acoustic impedance) of an instrument that determine the subjective quality. In particular, this study attempts to determine some correlations between features of the impedance spectra and subjective assessments of various trombones. They focused on the subjective qualities of timbre and ease of playing, and compared players’ assessments with the harmonicity of the impedance spectra, and the amplitude and $Q$ values of the impedance peaks. No correlations were found between these subjective and objective parameters, although results showed that there was some correlation between the shape of the impedance envelope and the subjective assessment of the trombones.

Widholm (1999) looked at the subjective parameters of intonation and response on the trumpet. He found that players’ assessments of the intonation of an instrument correlated very well with weighted impedance spectra, where the weighting factor differed for different dynamic levels of playing (piano being unweighted). The
<table>
<thead>
<tr>
<th>Subjective parameters</th>
<th>Objective parameters</th>
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<td><strong>Subjective parameters relating to instrument</strong></td>
<td><strong>Objective parameters</strong></td>
</tr>
<tr>
<td>intonation</td>
<td>- weighted $Z$ spectra – convolution of the impedance spectra with weighting factor (based on comparison dynamic level played)</td>
</tr>
<tr>
<td>ease of playing/response</td>
<td>- group delay – delay time for each frequency to be reflected back to the mouthpiece (pulse response calculated from inverse of $Z$ FFT data)</td>
</tr>
<tr>
<td>tonal power/radiated sound strength</td>
<td>- 3 dB-range ($Q$) of $Z$ peak</td>
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<tr>
<td>ease of lipping notes/centred</td>
<td>- 3 dB-range ($Q$) of $Z$ peak</td>
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<tr>
<td>dynamic range</td>
<td>- group delay – delay time for each frequency to be reflected back to the mouthpiece (pulse response calculated from inverse of $Z$ FFT data)</td>
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<tr>
<td><strong>Subjective parameters relating to sound</strong></td>
<td><strong>Objective parameters</strong></td>
</tr>
<tr>
<td>brightness</td>
<td>- spectral centroid of sound spectra</td>
</tr>
<tr>
<td></td>
<td>- ratio of $Z$ magnitudes ($\frac{Z_{F_2}}{Z_{F_1}}$), frequencies ($\frac{</td>
</tr>
<tr>
<td>timbre</td>
<td>- multidimensional</td>
</tr>
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</table>

response of the instrument (or how easy it is to produce correct notes) correlated well with the response factor which is calculated from the impedance data and is essentially a measure of the delay time for each frequency to be reflected back to the mouthpiece (group delay).

Bertsch et al. (2005) extracted several different measures from the impedance data and related these to various subjective parameters of trumpets. They found that the tonal power (or strength of radiated sound) correlated with several of the impedance data measures (such as 3 dB-range ($Q$), magnitude and frequency of $Z$ peak), but only for the middle register of the trumpet. The difficulty of a note to be lipped up or down also generally correlated well with the same impedance data measures and the dynamic range in the middle register was found to correlate with group delay. Other subjective parameters, such as brilliance and overall quality of the instrument, were not found to correlate with any features of the impedance spectrum.

The subjective parameter of brightness of trumpet sounds was investigated by Poirson et al. (2005). They found that brightness did correlate with the spectral centroid of the sound (as found in general sounds by Grey and Gordon, 1978), but only for trumpet sounds produced by an artificial mouth or simulation. There was no correlation found for notes played by an actual trumpet player. They also found that brightness tended to correlate with various features of the impedance spectrum.
spectra, such as the ratio of the magnitudes \( \left| \frac{Z_{F_2}}{Z_{F_1}} \right| \), ratio of the frequencies \( \left| \frac{f_{F_2}}{f_{F_1}} \right| \), and the ratio of the \( Q \) \( \left| \frac{Q_{F_2}}{Q_{F_1}} \right| \) values of the two impedance peaks correlating to the fundamental frequency \( (F_1) \) and second harmonic \( (F_2) \) of the played note. Poirson et al. observed that the higher the magnitude ratio and the lower the \( Q \) ratio, the brighter the sound. Of smaller influence was the frequency ratio, which was found to be lower for brighter sounds.

Schubert and Wolfe (2006) further investigated the correlation between timbral brightness and spectral centroid. They compared subjective assessments of sounds with both the spectral centroid and the ratio of the spectral centroid with fundamental frequency, and found that the spectral centroid was the most appropriate correlate to brightness of sound. For the didjeridu, Smith et al. (2007) found that the most important determinant of quality was a feature of the impedance spectrum. All didjeridus rated by players as being of good quality, had low impedance peaks in the frequency range around 1kHz.

### 2.2.2 Measuring subjectivity

There are two methods commonly used to measure a subject’s response to some aspect of playing or listening to sound – multi-dimensional scaling and semantic differential scaling. In multi-dimensional scaling (MDS), the subject is tasked with rating the dissimilarity between various stimuli. There are two different techniques which can be used: diadic comparison – the subject must assign a number to indicate the degree of dissimilarity between a pair of stimuli; and triadic comparison – three stimuli are presented and the subject must indicate which pair is the most similar and which is the most dissimilar (Pratt and Bowsher, 1978). This technique is often used for investigating various effects on the timbre of sounds (e.g. Grey, 1977).

The background and logic behind the use of the semantic differential scale (SDS) is described in detail in Osgood et al. (1971). Essentially, it consists of a one-dimensional scale with polar opposite adjectives (e.g. happy–sad or easy to centre notes–hard to centre notes) at either end relating to a concept, or in the case of musical acoustics, a subjective musical parameter or perception. A subject is then tasked with rating the intensity (and direction) of the concept. Traditionally, the scale consists of seven steps and the subject must rate the concept at one of the seven points on the scale. However, Pratt and Bowsher (1978) modified the scale to be a continuous line between two extremes (Figure 2.4). This enabled the subject to mark the scale at any point along the fixed length line. Pratt and Bowsher reasoned that the use of a continuous line, rather than a series of steps, eliminated the need for “verbal descriptions of the seven subdivisions, whose meaning might be interpreted differently by individual subjects” (Pratt and Bowsher, 1978). Usually a set of scales is used for rating the same concept in order to investigate a subject’s response to different facets of the concept.
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2.2.3 Player responses

Experiments aimed to elicit players’ responses to different instruments for the purposes of comparison, can be separated into three categories: blind – the player has no visual feedback (and if possible, limited tactile feedback) of the instrument; semi-blind experiments – instruments have all labelling removed so that the makes and models cannot be visually identified; and unblind experiments – players are free to know the make and model of the instruments. Unblind experiments may introduce bias as players often have preferences for certain makes of instruments and this can affect their responses either consciously or subconsciously. However, different instrument makes also often have particular designs (e.g. the tubing configuration on the horn) which many players would be able to identify even with all labelling removed. Thus, blind experiments introduce the least bias, but are also the most difficult to conduct. A further difficulty, noted by Widholm (1999), with obtaining players’ responses is that a player tends not to assess the actual instrument, but instead the playing of the instrument (i.e. the coupling of the player to the instrument). This, along with personal preference, means that it is common to obtain opposing responses to the same instrument.

Several studies (such as Coltman, 1971, Pratt and Bowsher, 1978, Poirson et al., 2005, Bertsch et al., 2005a and Bertsch et al., 2005b) have investigated players’ perceptions of various instruments using blind tests. Coltman (1971) investigated players’ abilities to identify between three keyless flutes made of silver, copper, and wood. All the flutes used an outwardly identical plastic head joint, so that the player could not identify the instrument whilst playing. As the flute was keyless, it was not necessary to finger the flute and the flute was mounted to a structure which the player held. This structure also blocked the flute’s tubing from the sight of the player. Using this blind setup, Coltman found that none of the four players were able to correctly identify the different flutes.

Pratt and Bowsher (1978) investigated the subjective evaluations of three trombones, whose weights and balance point had been adjusted to match each other. The slide was locked in first position so that no bias would be introduced by slide quality. The players (two students and one semi-professional) were blindfolded and wore thick gloves to remove both visual and tactile judgments. Players rated each instrument (five separate times) using various SDS scales designed to assess dynamic
range, intonation, ease of playing, and timbre. Results showed that players could not easily discriminate between the instruments. However, the same experiment yielded statistically significant results for a professional trombonist. The results of an MDS (paired comparisons) test were similar to those using the SDS scale relating to timbre.

Players’ assessments of various rotary and piston valve trumpets were investigated by Bertsch and Waldherr (2005) and Bertsch et al. (2005). The instruments were unlabelled and player evaluations took place in a dark room to limit visual feedback. Players evaluated (on a scale) each instrument on various aspects of playing, such as dynamic range, intonation, power of sound, etc. A large number of trumpet players participated in the experiment (55) and overall ratings of instruments (level of a particular instrument, e.g. beginner, student, advanced) were found to be highly reliable and significant. In contrast, only some of the detailed questions were judged consistently. For example, evaluations of the centredness of notes, the power of the sound, dynamic range, and ability to play fast repeated notes, were reliable, whereas evaluations of tone colour, resistance, intonation, and personal sound preference exhibited low reliability.

Plitnik and Lawson (1999) conducted a semi-blind test on horn mouthpieces. Replicas of seven different mouthpieces were constructed so as to be label free. Each mouthpiece was rated (liked, neutral, and disliked) by a professional horn player (played using own horn) in various categories, such as flexibility, ease of playing, intonation, and dynamic range. As this experiment included only one horn player, general results could not be drawn. An unblind (although the internal bores were blind) experiment on 38 didjeridus and 11 plastic cylindrical pipes was conducted by Smith et al. (2007) and players rated the overall quality of each of the instruments. They found that for the cylindrical pipes having the same internal diameter (different lengths), there was no significant difference in rankings for quality, but that for pipes with differing internal diameters, there was a significant difference in rankings. For the didjeridus, there was also a significant difference in rankings and players tended to rank them in a similar order.

### 2.2.4 Listener responses

Listener evaluations of instrument sounds have been investigated for many reasons: to assess synthesised sounds for the purpose of determining hearing thresholds (e.g. Järveläinen et al., 1999, Järveläinen et al., 2001, Carral and Campbell, 2002, Horner et al., 2004, Järveläinen and Karjalainen, 2005, Karjalainen and Järveläinen, 2005 and Poirson et al., 2005); to assess (re)synthesised sounds for the purpose of determining the elements of the sound that enable a listener to identify particular instruments and distinguish between their sounds (e.g. Strong and Clark, 1967, McAdams et al., 1999, Eronen and Klapuri, 2000, Horner and Beauchamp, 2003,
CHAPTER 2. REVIEW OF EXPERIMENTAL METHODS

Galembo et al., 2004, Järveläinen and Karjalainen, 2005, Poirson et al., 2005 and Beauchamp et al., 2006); to assess synthesised sounds for the purpose of comparing synthesised sounds with actual instrument sounds (e.g. Farina et al., 1998 and 2000); to assess synthesised or original instrument sounds for the purposes of obtaining correlates between the physical sound and listeners’ subjective responses (e.g. Grey, 1977, Nishimura et al., 2001, Järveläinen et al., 2002 and Caclin, et al., 2005); to evaluate venue acoustics (e.g. Lokki et al., 2011); to compare the quality of sound produced by different players on the same instrument (e.g. Pratt and Bowsher, 1978); and to compare and evaluate the quality of various instruments through the produced sound, either live or prerecorded (e.g. Coltman, 1971, Pratt and Bowsher, 1978, Guettler and Askenfelt, 1997, Widholm et al., 2001, Parker, 2003, Petiot et al., 2003, Sharp et al., 2003 and Nachtmann et al., 2007). Listeners’ evaluations may be affected by many factors, such as personal preferences, musical experience, method of presentation of sound (e.g. headphones, loudspeaker, live, room acoustics) and, to an extent, hearing (see section 2.2.4.1).

The effect of different playing styles (Guettler and Askenfelt, 1997), materials (Coltman, 1971 and Widholm et al., 2001), geometries (Petiot et al., 2003a and Sharp et al, 2003), and makes/models (Pratt and Bowsher, 2003 and Parker, 2003) on the instrument’s sound has been investigated through the use of listener evaluations. Guettler and Askenfelt (1997) investigated the quality of bowed string attacks. Sound was generated for various different styles of attack using an artificial bowing machine and recorded for playback to listeners. The sound was presented to the listening group via a single loudspeaker in a large room. Listeners rated each attack (presented three times during the experiment) on acceptance, and scales relating to quality and character. From the results, Guettler and Askenfelt were able to determine the maximum duration of the bowed attack transient for which the sound remains acceptable to the listener.

Coltman (1971) investigated the effect of the wall material on the sound of the flute. The three keyless flutes made of silver, copper and wood were played behind a screen in the same room as the listening group. Each trial consisted of a musical phrase played three times, twice by the same instrument, and listeners had to identify the one that was different. Results showed that listeners were unable to discriminate between the sounds produced by flutes of differing materials. Widholm et al. (2001) undertook a similar experiment using flutes made from silver, gold and platinum. Recordings were made of two flute players playing each of the instruments. These recordings were then presented to the listening group. Listeners were first presented with the same musical excerpt played on each flute by the first player and then each flute by the second player with the aim of identifying which flute was being played in each case. Secondly, listeners were presented with sounds from each flute played by both players and listeners rated the sound quality and guessed the material of
2.2. **SUBJECTIVE RESPONSES**

the flute. In both these tests, listeners were unable to correctly identify the flute material.

The geometry of certain parts of musical instruments, such as the trumpet mouthpiece or a bassoon crook are commonly believed to affect the sound produced on the instrument. Petiot et al. (2003a) investigated the effect that the depth of cup section of the mouthpiece has on the trumpet’s sound. Notes played on the trumpet (with various mouthpiece depths) by both an artificial mouth and a trumpet player, were recorded and presented in pairs to listeners. Paired sounds (produced either by the artificial mouth or player) were presented to listeners who rated how different the sounds were for each pair of sounds. Results showed that listeners were able to identify differences in the pairs of sounds and that sounds perceived as more different corresponded with a greater difference in the depth of the mouthpiece. Differences between the two sounds were also perceived as greater for sounds produced by the artificial mouth than by the trumpet player.

In a similar study, Sharp et al. (2003) investigated listeners’ perceptions of the timbre of the sound produced on a bassoon played with different crooks. Recordings were made of two players and six different crooks. Paired sounds were presented to listeners via headphones and listeners rated the differences in timbre between the two sounds. Results showed that listeners were easily able to distinguish between the different crooks.

Differences in sound produced by different models of trombones and trumpets have been investigated by Pratt and Bowsher (1978) and Parker (2003), respectively. Pratt and Bowsher (1978) investigated listeners’ perceptions of the sounds of three different trombones. The trombones were played by each of three players whilst the other two rated the sounds on three timbre related scales (dull/bright, compact/scattered, and not penetrating/penetrating). Results showed that listeners were able to discriminate between instruments on the dull/bright scale and between instruments and players on the not penetrating/penetrating scale. Pratt and Bowsher carried out a second experiment with recorded sounds using two trombones and two players. Listeners rated paired sounds, presented via headphones, on two scales (dull/bright and unpleasant timbre/pleasant timbre). Results showed that listeners were able to distinguish between instruments and players, but that volume and pitch of the played notes had the greatest influence over their ratings.

Parker (2003) recorded musical excerpts played on five different trumpets (pitched in Bb, C, D, and Eb, and a piccolo trumpet). For each trumpet, the excerpt was presented to the listener twice and in random order and the listener had to guess which trumpet was being played. Results showed that none of the 24 listeners were able to identify correctly the trumpet being played in each of the excerpts, even though each listener (trumpet player) had expressed confidence in their own ability to recognise different trumpets from sound alone.
The evaluation of instrument sounds by listeners provides a useful comparison with the evaluations of players. Of course, a player’s rating of the playability of an instrument is important as the player is the one who has to produce the sound. However, the player’s evaluation of the sound quality of the instrument may or may not correspond to the listener’s evaluation of the sound produced. Indeed, the listener may not be able to distinguish between sounds played on different instruments, even if the player perceives the instruments to have different sound qualities. Thus, several experiments have included both player and listener evaluations (e.g. Coltman, 1971 and Pratt and Bowsher, 1978).

2.2.4.1 Factors affecting hearing

There are many factors that affect hearing. Even in a normal hearing adult, hearing thresholds increase with age. Lee et al. (2005) report that the average rate of change of hearing thresholds was 0.7 dB per year for low frequencies (250 Hz) and up to 1.23 dB (12 kHz) per year for high frequencies. They noted that the rate of change of thresholds was affected by age, gender and initial threshold levels. In a longitudinal study of normal hearing adults, Morrell et al. (1996) found that hearing in men tended to decline at a constant rate as age increased, whereas hearing in women declined slowly at first and then accelerated with increasing age. Wiley et al. (1998) also found that thresholds were significantly higher for men than women in the range of 9 to 14 kHz.

However, exposure to loud music can cause hearing damage. This is particularly of interest in musicians who are regularly in performance situations where the sound level has been measured, by Schmidt et al. (2011), to peak above 130 dB in certain parts of the orchestra. A review of the literature on the hearing loss in musicians and the sound levels they experience was undertaken by Peters et al. (2005). General concensus in the literature shows that musicians are at high risk of developing hearing loss and that up to 40% of musicians have hearing thresholds higher than the average for their age group. Of growing concern, is the rise in noise induced hearing loss (NIHL) in young people due to the prevalent use of personal music devices, especially with earphones.

2.3 Effect of auditory feedback on playing musical instruments

Auditory feedback is very important to musicians and is constantly used to monitor the pitch, tuning, loudness, and timbre of the sound whilst playing. Although there are other feedback channels available to the player (such as bone conducted sound and haptic feedback; see section 2.3.2), auditory feedback is generally considered
to be the most important and many studies have investigated its effects on the musician.

2.3.1 Manipulated auditory feedback

In order to investigate the effects of auditory feedback on the musician, studies have been undertaken in which the auditory feedback available to the player is altered or manipulated in some way (such as delayed, masked, volume altered, or pitch delayed). The majority of research in this area has investigated effects on singers and pianists. Singers are a logical first choice as the sound produced by the human voice is not dictated by the resonances of the instrument and thus, it could reasonably be presumed that auditory feedback is of even greater importance to singers. Pianists have also been studied as it is possible to remove auditory feedback altogether if an electric keyboard is used and any manipulated auditory feedback can then be presented via headphones without any interference from the actual instrument’s sound. Although most of the research has been limited to these two instruments, there have been several studies that have included other instruments.

2.3.1.1 Delayed auditory feedback

Although the effect that delayed auditory feedback (DAF) has on speech has been studied since the 1950s, research into its effect on musicians has been slow to catch up (Havlicek, 1968, Gates et al., 1974, Finney, 1997, Pfordresher and Palmer, 2002, Pfordresher, 2003, Bartlette et al., 2006 and Moelants et al., 2009). A pioneering study was undertaken by Havlicek (1968) who investigated the effect of DAF on the playing of various musical instruments (grouped into brass, woodwinds, strings, and piano). Each of 21 musicians sight-read several musical excerpts whilst listening to their sound via headphones. The volume of the sound presented through the headphones was greatly increased in an attempt to mask bone and air conducted sound. Two excerpts were played with normal feedback and two with a delay of 0.2s and the number of errors produced by the player was recorded. Results showed that with the delayed feedback, the number of errors was significantly higher. Havlicek found that the most common reactions to playing with DAF were: an increasingly slower tempo; increasing intensity level; adding in extra notes; playing with heavy accents; and varying tempo. However, there were no significant differences between any of the different instrument groups, indicating that the effect of DAF on musicians was similar regardless of instrument played.

Gates et al. (1974) investigated the effect of DAF on playing an electronic organ. An excerpt was played with DAF heard through headphones. However, normal auditory feedback was also presented through speakers, but at a lower level. Thus, the players heard both the immediate sound and the delayed sound. They found that the majority of players decreased their playing speed, whilst several players
actually increased their playing speed. Different delay intervals were investigated, with 0.27 s found to cause the greatest disruption to playing. The results from this study were replicated by Finney (1997) using an electronic keyboard and the study extended to investigate the effect of altering the pitch of the DAF. He found that when the pitches of the DAF were changed, the disrupting effect of the DAF was decreased.

Pfordresher and Palmer (2002) investigated pianists’ reactions to DAF and in particular their preferences for tempo when presented with a particular delay. Each pianist played two short melodic excerpts on a keyboard with the keys obstructed from view to remove visual feedback. The piano sound was delayed and presented to the player via headphones and the timing of each key press was recorded. For each of several different delays, pianists were asked to choose a tempo that they felt fitted the delay. Results showed that pianists preferred slower tempos for larger delays and that the chosen tempo was influenced by the DAF and not by any personal tempo preferences. Pfordresher and Palmer also found that the preferred tempos were approximately twice the rate of the feedback delay, indicating that disruption of DAF may be reduced for certain relationships between tempo and delay which promote subdividing by the musician.

A further similar study by Pfordresher (2003) investigated the effect of different types of DAF on pianists. The types of DAF used were: phase shifted – delay was a third, half, or two thirds of a note behind; period shifted – the delay was a whole one, two, or three notes behind; and a combination of the previous two delays. The number of incorrect pitches (accuracy) as well as timing errors were recorded. He found that phase shifted DAF mainly affected timing whereas period shifted DAF mainly affected accuracy. For the combined phase and period shifted DAF, results showed that both timing and accuracy were affected, but not simply as a sum of the results found for the separate delays, indicating possible interactions between the two different delay types.

The effect of delayed auditory feedback becomes musically significant in certain performance situations. For example, in organ playing where the player and pipes may be separated or when musicians are physically separated by a significant distance (e.g. two choirs or instrumental groups positioned on opposite sides of a large cathedral, or on opposite balconies in a large hall). However, even within an orchestra, musicians will experience delays in sound from other instruments. Bartlette et al. (2006) investigated the level of delay necessary before musicians considered themselves to no longer be playing musically with one another. Experiments were conducted separately on two pairs of musicians (a violin and viola, and two clarinets) playing duets. The two players were isolated (to remove visual and auditory feedback) and were connected via a microphone and headphone setup. Each player heard themselves in real time and the other player in various levels of delay. Results
2.3. AUDITORY FEEDBACK

showed that the tempo slowed and timing between parts decreased with increasing delay for both instrument pairs. Players also rated the performances as less musical with increasing delay.

The effect of DAF on pianists’ body movements were investigated by Moelants et al. (2009). The DAF was routed to the midi output of the digital piano, to eliminate the need for headphones and the movement of the player’s upper body was captured. Results showed that playing in the presence of DAF resulted in an increase in asynchrony between the left and right hands and larger body movements, especially of the head.

2.3.1.2 Absence of auditory feedback and masking noise

The most obvious way to determine the effect that auditory feedback has on musicians, is to remove all auditory feedback to the player. However, this is almost impossible to do except for pianists, where the sound of an electric piano can be muted (Gates and Bradshaw, 1974, Repp, 1999 and Takahashi and Tsuzaki, 2008). Therefore, in experiments involving musicians other than pianists, masking noise or tones are used so that the player cannot hear themselves over the background noise (Ward and Burns, 1978, Ternström et al., 1983, Cook, 1996, Mürbe et al., 2002, Watts et al., 2003 and Mürbe et al, 2004).

Gates and Bradshaw (1974) studied musicians playing the electronic organ and found that there was little difference between performances played with no auditory feedback and those played with normal auditory feedback, except that several players increased their playing speed in the absence of auditory feedback. Repp (1999) investigated the effect of receiving no auditory feedback on expressive piano performance. Six professional level pianists played the same musical excerpt ten times with normal auditory feedback via headphones and ten times with no auditory feedback. He found that eliminating auditory feedback to the pianist affected timing, dynamic level, and pedalling, but that the effects were small and varied from player to player.

Takahashi and Tsuzaki (2008) investigated the effect of auditory feedback on learning a piano piece. Both advanced and less advanced pianists were included in the study in which each pianist aimed to play a musical excerpt in the same style as a recording presented to them via headphones. Half the group was able to listen to themselves whilst practising and the other half practised without auditory feedback (although they could listen to the recording). After the practice session, all pianists played the piece through with auditory feedback. Results showed that for advanced players, there was no significant difference in the final play-through between those in the auditory feedback condition and those without auditory feedback. However, less advanced players who practised without auditory feedback performed significantly worse in the final play-through than those who had practised with auditory feedback.
Studies involving masking have predominantly been carried out on singers (e.g. Ward and Burns, 1978, Ternström et al., 1983, Mürbe et al., 2002, Watts et al., 2003 and Mürbe et al., 2004), a notable exception being a study on trombones by Cook (1996). Ward and Burns (1978) used a broadband noise to mask the sound produced by singers. Scales were sung in normal conditions, with headphones, and with masking noise presented via headphones. They found that with masking noise, singers tended to perform scales with worse intonation and this effect was greater for untrained singers than for trained singers. Ternström et al. (1983) reported on an experiment which investigated singers’ abilities to shift from one vowel sound to another without changing the pitch of the note with and without auditory feedback. The condition of no auditory feedback was achieved by playing masking noise through headphones. Results showed that the frequency of the sung note was less stable and the pitch was more likely to change between different vowel sounds when masking noise was present.

In a similar study to that of Ward and Burns (1978), Mürbe et al. (2002) and Mürbe et al. (2004) investigated the effect of masking noise on singers’ abilities to accurately sing arpeggios. Intonation was found to deteriorate when masking noise was present. However, after three years of professional singing education, the same subjects performed only marginally better, in terms of intonation, under conditions of masking noise. Watts et al. (2003) studied the effect of training on singers’ abilities to match pitches. Singers were presented with pure tones and then asked to sing the same pitch in either normal feedback conditions or in the presence of masking noise. Surprisingly, they found that in the presence of masking noise, untrained (but talented) singers were able to match pitches more accurately than trained singers.

In an attempt to investigate the role that auditory feedback has in playing instruments (other than the voice and piano), Cook (1996) studied trombonists’ playing with and without masking noise. Results showed that there was a small (but statistically insignificant) increase in incorrect notes played with masking noise whereas dynamic level increased significantly. Players also tended to use less vibrato when playing with masking noise. However, apart from the change in dynamic level, the presence of masking noise had little effect on the trombonists’ abilities to accurately play their instrument.

2.3.1.3 Volume altered auditory feedback

The effect of manipulating the volume of auditory feedback that a musician receives appears to have been only researched by Johnson et al. (1978). In speech, increasing the amplitude of normal auditory feedback results in a reduction of vocal intensity and this effect is greater if there is background noise present (e.g. Siegel and Pick, 1974). Johnson et al. (1978) investigated this effect in musicians playing electric guitar. Participants played the electric guitar and the auditory feedback (presented
2.3. AUDITORY FEEDBACK

via headphones) was amplified or attenuated by several different amounts. The
experiment was also conducted with noise included in the feedback. Results showed
that the player decreased the intensity of playing when the auditory feedback was
amplified. Similar to results with speech, this effect was greater in the presence of
noise and the higher the noise level, the greater the effect.

2.3.1.4 Pitch manipulated auditory feedback

In producing a sung pitch, there is no external resonating string or column available
to dictate the frequency of resonance. Thus, the voice is the ideal instrument on
which to study the effect of manipulating the pitch of the auditory feedback, as the
effects are likely to be larger than for other instruments where the player is able to
control the produced pitch only within a certain range. The effect on pianists of
manipulating the pitch of the auditory feedback is rather different, as the pianist
obviously has no control over the pitch of a particular note. Although it would be
interesting to examine the effects on wind and stringed instruments, research in this
area has, at this point, been limited to singers (e.g. Burnett et al., 1997 and 1998,
Larson et al., 2000, Hain et al., 2001 and Sivasankar et al., 2005) and pianists (e.g.
Pfordresher, 2005 and Pfordresher and Palmer, 2006). When the note sung is fed
back to the singer with a slight manipulation in the pitch frequency, the singer will
either try to ‘fix’ the tuning by shifting the sung pitch in the opposite direction to
the manipulation (compensating), or try to pitch match the note by shifting the
sung pitch in the same direction as the manipulation (following).

Burnett et al. (1997) investigated the effect of manipulating the pitch of the
auditory feedback on singers. They introduced an upwards or downwards pitch shift
of 100 cents (one semitone) at random points during the singing of a scale and found
that singers compensated for this so that the pitches that they heard were correct for
the scale. That is, when the pitch was increased by 100 cents, the singer decreased
their sung pitch by approximately the same amount, and vice versa. A further
study by Burnett et al. (1998) aimed to investigate factors affecting vocalisation
responses to pitch shifts in the auditory feedback. Factors included were: increasing
the intensity of the auditory feedback (to mask the bone conducted sound); adding
masking noise to the feedback; varying the magnitude of the pitch shift (between 25
and 300 cents); and varying the duration of the pitch shifted feedback (between 20
and 500 ms).

A preliminary study (Burnett et al., 1997) had shown that when the pitch was
shifted downwards, 96 % of vocalisations increased in pitch and when the pitch was
shifted upwards, 78 % of vocalisations decreased in pitch. Results from Burnett et al.
(1998) showed that amplification of the feedback signal or the addition of masking
noise was not found to change the responses of vocalisations to pitch shifts. However,
the magnitude of the pitch shift was found to affect the direction of the vocalisa-
tion pitch change. As the pitch shift was increased from 50 cents to 300 cents, the percentage of vocalisations that changed pitch in the opposite direction decreased, with a corresponding increase in responses in the same direction as the pitch shift. Longer durations of pitch shift stimuli also tended to increase both the magnitude and the duration of the change in pitch of the vocalisations. Thus, when the ideal pitch of the note is not set, as in a scale, the pitch of vocalisations either oppose or follow the pitch shift with the corresponding magnitude and duration dependent on several different factors.

Larson et al. (2000) undertook a similar study on vocalisations. However, the pitch shift was gradually increased or decreased from unity to 100 cents (rather than an immediate pitch shift) and the effect of this rate of shift was investigated. Results showed that 98.5% of the vocalisations changed pitch in the opposite direction to the pitch shift. As the rate of pitch shift increased, so too did the rate of change in the pitch of the vocalisation. The magnitude of the change in vocalisation pitch also tended to increase with an increased rate in the pitch shift. Hain et al. (2001) investigated the effect of adding a delay into the pitch shifted auditory feedback. That is, the subject hears the pitch shift for a period of time (50 to 500 ms) before hearing the response of their vocalisation to the pitch shift. Results showed that, again, the majority of vocalisations changed pitch in the opposite direction to the pitch shift, but there were also two separate changes in the vocalisation pitch corresponding to hearing firstly the pitch shift, and secondly the delayed change in vocalisation pitch.

Sivasankar et al. (2005) compared the effects, on vocalisations, of pitch shifting the auditory feedback with adding a pitch-shifted tone to the auditory feedback. Four conditions were compared in which the following auditory feedback was presented: pitch-shifted voice feedback; pitch-shifted triangle or pure tone feedback; triangle or pure tone and pitch-shifted voice feedback; and pitch-shifted triangle or pure tone and voice feedback. Across all conditions, 81% of vocalisations changed pitch in the opposite direction to the pitch shift. Results showed that changes in vocalisation pitch were greater when the pitch of the voice feedback was shifted, than when the pitch of the tone (triangle or pure) was shifted. However, the pitch of vocalisations did change (although to a lesser extent) when the pitch of the tone was shifted, indicating that vocalisations can be destabilised by external periodic signals.

As pianists cannot vary the pitch of the note produced on the instrument, the effect of manipulating the pitch of the auditory feedback tends to interfere with the ability to play the correct notes fluently. Pfordresher (2005) investigated this phenomenon by presenting pianists with auditory feedback consisting of notes with altered pitches (heard in time with keystrokes) whilst playing short melodies from memory. He found that accuracy and timing were decreased slightly when random pitches were assigned to each keystroke, but that there was greater disruption when
2.3. AUDITORY FEEDBACK

A similar pitch structure (to the one being played) was used. No differences were found between trained and untrained subjects. In a similar study, Pfordresher and Palmer (2006) further investigated the use of auditory feedback consisting of different pitches but similar pitch structures, on pianists’ abilities to play fluently. The pitch structures used were delays or prelays of the intended notes to be played. That is, the pitch assigned to a keystroke was that of either 1, 2, or 3 notes behind or ahead of the note being played. They found that all conditions affected the accuracy of the performance but not the timing, and pianists tended to change note order to compensate for the heard change in pitch position in the melody.

2.3.1.5 Spectral envelope manipulated auditory feedback

Little research has investigated the effect that manipulating the spectral envelope of the heard sound has on the performer or listener. Garber and Moller (1979) investigated this effect on speech and found that filtering the auditory feedback to the speaker resulted in a change in nasalisation (tone quality) of the speech. To date, there appear to be no studies investigating the effect of filtering on musicians, although the importance of the spectral envelope to the sound of an instrument and to the listeners’ abilities to identify the instrument have been studied (e.g. Strong and Clark, 1967, McAdams et al., 1999 and Horner et al., 2004). Strong and Clark (1967) resynthesised musical instrument tones with various combinations of spectral and temporal envelopes corresponding to different musical instruments and listeners were asked to determine the instrument ‘playing’ the sound. They found that the spectral envelope was generally the dominating factor in correctly identifying an instrument. However, for some instruments in which the spectral envelope is not unique (regarding the frequency of its maximum and overall playing range), the temporal envelope also becomes important for identification.

McAdams et al. (1999) investigated listeners’ abilities to discriminate between instrument sounds resynthesised with simplified spectral components. They found that differences between instrument sounds with and without smoothing of the spectral envelope were easily distinguishable, indicating that the spectral envelope is very important to the sound of an instrument. In a similar study, Horner and Beauchamp (2003) resynthesised instrument sounds with various different spectral envelopes and asked listeners to discriminate between sounds with and without modified spectral envelopes. Results showed that the greater the change in the spectral envelope, the higher the level of discrimination. However, the level of discrimination depended on the instrument and the musical experience of the listener.

2.3.2 Non-auditory feedback in playing

Although auditory feedback is important, there are also other feedback channels available to the musician, such as bone conducted sound and haptic feedback. The
player’s own muscle memory, although not technically a feedback channel, is closely related to kinaesthetic feedback and is thus included in this section on feedback channels. Indeed, feedback from these non-auditory channels are essential to the playing of musical instruments. Each of these feedback channels is usually present along with auditory feedback in normal playing situations and it is often very difficult to study the effects of any one feedback type due to the complex nature of their intercommunication. Although it has been possible to study (to an extent) the effects of auditory feedback through the process of manipulation (see section 2.3.1), it is much more difficult to study the individual effects of bone conducted sound, haptic feedback, or muscle memory as they are difficult to isolate.

Due to the difficulty of isolating bone conducted sound from air borne sound and other feedback channels available to a musician, the effect of this type of feedback on musicians has not been investigated. However, general properties and thresholds of bone conducted sound have been measured (von Békésy, 1948, Corso, 1963, Corso and Levine, 1965, Khanna et al., 1976, Carlsson et al., 1995, Sohmer et al., 2000, Stenfelt and Håkansson, 2002, Stenfelt et al., 2002, Stenfelt et al., 2003, Purcell et al., 2003, Stenfelt and Goode, 2005 and Stenfelt, 2006 and 2007). It is thus assumed that bone conducted sound is a valid feedback channel that is utilised in the playing of musical instruments (especially wind instruments) and is a factor considered when using masking noise to investigate the effect of auditory feedback (e.g. Burnett et al., 1998 and Havlíček, 1968).

Haptic feedback refers to two different groups of sensations (Rovan and Hayward, 2000) – tactile sensations and proprioceptive, or kinaesthetic perception (see Table 2.3 for a more detailed breakdown). The majority of research on the use of haptic feedback in the playing of musical instruments has focused on vibrotactile sensations (e.g. Sundberg, 1992, Askenfelt and Jansson, 1992 and Chafe, 1993) rather than kinaesthetic feedback (e.g. Guettler, 1992 and Moore, 1992). Various thresholds for vibrotactile feedback have been investigated and reviewed by Verrillo (1992). He demonstrates that various aspects of vibrotactile sensation (such as thresholds of detectability, frequency discrimination, and equal loudness curves)

<table>
<thead>
<tr>
<th>Tactile sensation</th>
<th>Proprioceptive or kinaesthetic perception</th>
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<tr>
<td>pressure</td>
<td>awareness of the body’s position</td>
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<tr>
<td>orientation</td>
<td>- velocity and forces supplied by muscles</td>
</tr>
<tr>
<td>texture</td>
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<td>thermal properties</td>
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<td>friction</td>
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<tr>
<td>vibration</td>
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2.3. AUDITORY FEEDBACK

depend on the part of the body that is in contact with the vibration, the size of the area of skin in contact, the temperature of the skin, and the age of the person. In general, the finger is the most sensitive to vibrotactile feedback, followed by the palm of the hand and the sternum area.

Sundberg (1992) investigated phonatory vibrations (vibrations felt in the body as a result of phonation) in singers and reviewed the results of several studies. General findings showed that vibrations in the chest wall may be utilised by singers in the control of phonation as they tend to be independent of the vowel sound used. However, other vibrations, such as those felt in the face and head are largely dependent on the vowel sound and should therefore be more difficult to utilise in the control of phonation. He emphasises the fact that vibrations are important to the singer’s perception of their sound as, unlike auditory feedback, the vibrations are not affected by the room’s acoustics. However, levels of vibration, when compared to the threshold of detectability, indicate that vibrations of the chest walls should not be perceivable by the singer for frequencies above 400 Hz (G4).

Askenfelt and Jansson (1992) investigated vibration levels during playing of the double bass, violin, guitar, and piano. For the double bass, vibrations were above the threshold of detectability (for at least the lowest frequencies) for the top and back plate, neck, bow, and riser, all of which are in contact with the player. For the violin, vibrations were above threshold (for the lowest notes) at the top plate, chin rest, neck, and bow frog. For both the double bass and violin, vibrations of the strings were large enough to be perceived by the fingers, but Askenfelt and Jansson questioned whether or not they could be perceived especially during fast fingering. Vibrations in the neck of the guitar were well above the threshold level, but vibrations from the side of the guitar could be felt in the arm and legs for fortissimo playing. Vibration levels at the keys and pedals of the piano were generally well below the threshold of detectability.

Although possible speculations have been made, all of the above studies have focused on measuring the magnitude of vibrations and determining whether or not they are above the threshold of detectability. That is, vibrations have been found that could potentially be felt and utilised by the player, but their effects on the musician or the playing of the instrument have not been investigated. However, Chafe (1993) measured the waveform of the fingertip placed on a bowed cello string and found that the vibrations at the fingertip can be used to monitor the time and length of bow articulations and the stability of oscillations of the string.

The kinaesthetics involved in certain aspects of playing the double bass, piano, and stringed instruments in general have been investigated by Guettler (1992), Moore (1992), and Askenfelt and Jansson (1992), respectively. Guettler (1992) made electromyography (EMG) recordings of a double bass player during playing in order to identify the specific muscles and forces involved in producing vibrato. The mus-
cle forces involved in producing a good vibrato sound were found to be absent in a player with poor vibrato. A similar study was undertaken by Moore (1992) in his investigation into the arm muscle forces and finger movements required in playing piano trills.

Askenfelt and Jansson (1992) hypothesised that kinaesthetic feedback assists in the musician’s timing when playing string instruments or the piano. However, they did not elaborate on this and instead measured the magnitude of the muscle forces involved in bowing and fingering. In conclusion, Askenfelt and Jansson stated that, for all instruments, the kinaesthetic finger forces were more likely to provide assistance for timing than vibrotactile cues from the instrument’s vibrations. However, musicians in the delayed auditory feedback study by Havlicek (1968) indicated that they utilised both tactile and kinaesthetic feedback in their attempts to ignore the delayed auditory feedback.

The importance of haptic feedback on the musician’s ability to play a musical instrument has recently been realised with the advent of digital musical instruments (e.g. O’Modhrain and Chafe, 2000 and Nichols, 2002) which do not rely on vibrations or forces to produce sound. O’Modhrain and Chafe (2000) investigated the effect, on playability, of adding haptic feedback to a computer-based musical instrument. They found that musicians were least accurate when no haptic feedback was supplied and most accurate when the feedback mapped exactly to the parameter being controlled (e.g. increasing the force applied causes an increase in pitch). Similarly, Nichols (2002) found that his virtual violin bow was difficult to control without any haptic feedback. However, when haptic feedback simulating friction, vibration, detents (feeling of bow moving over the string), and elasticity were added, the playability of the virtual instrument was greatly improved.

Thus, although haptic feedback is generally considered of secondary importance to that of auditory feedback, it is still an essential part of playing a musical instrument. A situation in which haptic feedback becomes more important than auditory feedback, is in the playing of musical instruments by the deaf and hard of hearing. Hash (2003) suggests certain instruments which may be suitable due to the haptic feedback available: electric bass as it produces a large amount of vibration; trumpet as pitches can be discriminated by holding onto the bell and feeling the vibrations, and; tuba as vibrations can be felt by wrapping the arm around the instrument.

Muscle memory, which is somewhat related to kinaesthetic feedback, is also of importance to the player both in the presence and absence of satisfactory auditory feedback. For example, a study by Cook (1996) found that trombonists were still able to play the trombone even in the presence of high levels of masking noise. He concluded that muscle memory was utilised in the setting up of notes and that haptic feedback channels were satisfactory in the absence of auditory feedback.
2.4 Aims and objectives for this research

From an examination of the literature relevant to the acoustics and playability of the horn, it is clear that the questions posed in the introduction to this thesis have not been satisfactorily answered. Thus, the objective of the remainder of this thesis is to experimentally address these questions. In order to accomplish this, the remainder of the thesis is devoted to the three following aims:

1. To investigate the effect of different hands and mutes on the acoustics of the horn.

2. To investigate the effect of different hands and mutes on the playability of the horn.

3. To investigate the effect of auditory feedback on the horn player’s production of sound.

Each of these aims is the focus of one of the following three experiment chapters, the results of which are then discussed together in the final chapter.

The effect on the acoustics of the horn of having different hands and mutes in the bell are investigated through the analysis of detailed and extensive acoustic impedance measurements. Subjective surveys are then undertaken by horn players playing with each of the hands and mutes in the bell, in order to investigate the effect, on the playability of the horn, of the hands and mutes. Correlations between these two sets of results will be presented in the final discussion chapter. The effect of auditory feedback on the horn player’s production of sound is investigated by focusing on the manipulation of the spectral envelope of the sound with the aim of reproducing spectral changes in the feedback corresponding to playing in different acoustic conditions. In this experiment horn players are presented with altered auditory feedback via headphones in real time and their sound recorded for analysis.

It is also interesting to note that much of the research that has been undertaken on the acoustics of the horn is now more than twentyfive years old. The advancement of technology since then means that it is possible to measure various properties of the horn with much greater precision than was possible at that time.
CHAPTER 2. REVIEW OF EXPERIMENTAL METHODS

Chapter 3

Effect of hand, mouthpiece, mute and valves on input $Z$ of the horn

3.1 Background

An important part of playing the horn is the placement of the player's right hand in the bell of the instrument (see section 1.4). Players note that different hand positions and shapes affect the pitch, loudness and timbre of notes played – and use the effects musically. Hand positions and shapes are also expected to affect transfer functions, including the input impedance spectrum $Z$. Backus (1976) and Benade (1976) have shown that without the hand in the bell, impedance peaks above 450 Hz are greatly diminished in magnitude and disappear entirely above 750 Hz (Figures 3.1 and 1.12). This is due to the cutoff frequency of the bell which occurs around 500 Hz on the horn. Above this frequency, waves are transmitted rather than reflected, so standing waves are weaker or nonexistent, resulting in weak impedance peaks. The placement of the hand in the bell increases reflection and hence the cutoff frequency. The frequencies of all resonances are also lowered when the hand is placed in the bell (see section 1.4).

In general, studies pertaining to the acoustic characteristics of brass instruments have tended to concentrate on the trumpet and trombone, with research on the acoustics of the horn lagging far behind. This is probably due to the extra factor of the player's hand in the bell which causes many added complications:

- In order to fully characterise the acoustics of the horn, a hand must be present in the bell.

- There are practical constraints with using an actual player's hand, such as reproducibility of hand placement and length of experiments.

- Alternatively, the use of an artificial hand may not easily replicate the shape and acoustic properties of a human hand.
Several experiments have used either real or artificial hands with generally little information given as to dimensions, materials used or reproducibility of placement in bell. Backus (1976) specifies that a “plasticene “hand” is used for comparison with the open bell, but no indication is given as to the shape or dimensions used. Widholm (1988) used an artificial hand in the bell to record the sound of the horn being artificially blown. Figure 3.2 shows the hand used, but no further information was given. Chick et al. (2004) undertook acoustic impedance measurements of various modern horns to investigate the intonation of different length horns. They used the same horn player’s hand in the bell for all measurements and measured the accuracy of replacing the hand in the bell over ten trials. Benoit and Chick (2006) measured the input impedance of a horn with two different players’ hands in the bell and concluded that the hand was of vital importance to any simulations of the horn.

An important accessory for a horn player is a mute. There are three different types of horn mute in common use – straight mute, stopping mute and practice mute. Unlike the trumpet and trombone, for which there exist numerous different types of mutes whose acoustic properties have been extensively studied, the acoustic properties of the horn with mute in the bell has not been widely investigated.

Smith (1980) investigated the acoustic properties of the horn straight mute as a Helmholtz resonator (see Section 1.7.1) and provided a review of the geometries, materials and sound qualities of fourteen different models of straight mute available.
at the time. Kurka (1961) compared the sound spectra of the horn with and without a straight and stopping mute in the bell and Luce and Clark (1967) analysed the sound spectra of a stopped horn. However, only two studies have investigated the effect of mutes on the impedance spectra of the horn. Backus (1976) demonstrated the effect that stopping has on the impedance spectra of the horn (see Figure 1.16) and Wachter (2008) undertook a detailed study of the effect of the stopping mute on the transfer functions of the horn. Interestingly, he found that detaching the bell of the horn with the stopping mute still in place (see Figure 1.19) has little effect on the impedance spectrum (see Figure 1.20).

Although the general properties of straight and stopping mutes have been studied, given that there are many different makes and models available for each type of mute and that differences are apparent to players, it is surprising that no objective comparison has been undertaken to try to qualify or quantify the differences in the effects on the impedance spectra of the horn for different models of the same type of mute.

The practice mute is an unusual mute as it is designed not for performance, but to make practice less disturbing for neighbours and cohabitants. Thus, its aim is not to change the timbre of the sound (as for the straight and stopping mutes), but to simply reduce the level of output sound. Practice mutes range from elaborate models, incorporating a feedback system to the player via headphones, to improvised arrangements. As players often spend many hours with such mutes, ideally the performance of a horn with such a mute should approximate that of the horn played normally with a hand. Of course, an object whose purpose is to diminish radiation from the bell will usually affect reflection back into the bore, so effects on
the impedance spectrum are expected, but have not previously been investigated.

Thus, the main aims of this study are to investigate the effect that the size, shape and placement of the hand has on the input acoustic impedance of the horn and to undertake an in-depth study into the effect that horn mutes have on the impedance spectra of the horn and the extent to which these effects vary between different mutes of the same type. Three different mouthpieces and two different models of horn (one professional model and one student model) will also be included in the study and differences in impedance spectra analysed. Variation in impedance spectra across different valve combinations are also expected due to the addition of cylindrical tubing to the length of the horn.

3.2 Methods

3.2.1 Replica hands

In order to investigate the effect of different hand shapes and positions on the input \(Z\) of the horn, the right hand (in playing position) of several different horn players was required. However, to increase accuracy and allow for extended measurements (in another city) it was decided that replica hands were needed. It was necessary for these hands to exactly mimic the shape, size and position in the bell of actual horn players’ hands as well as approximate the acoustic properties of the human hand.

Unfortunately information pertaining to replica body parts was limited to medical applications used for training and calibration of equipment, and props used in stage and film. The former of the two categories mainly consisted of companies developing and selling replica body parts. These were unsuitable as the replicas were generic rather than specific and guidelines were not provided on materials or methods used. The latter category consisted of detailed information on making a realistic looking hand, but not an acoustically equivalent one. Thus, it was necessary to develop a procedure for making replica hands for the purposes of this experiment.

Development of the procedure consisted of two main parts: materials for use and method of producing the final product. Both of these parts required special considerations. For example,

1. Materials

   (a) For casting the player’s hand:

   - Non-toxic.
   - Able to accurately cast hand shape.

   (b) For the completed replica hand:

   - Accurately hold hand shape for extended period (> 1 year).
   - Acoustically approximate human hand.
3.2. METHODS

- Flexible to fit into bell of horn.
- Does not corrode over time or on exposure to ultra-violet light or metal of instrument (e.g. brass).

2. Method

(a) For casting the player’s hand:
- Short time to cast as player has to hold hand in playing position.
- Able to remove hand from casting without distorting shape of cast.

(b) For the completed replica hand:
- Retain accurate shape and size of player’s hand.
- Time and cost efficient.

Many trials were carried out before the final procedure was adopted. The materials and procedure used are outlined below:

3.2.1.1 Materials used for making replica hand

After taking into account the considerations listed above, the following materials were used:

- Cromatic/Kromalgin Più – Dust free Chromatic alginate.
  - Used for making dental impressions, so non-toxic and holds shape whilst having enough flexibility to remove hand.

- Plaster of paris.

- Barnes Ultrasil – two component, tin catalysed RTV silicone rubber.
  - Fast curing to enable it to be painted onto plaster hands.

- Perma-gel – synthetic ballistics gelatin.
  - Approximates the density of human flesh and is stable over time and a wide range of temperatures.

3.2.1.2 Procedure for making replica hand

The procedure for producing the replica hand consisted of four main steps: 1. casting of player’s hand; 2. creation of positive mould; 3. formation of “skin”; and 4. filling the “skin”. The following is a synopsis of these steps (which is also represented pictorially in Figure 3.3):

1. Casting of player’s hand (Figure 3.3a to c):
Figure 3.3: Pictorial method for making replica hands, showing a) mixing of alginate, b) casting of player’s hand in alginate, c) player’s hand removed from alginate, d) plaster poured into alginate mould, e) removal of plaster hand from alginate, f) comparison of plaster hand with real hand, g) filling of deep creases with plaster filler before being sanded smooth, h) hands after coating with shellac, i) plaster hand coated with silicone rubber, j) removal of silicone rubber ‘skin’ and comparison of ‘skin’ with plaster hand, k) melting of Perma-gel in oven, l) silicone rubber ‘skins’ filled with Perma-gel, m) Perma-gel hand with ‘skin’ removed, and m) replica hand with metal rod inserted for support.
3.2. METHODS

(a) Player’s right hand was placed, in playing position, in dental alginate.

(b) When the alginate had set (approximately 4 minutes), the player gently removed their hand so as not to distort the casting.

2. Creation of positive mould (Figure 3.3d to h):

(a) Plaster of Paris was poured into the alginate mould immediately after player’s hand was removed.

(b) After plaster had set (at least 24 hours), the alginate was removed from around the plaster hand.

(c) Plaster was given time to air dry before being sanded to remove any sharp points or air bubbles and any deep creases or holes filled using a plaster filler.

(d) Plaster hand was varnished with several coats of shellac until surface became shiny.

3. Formation of ‘skin’ (Figure 3.3i and j):

(a) A layer of silicone rubber was applied to the plaster hand.

(b) Whilst still tacky (< 4 minutes), a second layer of silicone rubber was applied.

(c) After allowing to fully cure (approximately 24 hours), the ‘skin’ was very gently removed from the plaster hand so as not to tear the silicon rubber.

4. Filling the skin (Figure 3.3k and l):

(a) Synthetic ballistics gelatin (Perma-gel) was melted in an oven at 130°C for several hours.

(b) The melted gelatin was cooled slightly before being poured into the “skin”, taking care not to stretch the silicon rubber.

(c) The gelatin was massaged into the correct shape within the “skin” whilst being cooled in a cold-room.

The synthetic ballistics gelatin did not bond to the silicone rubber ‘skin’ and during preliminary experiments using the replica hands in the bell of the horn, it was found that the air gap between the ‘skin’ and the gelatin caused sound to be absorbed. Thus, all experiments were carried out with the ‘skin’ removed (Figure 3.3m) and a metal rod was inserted into the hands for support (Figure 3.3n). This did not adversely affect the shape of the hand as the silicone rubber was strong enough to allow the ballistics gelatin to form a well shaped hand within it. The size of the hand was actually more accurate without the ‘skin’, as the outside of the silicone rubber was necessarily larger than the actual player’s hand due to its 1-2 mm thickness.
3.2.2 Materials

3.2.2.1 Horns

Two different horns were used (Figure 3.4):

- Yamaha YHR668 (ca. 2008), on loan courtesy of Yamaha Music Australia (PHorn) – professional model, large bore, double horn.
- F.E.Olds & Son Ambassador (1973) (SHorn) – student model, large bore, double horn.

![Figure 3.4: (a) Professional model horn and (b) Student model horn.](image)

3.2.2.2 Mouthpieces

Three mouthpieces were used (Figure 3.5):

1. J. Marcinkiewicz Model No. 7 (MP1).
2. L’Ollifant B8 Mod. 1789 with BR rim (MP2).
3. Halstead Paxman Chidell (25 mm cup) (MP3).

3.2.2.3 Hands

Replicas were made of three different horn player’s right hands in playing position (Hand1 - Hand3). These were used for both the input Z measurements and the experiments involving horn players (Chapter 4). The replica hands were positioned in the bell of the horns using a system of stays mounted to the bell in marked positions (Figure 3.6). Positions were determined through observation of photographs...
3.2. METHODS

Figure 3.5: Mouthpieces 1 (a), 2 (b) and 3 (c).

Figure 3.6: Replica hand positioned in bell of horn with stays mounted to the bell. Note that the rotation of the replica hand in the bell did not affect the results and was purely for ease of positioning the hand in the bell during experiments.

### 3.2.2.4 Mutes

Three different types of horn mutes were used: Straight mutes; stopping mutes; and practice mutes. Several models, made of different materials, were used of each type of mute:

- **Straight mutes (Figure 3.8):**
  1. Don Maslet straight mute (M1) – fibre.
  2. Denis Wick straight mute (M2) – aluminium.
CHAPTER 3. INPUT Z OF HORN

Figure 3.7: Position of players’ hands in bell. Hand 1 (left), Hand 2 (centre) and Hand 3 (right).

Figure 3.8: Straight mutes M1 (left) and M2 (right).

- Stopping mutes (Figure 3.9):
  1. Stopping mute - unknown make (S1) – brass.
  2. Humes & Berg stopping mute (S2) – brass.
  3. Ion Balu stop mute (S3) – matte brass.
  4. Woodstop mute\(^1\) (S4) – wood.

- Practice mutes (Figure 3.10):
  1. Yamaha Silent Brass practice mute (P1) – composite.
  2. Denis Wick practice mute (P2) – aluminium.
  4. Trumcor Stealth # 5 practice mute (P4) – fibre and wood.

\(^1\)Courtesy of Prof. Darryl Poulsen
3.2.3 Z measurements

Acoustic impedance measurements were made in the Acoustics Lab in the School of Physics at UNSW using the three microphone, two calibration technique and hardware described by Dickens et al. (2007) (see Section 2.1.1). Figures 3.11 and 3.12 show a diagram and photograph, respectively, of the experimental setup. Measurements were made with representative fingerings (complete for some sets) on both sides of the horn (F and Bb) for both the professional and student horns with each of the three mouthpieces and each of the three replica hands or ten mutes in the bell. For the complete set of impedance measurements, see Appendix B.

3.2.4 Analysis of Z data

Variation in frequency of resonance peaks from harmonicity was calculated using the following method:

1. A fitted ‘fundamental’ ($f_{F1}$) was calculated as the frequency of the first resonance ($f_1$) lies far from harmonicity:

$$f_{F1} = \frac{f_3 + f_4 + f_5 + f_6}{4}$$

(3.1)

the second resonance was not included in the fit as its frequency also lies far from harmonicity (although it is closer than for the first resonance).
2. Variation from harmonicity ($\Delta f_n$) for each resonance was calculated in cents:

$$\Delta f_n = 1200 \log_2 \left( \frac{f_n}{n f_1} \right)$$

(3.2)

It is important to note that inharmonicity present in the impedance spectrum does not introduce inharmonicity in the sound spectrum because of the periodicity of the lip vibration.

Average RMS error ($RMS_{err}$), RMS difference between conditions ($RMS_{diff}$) and RMS variation from harmonicity ($RMS_{harm}$) were calculated using the following method:

- Average RMS error was calculated over resonances 1 to 20:
  1. RMS over six repetitions was calculated for each resonance:

$$f_{\text{rms}} = \sqrt{\frac{\sum_1^m (f_n^2)}{m}} \quad m = 6$$

(3.3)

2. RMS error was calculated for each resonance:

$$f_{\text{err}} = \sqrt{\frac{\sum_1^m (f_{\text{rms}} - f_n)^2}{m}} \quad m = 6$$

(3.4)

3. Average RMS error over resonances 1 to 20 was calculated:

$$RMS_{err} = \frac{\sum_1^m (f_{\text{err}}^2)}{20} \quad m = 20$$

(3.5)

- Average RMS difference between conditions was calculated over resonances 1
3.2. METHODS

Figure 3.11: Diagram of setup used for measuring $Z$.

Figure 3.12: Setup for measuring $Z$ of horn (left) and closeup of mouthpiece coupled to impedance head (right).
to 20:
\[
\text{RMS}_{\text{diff}} = \sqrt{\frac{\sum_{1}^{m}(f_{n2} - f_{n1\text{rms}})^{2}}{m}} \quad m = 20
\] (3.6)

- RMS variation from harmonicity was calculated over resonances 2 to 20 for the F horn of the professional and student model horns and resonances 2 to 15 for the Bb horn of the professional model and 2 to 13 of the Bb horn of the student model:

\[
\text{RMS}_{\text{harm}} = \sqrt{\frac{\sum_{2}^{m}(\Delta f_{n}^{2})}{m-1}}
\] (3.7)

### 3.3 Results

Unless otherwise stated, the presented data in this section is from measurements made with the Professional model horn (PHorn), mouthpiece 1 and Hand 1. Valve combinations (fingerings) are notated as shown in Table 3.1. Representative impedance spectra are presented in Appendix B.

#### 3.3.1 Reproducibility

Multiple acoustic impedance measurements made for the same horn and mouthpiece with an open bell (no hand or mute) showed a reproducibility in the peaks of 0.8% average error in magnitude and 0.1% average error in frequency. The inclusion of measurements after resetting the mouthpiece and horn increased the average error to 1.3% in magnitude and 0.2% in frequency. Figure 3.13 shows the difference between the average magnitudes of the peaks before changing the setup (Experiment 1a) and the magnitudes of the peaks after changing the setup (Experiment 1b). After resetting the mouthpiece and horn, the magnitudes of resonance peaks 2 to 11 were higher than before the reset. From this point, the combined error (of 1.3% in magnitude and 0.2% in frequency) will be considered that of Experiment 1 and will be used for comparison purposes. Multiple acoustic impedance measurements made for each of the replica hands showed that they could be reinserted in the bell with

<table>
<thead>
<tr>
<th>Bb horn</th>
<th>F horn</th>
<th>Valve(s) depressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxBb</td>
<td>xxxF</td>
<td>none (open horn)</td>
</tr>
<tr>
<td>1xxBb</td>
<td>1xxF</td>
<td>1</td>
</tr>
<tr>
<td>x2xBb</td>
<td>x2xF</td>
<td>2</td>
</tr>
<tr>
<td>xx3Bb</td>
<td>xx3F</td>
<td>3</td>
</tr>
<tr>
<td>12xBb</td>
<td>12xF</td>
<td>1 and 2</td>
</tr>
<tr>
<td>x23Bb</td>
<td>x23F</td>
<td>2 and 3</td>
</tr>
<tr>
<td>1x3Bb</td>
<td>1x3F</td>
<td>1 and 3</td>
</tr>
<tr>
<td>123Bb</td>
<td>123F</td>
<td>1, 2 and 3</td>
</tr>
</tbody>
</table>
3.3. RESULTS

Figure 3.13: Differences in magnitudes of $Z$ peaks between Experiment 1a and Experiment 1b.

A typical reproducibility in the peaks of 1.6\% average error in magnitude and 0.2\% average error in frequency (including changes in mouthpiece and horn setup).

A second experiment run (Experiment 2) was also carried out in which it was not possible to get the magnitudes and frequencies of the peaks to lie within the error obtained in experiment 1 (Figure 3.14). This was observed to be due to the cleanliness of the mouthpiece (see section 3.3.3). However, the error within experiment 2 was consistent with that obtained in experiment 1 and so the data from experiment 2 has been used in the analysis. Unless specifically stated however, no comparisons have been made between experiments 1 and 2.

It was possible to place the replica hand in the bell so that the impedance peaks closely matched those of the corresponding real hand placed in the bell (Figure 3.15). The replica hands were mounted on the bell by a system of stays (Figure 3.6) however, these were not found to affect the impedance data as shown by the similarity of impedance spectra for the open F horn (no hand in bell) with and without the stays (Figure 3.16).
Figure 3.14: Differences in magnitudes of $Z$ peaks between Experiment 1 and Experiment 2.

Figure 3.15: Impedance spectra for the open F horn (xxxF) with real hand and replica hand in bell.
3.3.2 Hand

Placing the hand in the bell (in normal playing position) greatly affects the resonance peaks above the cutoff frequency of the bell (around 500 Hz). Figures 3.17 and 3.18 show the differences in impedance and phase spectra between an open bell and hand in bell for the F horn and Bb horn, respectively. Placing the hand in the bell in normal playing position lowers the frequencies of the resonance peaks and greatly increases the magnitudes above the cutoff frequency of the bell (around 500 Hz).

When the same setup (horn, mouthpiece, and replica hand) was measured in independent trials, the RMS error in the magnitude and frequency of the impedance peaks 1 to 20 was 0.1 dB and 0.9 Hz, respectively. Measurements were made with replica hands which corresponded to three different horn players’ right hands in playing position. The three different replica hands (with the same horn and mouthpiece) showed reproducible, measurable changes in $Z$, with an RMS difference in the magnitude and frequency of impedance peaks 1 to 20 of up to 0.6 dB and 1.3 Hz, respectively. Figure 3.19 shows the impedance spectra for the three different hands and no hand in bell for the open Bb horn. magnitudes of resonance peaks for various valve combinations on the horn and the three different hands are shown in Figure 3.20. Differences are apparent above the fourth resonance for most valve combinations. Hand 3 tends to have higher peak magnitudes than the other two hands above the ninth resonance. The magnitudes for Hands 1 and 2 are fairly similar across all resonance peaks.
Figure 3.17: Impedance and phase spectra for the open F horn (xxxF) with and without hand in bell, illustrating the effect of the hand on the cutoff frequency of the bell.

Figure 3.18: Impedance and phase spectra for the open Bb horn (xxxBb) with and without hand in bell.
Figure 3.19: Impedance spectra of open Bb horn (xxxBb) with Hands 1 to 3 in bell and no hand in bell.
Figure 3.20: Magnitudes of resonance peaks for open F horn (xxxF), open Bb horn (xxxBb), and various valve combinations with three different hands in the bell. (Error bars typically within size of symbol).
3.3. RESULTS

The frequencies of resonance peaks also differed between hands. Figure 3.21 shows the variation in frequency of resonance peaks from harmonicity for various valve combinations on the horn and the three different hands. The first resonance is missing from the graphs as it is not close to a member of the harmonic series (around 500-700 cents below the first harmonic) and is of little musical significance as it is not used in general playing. The three hands differ in their variation in frequency from harmonicity across all resonance peaks. All the hands follow the same pattern – resonances three to five are sharp (up to 30 cents), resonances six and above are flat (up to 25 cents), and the highest few resonances are sharp (up to 30 cents) with respect to the fitted series for the respective hands. In general, Hand 2 has a higher (more positive) variation in frequency from harmonicity than the other two hands above the sixth resonance for all valve combinations.

The musical significance of the differences between the three hands is demonstrated by analysing seven notes that are commonly played on the open Bb horn (xxxBb). Figure 3.22 shows that the frequency of the corresponding resonance peaks (measured at room temperature) tend to lie at frequencies below the nominal equal temperament frequencies for these notes. As can be seen, for all hands, the resonance peaks are flat relative to the equal temperament frequency for F4 and above. However, the impedance peaks for Hand 3 are consistently flatter than those of either Hand 1 or Hand 2.

3.3.3 Mouthpiece

Each of the three mouthpieces has a different resonance frequency (corresponding to the popping frequency) and magnitude as shown in Figure 3.23. The differences in $Z$ spectra when coupled to the horn are shown in Figures 3.24 and 3.25. Mouthpiece 2 has the highest resonance peak magnitude and also tends to have the highest peak magnitudes when coupled to the horn and the opposite is true for mouthpiece 1. The different mouthpieces with the same horn and replica hand, showed reproducible, measurable changes in $Z$, with an RMS difference in the magnitude and frequency of impedance peaks 1 to 20 of up to 0.4 dB and 2.0 Hz, respectively.

Magnitudes of resonance peaks for various valve combinations on the horn with Hand 1 in bell and the three different mouthpieces are shown in Figure 3.26. Differences can be seen above the fourth resonance, but are much smaller than those for the three different hands. The magnitudes of the resonance peaks for mouthpiece 1 are generally lower than for the other two mouthpieces, especially for the higher frequency resonances. Variation in frequency of resonance peaks from harmonicity for the three mouthpieces can be seen for most resonances across all valve combinations (Figure 3.27). The frequencies of the resonance peaks for mouthpiece 1 tend to be flatter than those for the other two mouthpieces, especially for high frequency resonances.
Figure 3.21: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb), and various valve combinations with three different hands in the bell. (Error bars typically within size of symbol).
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Figure 3.22: Variation in frequency of resonance peaks from nominal equal temperament frequencies for F3, Bb3, F4, Bb4, C5, D5 and F5 for three different hands in open Bb horn (xxxBb). (Measurements of impedance were made at room temperature.)

Figure 3.23: Impedance spectra for three different mouthpieces without horn, loaded only with unbaffled radiation impedance at the backbore.
Figure 3.24: Impedance spectra of open F horn (no hand in bell) with three different mouthpieces.
Figure 3.25: Impedance spectra of open Bb horn (no hand in bell) with three different mouthpieces.
Figure 3.26: Magnitudes of resonance peaks for open F horn (xxxF), open Bb horn (xxxBb), and various valve combinations with Hand 1 in the bell and three different mouthpieces. (Error bars typically within size of symbol).
Figure 3.27: Variation in frequency of resonance peaks from harmonicity for open 
F horn (xxxF), open Bb horn (xxxBb), and various valve combinations with Hand 
1 in the bell and three different mouthpieces. (Error bars typically within size of 
symbol).
The effect of the cleanliness of the mouthpiece on the impedance spectra was also investigated. Mouthpiece 1 (MP1) was not cleaned prior to Experiment 1 however, it had been in use and was in a ‘semi-clean’ condition (here on referred to as ‘typical’) which could be considered a typical playing condition given that brass players do not clean their mouthpiece regularly. At the beginning of Experiment 2, Mouthpiece 1 had not been used for several months and was discovered to have a fairly thick layer of dirt built up inside the throat and backbore. It is unclear exactly what the dirt consisted of, but it is common in brass instrument mouthpieces for dirt to build up over time or if being played after eating. Measurements were made before and after cleaning the mouthpiece.

Differences were found between the impedance spectra of the three different conditions for the one mouthpiece, but were much smaller than differences between the impedance spectra of the three different mouthpieces. The effect of these three conditions (typical, dirty, and clean) on the resonance frequency and magnitude of the mouthpiece can be seen in Figure 3.28 which shows that the resonance peak for the dirty mouthpiece is both lower in magnitude and frequency. Interestingly, the peak for the typical mouthpiece is slightly higher in both frequency and magnitude than that for the clean mouthpiece.

The differences in impedance spectra of the open F horn (no hand in bell) with the mouthpiece in the three different conditions is shown in Figure 3.29. For the majority of resonance peaks, the clean mouthpiece has the highest magnitudes and the dirty mouthpiece has the lowest (except for the eighth and tenth resonances for which the typical mouthpiece has the highest magnitude and the clean mouthpiece the lowest). For the low magnitude peaks above the cutoff frequency of the bell (600 to 650 Hz), the clean mouthpiece has much lower magnitudes and higher frequencies than both the other two mouthpiece conditions.

The effect of mouthpiece cleanliness on the magnitudes and frequency deviations from harmonicity of resonance peaks for the open F horn with hand in bell, are demonstrated in Figures 3.30 and 3.31, respectively. For the first seven resonance peaks the dirty mouthpiece has considerably lower magnitudes and above the fifth resonance, the dirty mouthpiece tends to have higher frequency resonance peaks than the other two mouthpiece conditions. For most resonances, the clean mouthpiece has higher frequency peaks than the typical mouthpiece. Above the thirteenth resonance, the clean mouthpiece has lower magnitude peaks than either of the other two mouthpiece conditions.
Figure 3.28: Impedance spectra of MP1 in typical, dirty and clean conditions.
Figure 3.29: Impedance spectra of open F horn (no hand in bell) with MP1 in typical, dirty and clean conditions.
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Figure 3.30: Magnitudes of resonance peaks of open F horn with Hand 1 in bell and MP1 in typical, dirty and clean conditions.

Figure 3.31: Variation in frequency of resonance peaks from harmonicity of open F horn with Hand 1 in bell and MP1 in typical, dirty and clean conditions.
3.3.4 Mute

In Figure 3.32, the impedance spectra of the horn with three different types of mute (straight, stopping and practice) are compared with the impedance spectra for the hand. As can be seen, the frequencies of resonance peaks for the straight and practice mutes are quite similar to those of the hand in bell, whereas the stopping mute introduces an extra resonance which causes the proceeding resonances to fall at a frequency higher than those of the hand in bell (see section 1.7.2). This corresponds to the fact that straight and practice mutes are non-transposing and the stopping mute is a transposing mute.

Several of the straight and practice mutes caused a prominent extra peak to appear in the impedance spectrum. This was the case for straight mute M2 and practice mutes P1 and P2. The frequency of this extra peak stays fairly constant across all valve combinations on both the F and Bb horns (Figure 3.33). The effect of these extra peaks on the impedance spectrum will be demonstrated later (see sections 3.3.4.1 and 3.3.4.3).

3.3.4.1 Straight mute

The impedance spectra of the open F and Bb horns with each of the two different straight mutes (M1 and M2), compared to a hand in the bell, is given in Figure 3.34. A comparison of the magnitudes of resonance peaks for the two mutes and hand in bell for various valve combinations on the F and Bb horns are shown in Figures 3.35 and 3.36, respectively. In general, above the eighth resonance the straight mutes have higher magnitudes than the hand, but are lower than the hand for the first three resonances. Magnitudes for M2 are consistently higher than for M1 across nearly all resonances.

Variation in frequency of the resonance peaks from harmonicity is shown in Figures 3.37 and 3.38 for the two straight mutes and hand in bell. Both straight mutes are less harmonic than the hand, with M2 being the least harmonic. Resonances for M2 tend to be sharper than M1 for the first four resonances and flatter above the fourth resonance.

Straight mute M2 was found to have a prominent extra peak around 90 Hz (see Figure 3.33) which also affected the magnitude and frequency of its closest neighbouring peak. Straight mute M1 also showed evidence of an extra peak, but with a magnitude too small to affect its neighbouring peak. This difference between the two mutes is shown in Figure 3.39 for the open F horn.

When M2 was held out slightly from the throat of the bell (Figure 3.40), the frequency of the extra peak was found to increase to about 120 Hz (Figure 3.41). Changing the position of M2 in the bell of the horn was also found to affect the magnitudes and frequencies of the other resonance peaks, not just the extra peak, as shown in Figure 3.42. Holding the mute out from the throat of the bell caused the
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Figure 3.32: Impedance spectra for valve 1, F horn (1xF) with hand in bell and straight mute (top), stopping mute (middle), and practice mute (bottom) in bell.
frequencies of the resonance peaks to increase, actually making it more harmonic. Peak magnitudes of the first eight resonances were increased and above the eighth resonance were decreased.

There were very little differences in the resonance peaks for various holding positions (twisted in (normal position), twisted in with palm resting on base, or rested in with hand holding base (Figure 3.43)) of straight mute M1 (Figure 3.44). However, resting the mute in the bell did have a small effect on the magnitudes and frequencies of a few resonance peaks.

M1 is a tunable straight mute and Figure 3.45 shows the differences in impedance spectra with the tuner in its maximum (fully out) and minimum (fully in) positions. The effect of the tuner’s position on the magnitude and variation in frequency from harmonicity of the resonance peaks is shown in Figure 3.46. Small differences are apparent for the first twelve resonance peak magnitudes, but differences are greater for the variation in frequency from harmonicity for the resonance peaks (especially above the sixteenth resonance). M1 with the tuner fully out is more harmonic than with the tuner fully in.

3.3.4.2 Stopping mute

Differences in impedance spectra for the four different stopping mutes (S1 to S4), compared to hand in bell, are shown in Figure 3.47 for the open F and Bb horns. The spectra are very similar for stopping mutes S1, S2 and S4, with slight variations
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Figure 3.34: Impedance spectra of open F (left) and open Bb (right) horn with Hand 1 in bell and straight mutes M1 (top) and M2 (Bottom) in bell. Note extra peak in straight mute spectra.
Figure 3.35: Magnitudes of resonance peaks for open F horn (xxxF) and various valve combinations with Hand 1 in bell and straight mutes M1 and M2 in bell. (Error bars typically within size of symbol).
Figure 3.36: Magnitudes of resonance peaks for open Bb horn (xxxBb) and various valve combinations with Hand 1 in bell and straight mutes M1 and M2 in bell. (Error bars typically within size of symbol).
Figure 3.37: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and various valve combinations with Hand 1 in bell and straight mutes M1 and M2 in bell. (Error bars typically within size of symbol).
Figure 3.38: Variation in frequency of resonance peaks from harmonicity for open Bb horn (xxxBb) and various valve combinations with Hand 1 in bell and straight mutes M1 and M2 in bell. (Error bars typically within size of symbol).
Figure 3.39: Close up of impedance spectra of open F horn (xxxF) with straight mutes M1 (left) and M2 (right), illustrating the effect of the extra peak.

Figure 3.40: Straight mute M2 in bell of horn in normal position (left) and held out from throat of bell (right).
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Figure 3.41: Impedance spectra of open F horn (xxxF) with straight mute M2 placed in normal position in bell and held out from throat of bell.

Figure 3.42: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of open F horn with M2 placed in normal position in bell and held out from throat of bell.

Figure 3.43: Straight mute M1 in bell of horn with palm of hand holding base of mute.
Figure 3.44: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of open F horn with M1 twisted into the bell (normal position), twisted into the bell with palm against base and rested in bell with hand holding base.

Figure 3.45: Impedance spectra of open F horn with M1 in bell with tuner fully out and fully in.
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Figure 3.46: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of open F horn with M1 in bell with tuner fully out and fully in.

All the stopping mutes introduce an extra peak into the impedance spectra between the first two resonances. Instead of interfering with the neighbouring peak, it causes all the resonances to displace, essentially introducing an extra resonance into the spectrum (Figure 3.48). Thus, the third resonance with the stopping mute has a slightly higher frequency than that of the second resonance with the hand and this frequency difference (in Hz) increases with increasing resonance number. That is, the harmonics of the stopping mute are stretched greatly from harmonicity (Figure 3.49). Although the frequency difference (in Hz) increases with increasing resonance number, the ratio of the frequencies between the resonances with the stopping mute and those with the hand tend to decrease with increasing resonance number as shown in Figure 3.50.

The magnitudes of resonance peaks for the horn with the four different stopping mutes in bell are shown in Figure 3.51. It can be seen that above around 750 Hz, the resonances of all four mutes have low magnitudes and do not vary from one another. Stopping mutes S1, S2 and S4 have very similar peak magnitudes, although S4 tends to be slightly lower than S1 and S2. Stopping mute S3 has the greatest variation from the other mutes, with lower magnitude peaks between resonance four and ten. In particular, the resonance peak around 720-740 Hz has a much lower magnitude than any of the other mutes. This is due to a small extra resonance at approximately 725 Hz influencing the magnitude of this resonance peak (Figure 3.52). The frequency of the peak around 720-740 Hz is also affected and tends to be sharper than that of the other mutes (Figure 3.49).
Figure 3.47: Impedance spectra of open F (left) and open Bb (right) horn with Hand 1 in bell and stopping mutes S1, S2, S3 and S4 (top to bottom) in bell.
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Figure 3.48: Impedance spectra of open F horn with hand in bell and stopping mute in bell, illustrating the addition of an extra impedance peak with the stopping mute.

Figure 3.49: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and open Bb horn (xxxBb) with stopping mutes S1, S2, S3 and S4 in bell. (Error bars typically within size of symbol).
Figure 3.50: Variation in frequency of resonances of open F horn, open Bb horn and various valve combinations between hand in bell and stopping mute S1, S2, S3 and S4 in bell.
3.3. RESULTS

Figure 3.51: Magnitudes of resonance peaks for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with stopping mutes S1, S2, S3 and S4 in bell. (Error bars typically within size of symbol).

Figure 3.52: Close up of impedance spectra of open F horn (left) and open Bb horn (right) with stopping mute S3, illustrating the effect of the extra resonance on the magnitude and frequency of the neighbouring peak.
3.3.4.3 Practice mute

A comparison of the impedance spectra of the open F and Bb horns with a hand in bell and the four different practice mutes (P1-P4) in bell is presented in Figure 3.53. The shape of the impedance spectrum changes when the hand is replaced with a practice mute. The magnitudes of low frequency resonances are lowered and the magnitudes of high frequency resonances are raised. There is also a measurable frequency shift which decreases the harmonicity of the resonance peaks as can be seen in Table 3.2 which shows the RMS variation in frequency of resonance peaks from harmonicity for the horn with hand in bell and the four practice mutes in bell.

The relative magnitudes of the resonance peaks for the practice mutes were measurably different to those for a hand (Figures 3.54 and 3.55) and also differed markedly among practice mutes. The magnitudes for all practice mutes were lower than the hand for the first five resonances and higher than the hand above about the eighth resonance. In general, the magnitudes of resonance peaks for P3 were lower and for P1 were higher than for the other practice mutes.

The frequencies of resonance peaks also differed between the hand and practice mutes (Figures 3.56 and 3.57). All of the practice mutes were less harmonic than the hand, which is confirmed in Table 3.2. These figures show that practice mute P1 is closest to the hand in its harmonicity (at least for the F horn) and practice mute P2 is least harmonic, with resonances 2 and 3 sharper than for the other mutes and resonances 6 to 17 flatter than for the other mutes.

Two of the practice mutes (P1 and P2) were found to produce a prominent extra peak in the impedance spectrum as shown in Figure 3.58. For P1, the extra peak occurs at around 30 Hz – a frequency well below the second resonance – and consequently does not interfere with the useful resonance peaks. However, the extra peak produced by P2 occurs at around 110 Hz and affects both the frequency and magnitude of its neighbouring resonance. In fact, the extra peak tends to cause a split resonance, in which the two peaks have roughly the same magnitude and sit either side of the expected resonance frequency.

Table 3.2: RMS variation in frequency of resonance peaks from harmonicity of open F horn (xxxF) and open Bb horn (xxxBb) with hand in bell and practice mutes P1, P2, P3 and P4 in bell.

<table>
<thead>
<tr>
<th>RMS variation from harmonicity</th>
<th>xxxF</th>
<th>xxxBb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand</td>
<td>19.3</td>
<td>15.0</td>
</tr>
<tr>
<td>P1</td>
<td>26.2</td>
<td>38.6</td>
</tr>
<tr>
<td>P2</td>
<td>105.3</td>
<td>110.1</td>
</tr>
<tr>
<td>P3</td>
<td>44.9</td>
<td>37.6</td>
</tr>
<tr>
<td>P4</td>
<td>42.7</td>
<td>40.6</td>
</tr>
</tbody>
</table>
Figure 3.53: Impedance spectra of open F (left) and open Bb (right) horn with Hand 1 in bell and practice mutes P1, P2, P3 and P4 (top to bottom) in bell.
Figure 3.54: Magnitudes of resonance peaks for open F horn (xxxF) and various valve combinations with Hand 1 in bell and practice mutes P1, P2, P3 and P4 in bell. (Error bars typically within size of symbol).
3.3. RESULTS

Figure 3.55: Magnitudes of resonance peaks for open Bb horn (xxxBb) and various valve combinations with Hand 1 in bell and practice mutes P1, P2, P3 and P4 in bell. (Error bars typically within size of symbol).
Figure 3.56: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and various valve combinations with Hand 1 in bell and practice mutes P1, P2, P3 and P4 in bell. (Error bars typically within size of symbol).
Figure 3.57: Variation in frequency of resonance peaks from harmonicity for open Bb horn (xxxBb) and various valve combinations with Hand 1 in bell and practice mutes P1, P2, P3 and P4 in bell. (Error bars typically within size of symbol).
The impedance spectra for the horn with practice mute P3 in bell showed a small amount of roughness in the spectrum up to approximately 300 Hz. As the measurement signal was decreased, this measured roughness reduced (in comparison with other features of the impedance spectrum; Figure 3.59). This shows it is a nonlinear effect, possibly associated with energy loss via an inelastic mechanical vibration such as a rattle. When the inner tube was removed from the centre of the mute, the roughness in the impedance spectrum disappeared, but the magnitudes and frequencies of the first six resonance peaks were also affected as shown in Figures 3.60 and 3.61.
Figure 3.59: Closeup of impedance spectra of open F horn (xxxF) with practice mute P3 in bell, illustrating the effect of input signal strength on the noise present in the spectrum.

Figure 3.60: Impedance spectra of open F horn (xxxF) with practice mute P3 in bell with and without tube insert.
Figure 3.61: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of open F horn (xxxF) with P3 in bell with and without tube insert.

### 3.3.5 Professional vs. student horn

The differences in impedance spectra between the professional model horn and the student model horn are demonstrated in Figures 3.62 and 3.63 for the open F horn (xxxF) with and without a hand in bell, respectively. The magnitudes of resonance peaks are considerably lower for the student model (except for resonances three, nine, ten and thirteen which are considerably higher). With the hand in bell, the high frequency resonances die away more quickly for the student model. The different horns (with the same mouthpiece and hand) showed reproducible, measurable changes in $Z$, with an RMS difference in the magnitude and frequency of impedance peaks 1 to 20 of up to 0.8 dB and 1.6 Hz, respectively.

Figures 3.64 and 3.65 show the differences in magnitude of the resonance peaks between the professional and student models of the F and Bb horns, respectively. Differences are apparent for all resonance peaks across all valve combinations. Magnitudes are generally lower for the student model horn. However, as seen in Figure 3.63, for particular resonance peaks, the student model has higher magnitudes. These seem to occur at similar frequencies across different valve combinations, particularly on the F horn (Figure 3.66).

There were also differences in the frequencies of resonance peaks between the professional and student model horns (Figures 3.67 and 3.68). In general, the resonance peaks for the student horn lie further away from harmonicity than for the professional horn. This is confirmed by comparing the RMS variation in frequency of resonance peaks from harmonicity for the professional and student model horns. Table 3.3 shows that the student model is less harmonic than the professional model, especially for the Bb horn.
3.3. RESULTS

Figure 3.62: Impedance spectra of open F horn (xxxF) for professional and student model horns with no hand in bell.

Figure 3.63: Impedance spectra of open F horn (xxxF) for professional and student model horns with Hand 1 in bell.
Figure 3.64: Magnitudes of resonance peaks for open F horn (xxxF) and all valve combinations with Hand 1 in bell for professional and student model horns. (Error bars typically within size of symbol).
Figure 3.65: Magnitudes of resonance peaks for open Bb horn (xxxBb) and all valve combinations with Hand 1 in bell for professional and student model horns. (Error bars typically within size of symbol).
Figure 3.66: Frequency of resonance peaks for which the student model horn has higher peak magnitudes than the professional model horn across different valve combinations on the F and Bb horns.

Table 3.3: RMS variation in frequency of resonance peaks from harmonicity of open F horn (xxxF) and open Bb horn (xxxBb) with hand in bell of professional and student model horns.

<table>
<thead>
<tr>
<th></th>
<th>xxF</th>
<th>xxxBb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professional</td>
<td>19.3</td>
<td>15.0</td>
</tr>
<tr>
<td>Student model</td>
<td>21.5</td>
<td>20.1</td>
</tr>
</tbody>
</table>
Figure 3.67: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and all valve combinations with Hand 1 in bell for professional and student model horns. (Error bars typically within size of symbol).
Figure 3.68: Variation in frequency of resonance peaks from harmonicity for open Bb horn (xxxBb) and all valve combinations with Hand 1 in bell for professional and student model horns. (Error bars typically within size of symbol).
3.3. RESULTS

3.3.6 Valves

The magnitudes of resonance peaks on the horn are affected by the combination of valves used. There are three different sets of alternative fingerings (i.e. different valve combinations that add very similar lengths of cylindrical tubing) available on the horn – 12xBb/xx3Bb, 1x3Bb/xxxF and 12xF/xx3F. Differences in the peak magnitudes and variations in frequency from harmonicity between the three sets of alternative fingerings are shown in Figures 3.69 to 3.71 for the professional model horn. It is apparent that there are variations in both peak magnitudes and deviations from harmonicity for nearly all resonance peaks between alternative fingerings. Similar results were found for the student horn and the figures are presented in Appendix D.

Figure 3.72 shows that for the professional model horn, the first six resonances decrease in magnitude as the length of valve tubing is increased. The opposite occurs above the twelfth resonance. A similar pattern was found for the magnitudes of the resonance peaks on the student horn (Figure 3.73). The variation in frequency of resonance peaks from harmonicity was also found to vary depending on the valves used (Figures 3.74 and 3.75), however, no clear pattern is readily derived from these graphs. (For figures showing the magnitudes and variation from harmonicity of resonance peaks for all valve combinations on the Bb horn with a hand in the bell of the professional and student model horns, see Appendix E).

An overall value of variation from harmonicity for each impedance spectrum is given by the RMS variation in frequency of resonance peaks from harmonicity. Figure 3.76 shows the variation from harmonicity for all valve combinations on the professional model horn displayed against the number of semitones by which the extra valve tubing increases the length of the horn. Once the length of added valve tubing increases beyond that needed to increase the length of the horn by five semitones, so too does the inharmonicity increase. (This increase is equivalent to changing the Bb horn to an F horn.) The RMS inharmonicity values are very similar for alternative fingerings. A similar trend is apparent for the student model horn (Figure 3.77), although the values for alternative fingerings are less similar than for the professional model.

On closer examination of the variation of frequency for all resonances across all valve combinations, it is apparent that the RMS values for valve combinations greater than four semitones are greatly skewed by a single point in each spectrum – the variation from harmonicity of the second resonance (Figure 3.78). Thus, as the length of valve tubing increases, so too does the inharmonicity of the second resonance. The student model horn shows a similar pattern (Figure 3.79). Excluding the second resonance from the RMS values (Figure 3.80) shows that apart from the second resonance, the variation from harmonicity is very similar for all valve combinations and actually tends to decrease slightly with increasing length of valve.
Figure 3.69: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of the professional model horn with Hand 1 in bell with valve combinations xxxF and 1x3Bb.

Figure 3.70: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of the professional model horn with Hand 1 in bell with valve combinations xx3F and 12xF.
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As the length of valve tubing is increased, the variation from harmonicity for each resonance (above the third) falls above and below harmonicity, showing no particular pattern. However, the second and third resonances show a distinct pattern in their variation from harmonicity as the valve tubing increases in length, as can be seen in Figures 3.78 and 3.79. As Figures 3.81 to 3.84 show, the impedance spectra for the horn with straight and practice mutes in bell also exhibit a similar pattern. (For figures showing the variation in frequency of resonance peaks from harmonicity for various valve combinations on the F and Bb horns with straight mutes M1 and M2, and practice mutes P1 to P4 in the bell of the professional model horn, see Appendix F).

The variation in frequency between the resonance peaks of the horn with stopping mute and the corresponding resonance peaks of the horn with hand (see section 3.3.4.2) tends to decrease as the length of valve tubing is increased (Figure 3.85). Although from this figure it appears that there is the same decreasing trend (with increasing valve length) across both the Bb and F horns, the RMS variation in frequency difference between the horn with hand in bell and the horn with stopping mute in bell indicates that the decrease in frequency difference with increasing valve length varies between the Bb and F horns (Figure 3.86).
Figure 3.72: Magnitudes of resonance peaks for open F horn (xxxF) and all valve combinations with Hand 1 in bell for professional model horn.
Figure 3.73: Magnitudes of resonance peaks for open F horn (xxxF) and all valve combinations with Hand 1 in bell for student model horn.
Figure 3.74: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and all valve combinations with Hand 1 in bell for professional model horn.
Figure 3.75: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF) and all valve combinations with Hand 1 in bell for student model horn.
Figure 3.76: RMS variation in frequency of resonance peaks from harmonicity of professional model horn with Hand 1 in bell for all valve combinations. Note that the overlapping points are due to alternative fingerings.

Figure 3.77: RMS variation in frequency of resonance peaks from harmonicity of student model horn with Hand 1 in bell for all valve combinations. Note that the overlapping points are due to alternative fingerings.
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Figure 3.78: Difference in frequency of resonance peaks from harmonicity for professional model horn with hand in bell for all resonance peaks across all valve combinations.

Figure 3.79: Difference in frequency of resonance peaks from harmonicity for student model horn with hand in bell for all resonance peaks across all valve combinations.
CHAPTER 3. INPUT Z OF HORN

Figure 3.80: RMS variation in frequency of resonance peaks from harmonicity of professional and student model horns with Hand 1 in bell for all valve combinations.

Figure 3.81: Difference in frequency of resonance peaks from harmonicity for professional model horn with straight mute M1 in bell for all resonance peaks across all valve combinations.
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Figure 3.82: Difference in frequency of resonance peaks from harmonicity for professional model horn with practice mute P1 in bell for all resonance peaks across all valve combinations.

Figure 3.83: Difference in frequency of resonance peaks from harmonicity for professional model horn with practice mute P3 in bell for all resonance peaks across all valve combinations.
CHAPTER 3. INPUT \( Z \) OF HORN

Figure 3.84: Difference in frequency of resonance peaks from harmonicity for professional model horn with practice mute P4 in bell for all resonance peaks across all valve combinations.

Figure 3.85: Difference in frequency of resonance peaks between horn with hand in bell and horn with stopping mute S1 in bell for all resonance peaks across all valve combinations.
3.3.7 Absence of player

Often during normal playing, the bell is rested on the player’s leg and when being played with a mute in the bell, the bell is either supported by the palm of the hand or rested on the leg. Resting the palm of the hand (real hand and side of torso) on the edge of the bell of the horn with a replica hand in the bell (Figure 3.87) has a measurable affect on the impedance spectrum (Figure 3.88). The differences in magnitudes and variation in frequency from harmonicity of the resonance peaks are shown in Figure 3.89. Differences are apparent above the seventh resonance. With the palm resting on the edge of the bell, peak magnitudes are decreased above the seventh resonance and resonance peaks are closer to harmonicity above the tenth resonance.
Figure 3.87: Setup for measuring $Z$ of horn with palm of hand resting on bell with replica hand in the bell.

Figure 3.88: Impedance spectra of open F horn (xxxF) with Hand 1 in bell with and without palm resting on edge of bell.
3.4 DISCUSSION

Multiple acoustic impedance measurements made for the same horn and mouthpiece with an open bell (no hand or mute) showed a reproducibility in the peaks of 1.3 % average error in magnitude and 0.2 % average error in frequency. This error increased to 1.6 % average error in magnitude and 0.2 % average error in frequency when reinserting a replica hand in the bell. This level of reproducibility is important as the differences in the impedance spectra between different hands, different mouthpieces and different horns are relatively small as shown in Table 3.4.

Table 3.4: Comparison of the RMS error in repeatability (same hand, mouthpiece and horn) with the maximum RMS differences between different hands, mouthpieces and horns.

<table>
<thead>
<tr>
<th></th>
<th>Hands</th>
<th>Mouthpieces</th>
<th>Horns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude (dB)</td>
<td>0.1</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>0.9</td>
<td>1.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Figure 3.89: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of open F horn (xxxF) with Hand 1 in bell with and without palm resting on edge of bell.
3.4.1 Hand

The placement of the hand in the bell is of vital importance to the impedance spectra of the horn. Differences in both magnitudes and frequencies of the resonance peaks were found between the three hands and these became greater near and above the cutoff frequency of the bell (around 500 Hz). The external radius of curvature of the flaring bore decreases rapidly near the bell so, for lower frequencies, reflection occurs in narrower parts of the bore, before reaching the hand. This is demonstrated by the difference in impedance spectra between a horn with a hand in the bell (normal playing position) and a horn with no hand in the bell. Without the hand in the bell, resonances rapidly decrease in magnitude above the cutoff frequency of the bell and disappear entirely above 650 Hz. The figures presented (Figures 3.17 and 3.18) are consistent with those published previously by Backus (1976) and Benade (1976), shown in Figures 3.1 and 1.12, respectively.

As each horn player’s hand is necessarily a different size and shape and is placed in the bell of the horn in a slightly different position, the effect of different hands on the impedance spectra of the horn was investigated. Replicas of three horn players’ right hands in playing position were used to enable extensive measurements with a high level of reproducibility. Measurable changes were found for both the frequencies and magnitudes of resonance peaks for the three different hands and differences were greater above the cutoff frequency of the bell, where the hand has more influence over the resonance peaks.

The effect that different hands have on the impedance spectrum has previously been demonstrated by Benoit and Chick (2006) who showed the impedance spectra of two different hands in the bell of the open Bb horn (Figure 3.90). However, no attempt was made to discuss or even describe the differences found and it was used solely to demonstrate the inadequacies of modelling the impedance spectrum of the horn without taking into account the hand in the bell. Differences in magnitudes and frequencies of resonance peaks between the three hands in this experiment were smaller than those shown between the two different hands by Benoit and Chick (2006).

Figure 3.91 shows a comparison of the two sets of data. Differences in frequency of impedance peaks between the two sets of data are likely due to the use of different models of horn. The impedance spectra are quite similar for Hands 1 to 3 and Player A. The large difference in the impedance spectrum of Player B is most likely due to an ‘incorrect’ hand position in the bell, as a very open hand position (either not curved enough over the face of the bell or not inserted far enough into the bell) would result in less flattening in the frequency of the resonance peaks and a decrease in magnitude of the resonance peaks above the cutoff frequency of the bell, both of which are observed for Player B. Thus, there is less difference between the impedance spectra for the three hands used in this experiment as they are all correct.
3.4. DISCUSSION

Figure 3.90: Impedance spectra for open Bb horn (xxxBb) with no hand in bell and two different players’ hands in bell. (Benoit and Chick, 2005)

Figure 3.91: Comparison of impedance spectra for different hands in the bell of the open Bb horn (xxxBb) presented by Benoit and Chick (2005) and data collected in this experiment.
hand positions used by horn players.

Results showed that magnitudes of the resonance peaks were higher for Hand 3 than for the other two hands above the ninth resonance and that Hands 1 and 2 had very similar peak magnitudes across all resonance peaks. This could be explained by looking at the size of the hands. Hands 1 and 2 were both slim female hands of much smaller size than Hand 3 which belonged to a large male horn player. Not only was Hand 3 larger, but it was also held in a more curved shape. Hence, Hand 3 took up more space in the bell than either of the other two hands. As a result, it could be expected that Hand 3 would reflect more of the high frequencies back into the horn, causing the resonance peaks to be larger, especially above the cutoff frequency of the bell.

Placing the hand in the bell in normal playing position decreases the frequencies of the impedance peaks, especially above 300 Hz. The more the hand is curved across the face of the bell, the greater the decrease in frequency. It was found that the resonance peaks for Hand 2 were sharper than for the other two hands above the sixth resonance. Hand 2 also had the most open hand shape of the three hands (less curved over the face of the bell) and thus would not have decreased the frequencies of the resonance peaks above the cutoff frequency of the bell to the same extent as the other two hands.

It was found that the resonance peaks on the open Bb horn corresponding to the notes F3, Bb3, F4, Bb4, C5, D5, and F5 had frequencies below the nominal equal temperament frequencies for these notes. This is not surprising: firstly, the impedance curves were measured at room temperature in dry air, whereas players would fill the bore with warm, humid air; and secondly, the playing frequency does not coincide exactly with the impedance peak (see section 2.1.1.3). However, Hand 3 is consistently flatter than the other two hands which is likely due to the more curved shape and larger size of this hand.

### 3.4.2 Mouthpiece

Although each of the three horn mouthpieces had a different resonance frequency, they were all very similar, ranging between 650 Hz and 700 Hz. This frequency corresponds to the highest notes that are commonly played on the horn (around F5) and confirms the statement made by Fletcher and Rossing (1991) that the resonance frequency of the mouthpiece is usually high to correspond to the upper end of the playing range. Impedance measurements were not made of the horn without being coupled to the mouthpiece, so the effect of the impedance spectra of coupling a mouthpiece to the horn was not investigated. Small differences in impedance spectra were found between the three different mouthpieces and the cleanliness of the mouthpiece was also found to affect the resonance peaks.

Differences in magnitudes of resonance peaks for the horn coupled to the three
3.4. DISCUSSION

different mouthpieces (and with hand in bell) appear above the fourth resonance. These differences are fairly small and are definitely much smaller than those shown by Plitnik and Lawson (1999) in their comparison of the peak magnitudes of three different mouthpieces (Figure 3.92). As these data were calculated using a computer model based on measurements of the mouthpiece and horn geometries, they are not directly comparable with the results of this experiment. It is interesting to note that the mouthpieces used by Plitnik and Lawson all had similar resonance frequencies which were considerably lower (below 600 Hz) than the three mouthpieces investigated here (Table 3.5).

Mouthpiece 1 had both a lower magnitude and frequency resonance peak than the other two mouthpieces and tended to also have lower magnitude resonance peaks when coupled to the horn, especially for resonances above the cutoff frequency of the bell. The resonance peaks of mouthpiece 1 coupled to the horn were also flatter than those of the other two mouthpieces, especially for high frequency resonances. Differences between all three mouthpieces are apparent in the variation in frequency from harmonicity of the resonance peaks and these differences are greater above the fourth resonance. These are similar to findings from Plitnik and Lawson (1999) (Figure 3.93; note that only the differences between the mouthpieces are relevant as the measurements were done with the mouthpieces coupled to a cylindrical pipe rather than a horn).

The cleanliness of the mouthpiece was found to have an effect on the resonance frequency of the mouthpiece. The typical (semi-clean) and clean conditions for mouthpiece 1 gave a very similar frequency (the clean mouthpiece was 2.5 cents flatter than the typical mouthpiece) and the resonance peak for the dirty mouthpiece was 29.5 cents flatter than that of the typical mouthpiece. The magnitude of the resonance peak was also affected, with the dirty condition lower than the other two. Interestingly, the peak magnitude for the clean condition was lower than that for the typical condition. Possibly, there was a small amount of dirt present in the typical condition which constricted the throat and bore (constriction point) of the mouthpiece, increasing the reflection and lowering the popping frequency. However, this was not measured or observed at the time. When coupled to the horn, the resonance peaks for the dirty mouthpiece were lower in magnitude for the lower

Table 3.5: Resonance frequencies of the three mouthpieces used in the present study and those used by Plitnik and Lawson (1999).

<table>
<thead>
<tr>
<th>Present study</th>
<th>Plitnik and Lawson (1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make &amp; model</td>
<td>Resonance frequency</td>
</tr>
<tr>
<td>Marcinkiewicz 7</td>
<td>642.6</td>
</tr>
<tr>
<td>L'Olifant B8 1789</td>
<td>661.0</td>
</tr>
<tr>
<td>Halstead Paxman Chidell</td>
<td>675.7</td>
</tr>
</tbody>
</table>
Figure 3.92: Impedance spectra for a horn with three different mouthpieces: Lawson L5, Holton MDC and Giardinell S14. (Plitnik and Lawson, 1999)

Figure 3.93: Frequency deviation from integer values, defined by the third harmonic, for three different mouthpieces coupled to a cylindrical pipe. The points along the axis are the frequency deviations for the L5 coupled to a horn. (Plitnik and Lawson, 1999)
frequency resonances and closer to harmonicity above the fifth resonance than for the clean and typical conditions. The clean mouthpiece tended to be more harmonic than the typical mouthpiece.

It is interesting to note that mouthpiece 2 was a brand new mouthpiece at the time the measurements were made and thus would have been in a clean state (whereas the other two mouthpieces were in a ‘typical’ state). However, this does not explain the fact that the magnitude of the resonance peak for this mouthpiece was considerably higher than those of the other two mouthpieces as the peak magnitude for mouthpiece 1 in the clean condition was actually lower than in the typical condition. Hence, the differences in magnitude of the resonance peaks of the three mouthpieces must be considered a property of the mouthpiece, rather than being due to their cleanliness.

The effect of the cleanliness of the mouthpiece on the acoustics of the horn or indeed any brass instrument does not appear in the literature. However, the Denis Wick online catalogue for a mouthpiece brush states that “the sound of an instrument can be affected if debris is allowed to constrict the backbore of the mouthpiece” (Mouthpiece brush n.d.). Pratt and Bowsher (1979) investigated the effect of the cleanliness of trombone tubing on the impedance spectra and found that all resonance peak magnitudes were slightly increased after the instruments’ tubing was cleaned and that the peak around 240 Hz on both a tenor (4th resonance) and alto (3rd resonance) trombone had a greatly increased magnitude. Changes in frequencies of the resonance peaks were not considered and no details were given as to the state of the mouthpiece cleanliness.

3.4.3 Mute

The three different types of horn mute (straight, stopping and practice) each have distinct effects on the impedance spectra of the horn compared to that of the hand. The straight and practice mutes are both non-transposing mutes which is reflected in the similarity of their resonance peak frequencies to those of the horn with hand in the bell. The stopping mute however, is classified as a transposing mute which can be seen by the differences in frequency between the resonance peaks with the hand in bell and stopping mute in bell.

The prominent extra peak that appears in the impedance spectra for straight mute M2, and practice mutes P1 and P2 is referred to by Sluchin and Caussé (1991) as a parasitic peak. They state that the frequency of the extra peak is related to the size of the cavity of the mute and that the mute acts as a Helmholtz resonator and reflects a large amount of energy back into the instrument at that resonance frequency resulting in an extra peak in the impedance spectrum and a frequency region where it is difficult to play the instrument. Sluchin and Caussé observe that the peak magnitude is usually greater if the material the mute is made of is able
to vibrate. This could explain why mutes M2 and P2 have prominent extra peaks, as they are the only straight and practice mutes used in this experiment which are made of metal (aluminium).

As the frequency of the extra peak is related to the Helmholtz resonance, one might expect the peak frequency to vary relatively little across different valve combinations on the instrument. This is confirmed for the three mutes (M2, P1 and P2) for which the extra peaks show a fairly constant frequency. However, the frequency of the extra peak tends to be slightly lower for the Bb horn than for the F horn and also appears to decrease with increasing added valve tubing on both the F and Bb horns. Thus, although the frequency stays roughly constant across valve combinations, there is considerable variation between the highest frequency on the F horn and the lowest frequency on the Bb horn (greatest for practice mute P1 – just over six semitones).

3.4.3.1 Straight mute

Replacing the hand in the bell with a straight mute greatly increases the magnitudes of the high frequency resonance peaks and also increases their frequencies. This is similar for results previously obtained by Kühtreiber (2004) for the trumpet (Figure 3.94). Differences were found between the two different straight mutes investigated for both the magnitudes and frequencies of resonance peaks. The magnitudes of resonance peaks for straight mute M2 are higher than those for M1 across almost all resonances. Both of the straight mutes measured have impedance spectra that are less harmonic than the hand with M2 being the least harmonic.

Both straight mutes produce an extra peak in the impedance spectra and the effect of the magnitude and frequency of the extra peak on the other resonance peaks is evident when comparing the impedance spectra for straight mutes M1 and M2. Although M1 shows evidence of an extra peak, the frequency is well below the first usable resonance and the magnitude is so small as to make negligible its effect on the closest resonance peak. The extra peak for M2 however, has a frequency very close to resonance two or three and has a very large magnitude. Consequently, a split peak is formed with the closest resonance and, for certain valve combinations, the magnitude of the extra peak actually exceeds that of the resonance peak.

As this extra peak interferes with the usable resonance peak, it causes a frequency region of instability and it is virtually impossible to play a steady note on that resonance of the horn. This causes problems for the horn player and thus a work around must be found. Generally a horn player will hold the offending mute out slightly from the bell which then enables the particular note to be played. As the impedance spectra show, this is effective because holding the mute out slightly causes the frequency of the extra peak to increase and hence, interfere with the next resonance peak instead. Sluchin and Caussé (1991) also found this to be true for
the trombone (Figure 3.95). Also, changing the position of the mute in the bell of the horn resulted in changes to the magnitudes and frequencies of all the other resonance peaks as well.

As straight mute M1 is tunable, impedance measurements were made with the tuner fully in and fully out. Small differences were found for resonance peak magnitudes, but variations in the harmonicity were greater. With the tuner fully out (i.e. the inner tube is shortened and the mute is the sharpest it can be), M1 is more harmonic than with the tuner fully in (i.e. the inner tube is lengthened and the mute is the flattest it can be). This effect is also shown by Sluchin and Caussé (1991) (Figure 3.96).

### 3.4.3.2 Stopping mute

General results from the input impedance measurements of the stopped horn confirm those of Backus (1976) (see Figure 1.16) and Wachter (2008): with a stopping mute in the bell of the horn, an extra resonance (second peak) is introduced into the impedance spectra so that the third resonance now sits at a frequency slightly higher than that of the second resonance of the horn with hand in the bell.

Results obtained for the impedance spectra of the horn with stopping mute are very similar to those of Wachter (2008) and a comparison of impedance data from this experiment with that obtained by Wachter (2008) is presented in Appendix G. This experiment extends the study by Wachter in two important ways: Firstly, in
Figure 3.95: Variation in impedance spectra of the first two resonances for the trombone with degree of insertion of straight mute into bell, showing the effect on the extra peak. (Sluchin and Caussé, 1991)

Figure 3.96: Average spectrum of horn with straight mute in bell with inner tube in shortest position (—) and longest position (- - -). (Sluchin and Caussé, 1991)
3.4. DISCUSSION

Wachter’s experiment, comparisons were made between the horn with stopping mute and horn with an open bell, as he was not able to produce accurate and reproducible data using a hand in the bell of the horn. In this experiment, a replica hand was used allowing an accurate comparison between the impedance spectra of a horn with stopping mute in bell and hand in bell; Secondly, Wachter’s measurements pertain to a single stopping mute, whereas this study investigated four different models of stopping mutes.

The shape of the impedance spectra for the four stopping mutes (S1 to S4) are very similar, however, differences can be seen for S3 at around 700 Hz. The magnitudes of the resonance peaks above 750 Hz are the same for all four mutes and below 750 Hz, they are fairly similar for S1, S2 and S4, with S3 generally having lower magnitude peaks. In particular, the peak for S3 between 720 and 740 Hz is considerably lower than for the other three mutes, which is the result of an extra resonance interfering with the peak at this frequency. The frequency of this peak also varies from the other three mutes. It is expected that this extra resonance is caused by the length of cylindrical tubing between the mute and the bell of the mute (Figure 3.97). The normal length of this tube is 3.5 to 4 cm, but S3 has an extra long piece of tubing to allow the bell of the mute to point forwards towards the audience. This tubing is approximately 22 cm long and would thus be expected to produce a resonance around 780 Hz if considered as a simple, open-open cylinder. This is much higher than the measured frequency of the extra resonance which interferes with the peaks between 720 and 740 Hz. As the length of tubing has a bell-like structure on each end, the resonance of the cylindrical tubing would be lower, thus corresponding to the frequency of the observed extra resonance.

The frequencies of the resonance peaks for the stopped horn are not harmonic and the variation from harmonicity becomes increasingly sharper with increasing resonance number. The variation in frequency between the resonance peak for the stopped horn (e.g. third resonance) and the corresponding resonance peak for the horn with hand in bell (e.g. second resonance) tends to decrease with increasing resonance number. For the open F horn (xxxF) the frequency difference between the stopped resonance and the hand resonance lies within ±10 cents from one semitone (100 cents), whereas for the open Bb horn (xxxBb), the majority of resonances sit between 10 and 40 cents sharper than one semitone. This demonstrates that the frequency difference between the resonance peaks with the stopping mute and those with the hand are not always nearly equal to one semitone and that the difference does in fact depend on both the frequency of the resonance and also which valve combination is being used.

Although the magnitudes and frequencies of the resonance peaks for the horn with stopping mutes S1, S2 and S4 in the bell were very similar, S1 and S2 are virtually identical across nearly all resonances and valve combinations. S4 did show
a small amount of variation from S1 and S2 in both magnitudes and frequencies on various resonance peaks. Stopping mutes S1 and S2 are very similar in shape, dimensions and are made of the same material (brass). However, S4, although having a similar shape, is made from wood and necessarily has thicker walls than the brass equivalent. Some horn players may find it surprising that there is not a greater difference between the impedance spectra of S4 and those of S1 and S2. These results indicate that the material, from which the mute is made, does not play a large part in the acoustical impedance properties of the stopping mute, instead these properties are almost solely influenced by the internal shape and dimensions of the mute.

3.4.3.3 Practice mute

A comparison of the impedance spectra for the horn with hand in bell and practice mute in bell clearly shows that practice mutes are not ideal – that is, they do not simply reduce the radiation from the bell whilst approximating the performance of the horn with a hand in the bell. Replacing the hand with a practice mute changes the shape of the impedance spectrum by lowering the magnitudes of the low frequency resonance peaks and increasing the magnitudes of the high frequency resonance peaks. The frequencies of the resonance peaks are also affected making the horn less harmonic with a practice mute than with a hand in the bell.

There is great variation in both magnitudes and variation in frequency from harmonicity across all resonance peaks and valve combinations for the four different practice mutes (P1 to P4). In general, P1 had the highest magnitude peaks and P3 had the lowest. All four practice mutes showed the same general trend across
resonance number for variation in frequency from harmonicity. P1 was closest to the hand in harmonicity and P2 was by far the least harmonic of the four practice mutes. Differences between the mutes could be due to the fact that each mute has a different shape. (They are also made of different materials.) These results indicate that there is considerable variation in the impedance spectra for the different practice mutes, which could conceivably affect the ease of playing with the particular mute.

As was noted for the straight mutes, two of the practice mutes (P1 and P2) were found to introduce an extra peak into the impedance spectra. The effect of this extra peak is very different for the two practice mutes. For P1, the extra peak occurs well below the second resonance (first usable resonance) and thus does not affect the impedance spectra. In contrast, the extra peak produced by P2 occurs around 110 Hz and interferes with both the frequency and magnitude of the closest peak, creating a split resonance in which the two peaks have roughly the same magnitude and sit either side of the expected resonance frequency. As this extra peak interferes with the usable resonance peak, it causes a frequency region of instability around that harmonic of the horn. It is expected that, as for straight mute M2, if the mute was held out slightly from the throat of the bell, the frequency of the extra peak would increase. However, this was not investigated and would rather defeat the purpose of using a practice mute as the sound would then be less attenuated.

Practice mute P3 has an unusual design as it contains an inner tube which is completely removable. A small amount of roughness was exhibited in the impedance spectra below 300 Hz for the horn with P3 in the bell. When the input signal strength was decreased, the amount of roughness also decreased and when the inner tube was removed, the roughness in the spectrum disappeared. This indicates that it was a nonlinear effect likely due to the mechanical vibration of the inner tube inside the mute. This could potentially affect the playing of notes in this range. Thus, removing the inner tube removes the vibration noise, but also alters the magnitudes and frequencies of the resonance peaks below 300 Hz.

3.4.4 Professional vs. student horn

There does not appear to be any previous research into the comparison of the acoustics of student and professional model brass instruments. It is generally considered that a professional model instrument exhibits better intonation and is easier to play in the extreme registers (amongst many other things). Thus, it could be expected that a professional model instrument would have resonance peaks which were more harmonically related than those of a student model and would also have higher magnitude peaks in the extreme registers, making them easier to play.

Results showed that, indeed, the student model horn did have lower magnitude resonances than the professional model horn, except at specific frequencies which stayed relatively consistent across most valve combinations (especially on the F horn)
for which the peak magnitudes were considerably higher on the student model. The resonance peaks for the student horn were also less harmonic than for the professional horn.

Although this appears to confirm the above hypothesis, there are two main factors which need to be considered: Firstly, only one professional and one student model horn were measured. Thus the differences could purely be due to the fact that they are different model instruments, rather than because one is a professional model and the other is a student model. It is possible that the same variation in impedance spectra would be obtained when comparing two professional model horns; Secondly, the professional model horn was in near new condition and had recently been serviced, whereas the student model horn had been in circulation through high schools for over twenty years and then ‘retired’ from use without having been recently serviced. It could be reasonably assumed that the tubing of the student model horn contained built up dirt which has been shown by Pratt and Bowsher (1979) to decrease the magnitudes of the resonance peaks. Thus, further investigations with multiple professional and student model horns would need to be undertaken to draw any firm conclusions.

3.4.5 Valves

Increasing the length of added valve tubing on the horn was found to affect both the magnitudes and harmonicity of resonance peaks. As Benade (1976) states, the addition of a length of cylindrical valve tubing into the overall length of tubing on the horn has a greater percentage change for the lower notes than the higher notes. Thus, it would logically follow that the longer the length of added tubing, the greater the difference in percentage change for low versus high notes. It is therefore reasonable to expect that the harmonicity of the horn would be affected by adding in extra valve tubing and that this phenomenon could be investigated by measuring the input impedance of the horn with all valve combinations.

To this point it appears that no study of this effect has taken place, perhaps due to the lack of a reliable way of obtaining repeatable results with a hand in the bell. Wachter (2008) measured the input impedance for all valve combinations on the horn with an open bell, with a hand in the bell and with a stopping mute and wooden straight mute in the bell. However, this data was not analysed or discussed in the thesis and is presented, en masse, in graphs placed in an appendix. For a comparison of results from this experiment with those obtained by Wachter, see Appendix H.

As alternative fingerings consist of using different valves to add very similar lengths of cylindrical tubing, no strong effects on the impedance spectra are expected. The differences that do appear may be due to the valve tubing for the alternative fingerings being slightly differing lengths (Table 3.6) or, more likely, due
to higher order effects, such as the shapes in the valves and the bends in the tubing, and where these occur with respect to the standing waves.

Increasing the length of added valve tubing on the horn affects both the magnitudes and harmonicity of the resonance peaks. In general, as the length of valve tubing increases, the magnitudes of the low frequency resonances (first six to eight peaks) decrease and the magnitudes of the high frequency resonances (above peaks twelve to sixteen) increase. The variation in frequency of resonance peaks from harmonicity also varies with valve length. A comparison of the RMS variation in frequency of resonance peaks from harmonicity for each of the valve combinations shows a clear decrease in harmonicity with increasing length of valve tubing. However, this is due solely to the decrease in harmonicity of the second resonance as the length of valve tubing is increased. A similar decrease in inharmonicity for the second resonance with increasing length of valve tubing was demonstrated for the horn by Chick et al. (2004), but not all valve combinations were presented (Figure 3.98).

When the second resonance is excluded, the RMS variation in frequency of resonance peaks from harmonicity stays fairly constant with a slight increase in harmonicity with valve tubing length. This increase is not surprising in a well-designed instrument, because the average added length due to valves used is greater than zero. The second resonance is rarely used in horn playing except on the open Bb horn for which the second resonance is no more inharmonic than the other resonances.

There is a clearly defined pattern for the variation from harmonicity for both the second and third resonances. This is apparent for the horn with hand in bell and horn with straight and practice mutes in bell. The shape of the third order polynomial fit changes depending on the instrument and whether there is a hand or mute in the bell (Figures 3.99 and 3.100). For the second resonance, the shape of the curve is very similar for both the professional and student horns with the hand in bell and appear to be simply rotated versions of each other.

The variation in frequency between the resonance peaks of the horn with stopping mute in the bell compared to those for a hand in the bell tends to decrease as the length of valve tubing is increased. Thus for stopping on the open Bb horn, the difference in frequency between the stopped resonance and the equivalent hand resonance is much greater than a semitone and this difference decreases with increasing valve tubing, so that using all three valves together on the F horn results

<table>
<thead>
<tr>
<th>Fingering</th>
<th>Alternative fingering</th>
<th>Professional model</th>
<th>Student model</th>
</tr>
</thead>
<tbody>
<tr>
<td>12xBb</td>
<td>xx3Bb</td>
<td>-22.1</td>
<td>-0.4</td>
</tr>
<tr>
<td>xxxF</td>
<td>1x3Bb</td>
<td>31.8</td>
<td>36.5</td>
</tr>
<tr>
<td>x2xF</td>
<td>123Bb</td>
<td>52.5</td>
<td>62.4</td>
</tr>
<tr>
<td>12xF</td>
<td>xx3F</td>
<td>-20.6</td>
<td>-8.6</td>
</tr>
</tbody>
</table>

Table 3.6: Variation in frequency (cents) of alternative fingerings.
Figure 3.98: Deviation from harmonicity of resonance peaks for F and Bb horns. F1=xxxF, E1=x2xF, Eb1=1xxF, D1=12xF, Db1=x23F, Bb1=xxxBb, A1=x2xBb, Ab1=1xxBb, G1=12xBb and Gb1=x23Bb. (Chick, et al., 2004).

Figure 3.99: Third order polynomial fit to variation in frequency from harmonicity for 2nd resonance of student horn with hand in bell and professional horn with hand, straight mute M1, and practice mutes P1, P3 and P4 in bell.
in the difference being a lot less than a semitone. Consequently, playing a stopped note on the Bb horn will produce a sharp note and playing a stopped note with all three valves on the F horn will produce a very flat note.

3.4.6 Summary of findings

- Different hands showed measurable changes in the impedance spectra of the horn which were qualitatively explained by the size, shape and position of the hand in the bell.

- Changes in the impedance spectra due to different mouthpieces were smaller than for different hands and corresponded to differences in the resonance peak for each of the mouthpieces alone.

- The cleanliness of the mouthpiece affected both the frequency and magnitude of the resonance peak (lower and flatter, respectively) and consequently, the impedance spectra of the horn. Effects due to cleanliness were smaller than for different mouthpieces.

- There were measurable differences in the magnitudes and frequencies of resonance peaks for different models of all three different types of mute (straight, stopping and practice).
• The magnitude and frequency of the extra peak produced by the straight and practice mutes determines the extent to which it affects the neighbouring resonances and the frequency of the extra peak stays relatively constant over all valve combinations. The frequency of the extra peak can be altered by holding the mute out slightly from the throat of the bell.

• The difference in resonance peak frequency between the horn with stopping mute in bell and the horn with hand in bell increases with increasing resonance number, but decreases with increasing length of valve tubing.

• The material from which the stopping mute is made (wood or brass) has little effect on the impedance spectra. However, the addition of a longer cylindrical tube between the body of the mute and the bell of the mute causes disruption to peaks in a particular frequency region.

• Practice mutes change the shape of the impedance spectra of the horn compared to a hand in the bell by lowering the magnitudes of the low frequency resonance peaks and increasing the magnitudes of the high frequency resonance peaks. Practice mutes are also less harmonic than the hand.

• There was large variation in both magnitudes and harmonicity of resonance peaks for the horn with different practice mutes in the bell. Differences could be due to variation in shape, type of material, or a combination of both.

• Differences were found in the impedance spectra between the professional model horn and the student model horn. However, no conclusions can be drawn as to whether these differences are due to the different models or to the fact that one is a professional model and the other a student model.

• The variation from harmonicity of the second (and to a lesser extent the third) resonance is greatly dependent on the length of added valve tubing.

• The inclusion of the second resonance, results in the harmonicity of the horn decreasing with increasing length of valve tubing. However, excluding the second resonance results in the harmonicity of the horn staying relatively constant with a slight increase in harmonicity with increasing length of valve tubing.
Chapter 4

Effect of hand and mute on playability of the horn

4.1 Background

The horn is played with the player’s right hand in the bell and as such, the hand is part of the ‘setup’ of the instrument, which also includes the mouthpiece and horn. Although the horn player is unable to choose the size of their hand, the shape and position of the hand in the bell is something that the player must consider, in the same way as the mouthpiece and horn is chosen. Thus, playability of the instrument is affected by these three factors and each horn player chooses the hand position, mouthpiece and horn that enables them to produce the sound they desire with the greatest ease of playing.

The overall playability of an instrument is usually broken down into different categories, such as quality of sound, intonation, response, dynamic range, etc. Players then rate the playing of the instrument in each of these categories through the use of a stepped or continuous scale with polar opposite ends (SDS; see section 2.2.2) or in a series of categories (such as like, neutral, dislike).

The effect of different mouthpieces on the playability of the horn has been investigated by Plitnik and Lawson (1999). Seven different mouthpieces coupled to a horn were rated as either liked, neutral or disliked over six different categories (flexibility, pitch control, intonation, tone quality, dynamic range and attack clarity). Preliminary experiments showed that there was considerable player consensus across all categories and so the final experiment was carried out using only one professional horn player. It was found that none of the mouthpieces received the same rating across all categories, but that one mouthpiece was ‘liked’ in five out of seven of the categories and another was ‘disliked’ in six out of the seven categories.

The playability of different instruments has been investigated for the trombone by Pratt and Bowsher (1978) and the trumpet by Bertsch and Waldherr (2005) and Bertsch et al. (2005). An initial experiment by Pratt and Bowsher (1978)
required three non-professional trombone players to rate the playability of three different trombones (with two different mouthpieces) on the following seven continuous scales: small dynamic range–large dynamic range, bad intonation–good intonation, unresponsive–responsive, heavy resistance–light resistance, stuffy–free blowing, unpleasant timbre–pleasant timbre and inflexible timbre–flexible timbre. However, players were not able to distinguish between the different instruments. Thus, a second experiment was undertaken in which a professional trombone player successfully distinguished between five different trombones (played using his own mouthpiece) on the same scales of intonation, responsiveness and free blowing.

The study by Bertsch and Waldherr (2005) and Bertsch et al. (2005) is unique as it has a large sample player group (55) and as such, statistically significant results were obtained. Each player was asked to rate several different trumpets on a five-point stepped scale for forty different questions relating to the playability of the instrument. Some of the questions related to the same category and thus reliability of ratings could be determined. They found that players’ judgments were consistently reliable for only a small number of categories (ability to lip up and down, brilliance of sound, power output of sound, dynamic range and feedback at start of note). Interestingly, responses to questions relating to tone colour (dark–bright) were not found to be consistent.

To enable a mute to be used with the horn, the player’s hand is removed from the bell. Thus, the mute must compensate for the lack of hand as well as performing its own function (which depends on the type of mute: straight, stopping or practice). There are many different models available for each type of mute and they all sound and feel different to play with. Thus, the playability of the mute (coupled to the horn) is very important. Previous literature has focused on the straight mute. For example, Smith (1980) descriptively evaluated the intonation and sound quality of fourteen different horn straight mutes.

Although the effect of the stopping mute on the impedance and sound spectra of the horn have been studied, the playability and differences in sound for different models of stopping mute have not been investigated. Recently, two innovative new models of stopping mute have become commercially available: a stopping mute made of wood (instead of the usual brass) and a stopping mute with an extended cylindrical section to enable the bell of the mute to face towards the audience (Figure 3.97). In light of the quote from the website of the latter mentioned stopping mute manufacturer (Balu, n.d.),

We’ve been asked to compare our mute with other brands. We’ve been asked this in the past with our straight mutes, and we believe that this would be in bad taste. Our intention is to make the best possible mutes, and we can do this without insulting our competitors, whom we respect and have good relations with. We believe that there is a place in the market for all mutes, and our products are targeting a specific performer: the professional musician.
a comparison of the playability of these new designs with the normal stopping mute design would no doubt be of interest to horn players.

The playability of sixteen different trumpet practice mutes were evaluated by Dishman (2005). Each mute was given a rating on a scale of 0 to 10 for the following categories: openness (very restrictive–very open), pitch (very poor–very good) and tone quality (very brittle–very covered) by the player; pitch (+/- cents) of initial tuning note by an electronic tuner; and in-room volume (very loud–very soft) and outside-room volume (very loud–very soft) by a listener. The evaluation of these mutes was carried out by one player and one listener. Subjective comments were also given by the player. Ratings varied greatly between mutes for all categories.

The study by Dishman (2005) appears to be the only one that has examined, in detail, any aspect of practice mutes for brass instruments. There are however, anecdotes from horn players which suggest that the extended use of practice mutes is detrimental to playing due to the change in sound and intonation of the instrument. For example, Ericson (2003) states:

I was playing very high on the pitch on the mute and I also discovered that my personal sense of pitch placement is very much tied up with tonal color. The feedback of tone I was used to relying upon was basically lost on the practice mute.

This suggests that the playability of the practice mute is very important, not just to the practice session, but also to normal playing, as he goes on to say that this was affecting his normal playing as well.

As mentioned in section 2.2.3, playability is a subjective measure and many factors influence the player’s judgments, such as personal preferences, bias and coupling to the instrument. Thus, it is often very difficult to obtain player consensus in results. In order to remove player bias of specific brands from a study, it is necessary to use a blind or semi-blind setup (see section 2.2.3). It is also interesting to compare players’ judgments with listeners’ responses of hearing the exact same playing. This is especially pertinent to comparisons of mutes. For example, a particular mute could be easy to play, but produce a poor sound; the player may rate the mute highly, but the listener would not. However, the listener is also influenced by personal preference and thus, listeners’ responses will not necessarily be similar either. No listener studies have previously been carried out on brass instrument mutes, but it is expected that the player would have a greater influence, than the mute, over the sound.

Previous studies involving listener ratings of different trombones and trumpets have shown mixed results. For example, Pratt and Bowsher (1978), in a live experiment, found that listeners could distinguish between different trombones, but only on the dull–bright scale. In a paired comparison test, Pratt and Bowsher (1978) also showed that listeners could identify between instruments and players on the same scale, but that ratings were influenced the most by the volume and pitch of
the played notes. Parker (2003) found that listeners (trumpet players) were unable to correctly identify the model of trumpet playing in recordings.

As previous research has investigated the effect of different mouthpieces and different instruments on the playability of brass instruments, this study focuses on the effect of different hands and mutes on the playability of the horn. In the previous study (Chapter 3), objective measurements were made of a horn with three different replica hands and various models of three different types of mutes in the bell. The aim of this study is to investigate the playability of the horn with these same hands and mutes. As straight mutes have been extensively studied in the past, only the stopping mutes (three different models) and the practice mutes (four different models) are included in this study. The same horn and mouthpiece was used throughout the study. Horn players completed surveys after playing with each of the setups (horn with hand or mute in bell) and also completed listener surveys whilst the other participants were playing.

4.2 Methods

4.2.1 Materials

4.2.1.1 Horn and mouthpiece

For this experiment only the professional model horn (see section 3.2.2.1) was used with Mouthpiece number 1 (see section 3.2.2.2). Players were also required to play with their own mouthpiece for comparison, but details of these mouthpieces were not collected.

4.2.1.2 Hands

Players were required to play the horn once with their own hand in the bell and once with each of the replica hands 1 to 3 (see section 3.2.2.3) in the bell. The replica hands were positioned in the bell using the same system of stays mounted to the bell (see Figure 3.6).

4.2.1.3 Mutes

Several different models of horn stopping mutes and practice mutes were used (see section 3.2.2.4).

- Stopping mutes:
  2. Ion Balu stop mute.
  3. Woodstop mute.
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- Practice mutes:
  
  1. Yamaha Silent Brass practice mute.
  2. Denis Wick practice mute.
  4. Trumcor Stealth # 5 practice mute.

4.2.1.4 Musical excerpts

Six musical excerpts were used:

- For the replica hands:

1. Ascending chromatic scale from F4 to C6 (written horn pitch; Figure 4.1a).

2. Excerpt from Ravel's Concerto for Piano in G major, I. Allegro non troppo – Horn 1 in F (Figure 4.2a). This excerpt consists of notes in the very high horn range which correspond to resonance frequencies above the cutoff frequency of the bell (without hand) and is the region where the hand shape and position has been found to have the most influence on the resonance peaks (see section 3.4.1).

- For the stopping mutes:

3. Ascending chromatic scale from F3 to C5 (written horn pitch; Figure 4.1b).

4. Excerpt from Tchaikovsky’s Symphony No. 6, IV. – Horn 2 in F (Figure 4.2b). This excerpt is a notoriously difficult stopped passage in the horn repertoire and must be played with a stopping mute (rather than hand stopping) as it is in the extreme low register.

- For the practice mutes:

5. Descending chromatic scale from F5 to F3 (written horn pitch; Figure 4.1c).

6. Excerpt from Tchaikovsky’s Symphony No. 5, II. Andante cantabile, con alcuna licenza – Horn 1 in F (Figure 4.2c). This excerpt is a famous horn solo in the repertoire and requires a focus on good tone and intonation.

4.2.2 Recordings

Seven professional horn players\(^1\) (Player1 - Player7) were recorded playing the horn with their own hand and each of the three replica hands and four practice mutes. All

\(^1\)Thank you to Ben Jacks for participating in this experiment and for assisting with recruiting subjects.
players had experience in national symphony or opera orchestras. Recordings were carried out in a small greenroom at the Sydney Opera House and in a recording room at the Music Acoustics Lab, UNSW. The horn player was seated, with the edge of the bell resting on the palm of the right hand to support the horn (when playing with the replica hands and mutes). The sound was recorded using one Røde NT3 microphone placed behind the player at a distance of approximately one radius from the bell of the horn and another placed close to and over the player’s head. Players 1 to 4 completed the experiment in one group, players 5 and 6 in another, and Player 7 completed the experiment by himself. The running order for Players 1 to 4 is presented in Table 4.1 and instructions to participants can be found in Appendix I.

4.2.3 Subjective feedback

4.2.3.1 Player survey for replica hands

Each of the seven horn players also completed a player survey. In response to playing with each of the replica hands, they were asked to make judgments on the quality of sound, intonation, and ease of playing (Figure 4.3a to c) compared to playing with their own mouthpiece and hand. A similar scale system was employed as that used by Pratt and Bowsher (1978). For each of the areas of interest (quality of sound, intonation and ease of playing), a continuous scale was used with the following polarities: Dark–Bright for quality of sound; Flat–Sharp for Intonation; and Difficult–Easy for Ease of playing (Figure 4.3a to c). Players indicated their responses by placing a mark at a point on the scale. Players were also encouraged to write comments. See Appendix I for an example of the player survey for replica hands.

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2Ethics approval was obtained from the Human Research Ethics Committee at The University of Western Australia.
Figure 4.2: Musical excerpts.
Table 4.1: Experiment running order for Players 1 to 4.

<table>
<thead>
<tr>
<th>Mouthpiece + hand or mute</th>
<th>Player</th>
<th>Excerpts played (1x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Own mouthpiece + own hand</td>
<td>1, 2</td>
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</tr>
<tr>
<td>Mouthpiece 1 + Hand 1</td>
<td>1, 2</td>
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</tr>
<tr>
<td>Mouthpiece 1 + Hand 2</td>
<td>1, 2</td>
<td>1, 2</td>
</tr>
<tr>
<td>Mouthpiece 1 + Hand 3</td>
<td>1, 2</td>
<td>1, 2</td>
</tr>
<tr>
<td>Mouthpiece 1 + Stopping mute 1</td>
<td>3, 4</td>
<td>3, 4</td>
</tr>
<tr>
<td>Mouthpiece 1 + Stopping mute 2</td>
<td>3, 4</td>
<td>3, 4</td>
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<tr>
<td>Mouthpiece 1 + Stopping mute 3</td>
<td>3, 4</td>
<td>3, 4</td>
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<tr>
<td>Mouthpiece 1 + Stopping mute 1</td>
<td>5, 6</td>
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<tr>
<td>Mouthpiece 1 + Stopping mute 2</td>
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<td>5, 6</td>
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<tr>
<td>Mouthpiece 1 + Stopping mute 3</td>
<td>5, 6</td>
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<td>Mouthpiece 1 + Practice mute 1</td>
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</tr>
<tr>
<td>Mouthpiece 1 + Practice mute 4</td>
<td>5, 6</td>
<td>5, 6</td>
</tr>
</tbody>
</table>
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Figure 4.3: Subjective rating scales.

hands along with instructions to participants.

4.2.3.2 Player survey for mutes

Each of the seven horn players also rated the playability of each of the stopping and practice mutes. The same set of scales was used with the added scales of Soft–Loud for volume and Difficult to centre pitch–Easy to centre pitch for Accuracy (Figure 4.3d and e). Players indicated their responses by rating each of the stopping mutes on one set of scales and each of the practice mutes on another. Players were also asked whether or not they owned a practice mute and if so, the model and frequency of use. See Appendix I for an example of the player survey for mutes along with instructions to participants.

4.2.3.3 Listener survey for mutes

Players 1 to 6 also completed a listener survey for the mutes. Whilst listening to other players playing with the mutes, they rated each of the stopping and practice mutes on the scales of quality of sound, intonation, and volume (Figure 4.3a, b and d). See Appendix I for an example of the listener survey for mutes along with instructions to participants. Players 1 to 4 completed the experiment in one group and thus rated each others’ playing. Players 5 and 6 completed the experiment together and thus rated each others’ playing. Player 7 completed the experiment by himself and thus did not complete the listener survey.
4.2.3.4 Analysis of surveys

Two different methods of analysis were needed for the replica hand and mute surveys. For the replica hands, players were only rating one hand per scale and were instructed to use an ‘x’ to mark the scale. Thus, accurate measurements could be made in relation to the centre of the cross. However, for the mutes, both players and listeners rated several mutes on the same scale and were instructed to use ‘S1’, ‘S2’, etc. This meant that it was not possible to accurately determine the exact point on the scale that the player intended the mark to be and thus, a more general analysis was needed based on subdivisions of the scale, rather than detailed measurement. The two different methods of analysis are outlined below:

- Player survey for replica hands – players’ ratings were analysed by measuring the distance, from the centre of the scale, to the player’s mark (in cm to the closest mm). The right side of the scale was given a positive value and the left side was given a negative value.

- Player and listener surveys for mutes – each scale was divided into eight positive (right of centre) and eight negative (left of centre) divisions and player’s marks were given the value of the closest subdivision.

4.2.3.5 Analysis of recordings

The recordings of a section of chromatic scale common to all three scales (F4 to C5, written horn pitch) was analysed. A single FFT was done for each scale segment for analysis of the spectral centroid and spectral power. Methods of analysis are outlined below:

- Spectral centroid ($S_c$) was calculated for the scale and excerpt from the FFT data over the frequency range 200 Hz to 15 kHz:

$$S_c = \frac{\sum_{n=0}^{n-1} f(n)x(n)}{\sum_{n=0}^{n-1} x(n)} \quad (4.1)$$

where $x(n)$ is the magnitude for the frequency corresponding to bin number $n$ and $f(n)$ is the centre frequency of that bin, with both $x(n)$ and $n$ being linear.

- Spectral power ($S_p$) was calculated for the scale and excerpt from the FFT data by doing a trapezoidal integration over the frequency range 200 Hz to 15 kHz:

$$S_p = 20 \log\left(\frac{1}{2} \sum_{n=0}^{n-1} (x(n+1) + x(n))(f(n+1) - f(n))\right) \quad (4.2)$$

where $x(n)$ is the magnitude for the frequency corresponding to bin number $n$ and $f(n)$ is the centre frequency of that bin, with both $x(n)$ and $n$ being linear.
4.3 Results

Note that not all of the players/listeners rated all of the mutes on all of the scales, resulting in fewer data points for some of the sections.

4.3.1 Player subjective feedback

Due to the low group numbers, the level of significance, $\alpha = 0.1$ (rather than 0.05) has been used for the statistical analysis below. Thus, due to the low number of data points for each hand and mute condition, post hoc testing has been informed by examining the descriptive statistics which have been presented in figures showing the means and 90% confidence intervals (Figures 4.4, 4.17 and 4.9).

4.3.1.1 Hand

For players’ responses to playing the horn with three different hands in the bell, there was no correlation between any two of the three subjective rating scales used (quality of sound, intonation, and ease of playing). The mean responses to playing with each of the hands for the different scales is presented in Figure 4.4 along with the 90% confidence intervals.

Figure 4.5 shows the players’ responses to the quality of sound of playing with the three different hands. A paired samples t-test indicated that Hand 1 was considered to have a brighter quality of sound than Hand 3 and this difference approached significance $t(6) = 2.37, p = .055, d = 1.51$. Differences between responses for Hands 1 and 2 and Hands 2 and 3 were not significant. A two-tailed z-test was performed to compare the proportions of players who rated the quality of sound as brighter (than neutral (0)) for Hand 1 and Hand 3, and the difference between the two proportions was significant, $z = 5.54, p < .001$. Responses for quality of sound for Hand 2 were split between bright and dark, but tended to be considered brighter than Hand 3. Comments by Player 2 on the quality of sound of playing the horn with the three hands in the bell (Table 4.2) also reflected these results. He stated that Hand 1 had a “brittle” quality of sound, that the sound with Hand 2 was “duller” and “muffled”, and that Hand 3 had an even lower quality of sound.

On average, Hand 3 was judged as having flatter intonation than either of the other two hands (Figure 4.6), but this was not significant ($F(2,18) = 1.54$, ns). Hand 1 was also generally considered to have slightly sharper intonation than Hand 2. Again the comments by Player 2 reflect these data (see Table 4.2).

There was little difference between the three different hands for players’ judgments of ease of playing ($F(2,18) = 0.66$, ns). Figure 4.7 shows that almost all players rated the three hands as difficult to play. Players’ comments suggest that the difficulty ratings may have been partly due to playing on a different mouthpiece from what they were used to, rather than being a judgment solely on the different
CHAPTER 4. EFFECT OF HAND AND MUTE ON PLAYING

Figure 4.4: Mean response to playing with Hands 1 to 3 on the scales: Quality of sound, Intonation and Ease of playing. Error bars show 90% confidence intervals.

Figure 4.5: Players' responses to the quality of sound of playing the horn with three different hands in the bell.
Table 4.2: Players’ comments on quality of sound, intonation and ease of playing the horn with three different hands in the bell.

<table>
<thead>
<tr>
<th>Hand 1</th>
<th>Hand 2</th>
<th>Hand 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quality of sound</strong></td>
<td><strong>Player 2</strong>: feels more brittle</td>
<td><strong>Player 1</strong>: Hard to focus the sound <strong>Player 2</strong>: sound is duller, feels muffled</td>
</tr>
<tr>
<td><strong>Intonation</strong></td>
<td><strong>Player 2</strong>: higher due to openness</td>
<td><strong>Player 2</strong>: feels like a spongy hand</td>
</tr>
<tr>
<td><strong>Ease of playing</strong></td>
<td><strong>Player 2</strong>: hard to adjust with the combination of new mouthpiece + hand <strong>Player 3</strong>: Much smaller mouthpiece so not really an accurate test; It is much easier to play high on the mouthpiece provided as it is very small in comparison to mine as I generally play low. <strong>Player 4</strong>: mouthpiece very small</td>
<td><strong>Player 1</strong>: Harder to centre the notes <strong>Player 2</strong>: I find this harder, the higher partials of the notes seem to be gone, have to push against it. Sound doesn’t ring <strong>Player 4</strong>: very open sound</td>
</tr>
</tbody>
</table>

Figure 4.6: Players’ responses to the intonation of playing the horn with three different hands in the bell.
CHAPTER 4. EFFECT OF HAND AND MUTE ON PLAYING

Figure 4.7: Players’ responses to the ease of playing the horn with three different hands in the bell.

hands. This is especially evident in the comments for Hand 1 (Table 4.2) which mainly pertain to the mouthpiece.

4.3.1.2 Stopping mute

No correlations were found between any two subjective rating scales for the stopping mutes (quality of sound, intonation, ease of playing, accuracy, and volume) except between players’ ratings of accuracy and ease of playing (Figure 4.8). Analysis of variance and t-tests indicated no significant difference between the three stopping mutes for any of the scales. Figure 4.9 shows the mean and 90% confidence intervals of player responses for the stopping mutes.

As Figure 4.10 shows, players’ responses to the quality of sound of playing the horn with the three different stopping mutes in the bell were fairly similar across the three mutes. Players’ judgments of the intonation of the three different stopping mutes were also similar, with most players rating all three mutes as in tune (Figure 4.11). Stopping mute 2 had the most variation in responses and the intonation for this mute was considered “very movable” by Player 4 (Table 4.3).

Players’ responses to the ease of playing the horn with the three different stopping mutes in the bell varied widely (Figure 4.12). For example, Player 5 considered practice mute 2 the easiest to play, while Player 2 considered it the most difficult to play. Results were very similar for players’ ratings for accuracy (Figure 4.13). Ratings for the volume of playing the horn with the three different stopping mutes
in the bell were quite varied and all three stopping mutes were generally rated above the centre point on the soft–loud scale (Figure 4.14).

Figure 4.8: Correlation of players’ responses to ease of playing with accuracy of playing the horn with three different stopping mutes in the bell.

Table 4.3: Players’ comments on intonation and accuracy of playing the horn with two of the three different stopping mutes in the bell.

<table>
<thead>
<tr>
<th>Intonation</th>
<th>Stopping mute 2: very movable</th>
<th>Stopping mute 3:</th>
<th>Accuracy</th>
<th>Player 6:</th>
<th>but only in the G#+A (treble clef)</th>
<th>Player 6: became easier through the excerpts</th>
</tr>
</thead>
</table>
Figure 4.9: Mean response to playing with Stopping mutes 1 to 3 on the scales: Quality of sound, Intonation, Ease of playing, Accuracy and Volume. Error bars show 90% confidence intervals.
4.3. RESULTS

Figure 4.10: Players’ responses to the quality of sound of playing the horn with three different stopping mutes in the bell.

Figure 4.11: Players’ responses to the intonation of playing the horn with three different stopping mutes in the bell.
CHAPTER 4. EFFECT OF HAND AND MUTE ON PLAYING

Figure 4.12: Players’ responses to the ease of playing the horn with three different stopping mutes in the bell.

Figure 4.13: Players’ responses to the accuracy of playing the horn with three different stopping mutes in the bell.
4.3. RESULTS

4.3.1.3 Practice mute

Of the seven horn players, only one did not own a practice mute. The remaining six players were divided evenly between using a practice mute rarely, at least once a week, and every day. Figure 4.15 shows that there was no correlation between players’ ratings of volume and ease of playing for the four different practice mutes. In fact, there were no correlations between any two of the subjective rating scales employed (quality of sound, intonation, ease of playing, accuracy, and volume) except for accuracy and ease of playing for which there was a high correlation across players (Figure 4.16).

Figure 4.17 shows the mean rating for each of the four mutes on the five subjective scales. Analysis of variance indicated no significant difference between mutes on any of the scales.

Players’ responses to the quality of sound of playing the horn with the four different practice mutes in the bell were quite varied (Figure 4.18). Players’ ratings were closest for practice mute 1 and sat around the centre of the dark–bright scale. In contrast, the ratings for the other three mutes were spread over a wider range, with some players judging the practice mutes as bright and some as having a dark quality of sound. Analysis of variance showed no significant differences between the four mutes ($F(3, 12) = 0.362$, ns).

Responses to intonation of the four different practice mutes were also quite varied. However, as Figure 4.19 shows, almost all players rated practice mute 1 as in tune,
Figure 4.15: Correlation of players’ responses to ease of playing with volume of playing the horn with four different practice mutes in the bell.

Figure 4.16: Correlation of players’ responses to ease of playing with accuracy of playing the horn with four different practice mutes in the bell.
Figure 4.17: Mean response to playing with Practice mutes 1 to 4 on the scales: Quality of sound, Intonation, Ease of playing, Accuracy and Volume. Error bars show 90% confidence intervals.
whereas half of the players rated practice mute 2 as sharp and the other half rated it as flat. Player 5 commented that the intonation for practice mute 2 was “random” (Table 4.4), suggesting that some notes may have been sharp, while others were flat. Practice mutes 3 and 4 were generally considered to be in tune or have flat intonation. Testing showed no significant differences between the four mutes ($F(3, 18) = 0.291, \text{ns}$).

Apart from Player 4 who rated all four practice mutes above the centre point of the difficult–easy scale for ease of playing, the majority of players judged practice mutes 2 to 4 as difficult to play (Figure 4.20). Practice mute 2 was rated the most difficult to play and a paired t-test indicated that it was rated significantly more difficult to play than practice mute 1, $t(4) = 3.54$, $p = .024$, $d = 1.54$. Again, ratings for Practice mute 1 had the highest player consensus and were centred around the midpoint of the difficult–easy scale.

Table 4.4: Players’ comments on intonation and ease of playing the horn with three of the four different practice mutes in the bell.

<table>
<thead>
<tr>
<th>Practice mute 2</th>
<th>Practice mute 3</th>
<th>Practice mute 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intonation</td>
<td>$\text{Player 5: random}$</td>
<td>$\text{Player 6: [In tune] except G, Gb, F in stave which felt flat}$</td>
</tr>
<tr>
<td>Ease of playing</td>
<td>$\text{Player 5: P2=yuck!}$</td>
<td>$\text{Player 6: harder below stave}$</td>
</tr>
</tbody>
</table>
4.3. RESULTS

Figure 4.19: Players’ responses to the intonation of playing the horn with four different practice mutes in the bell.

Figure 4.20: Players’ responses to the ease of playing the horn with four different practice mutes in the bell.
Generally, all players (apart from Player 4) judged the accuracy of playing the horn with the four different practice mutes in the bell as difficult to centre pitch. As Figure 4.21 shows, practice mute 2 was judged as being the most difficult to centre pitch and a paired t-test showed that practice mute 2 was considered significantly more difficult to centre pitch, than practice mute 1, $t(3) = 5.96$, $p = .009$, $d = -0.90$. Practice mute 1 was considered the softest mute, closely followed by practice mute 3 (Figure 4.22). A paired samples t-test indicated that practice mute 2 was not rated significantly louder than practice mute 1 ($t(5) = 2.03$, ns). A two-tailed z-test was performed to compare the proportions of players who rated the volume as louder (than neutral (0)) for practice mute 1 and practice mute 2, and the difference between the two proportions was significant $z = -2.04$, $p = .04$.

### 4.3.2 Listener subjective feedback

#### 4.3.2.1 Stopping mute

For the stopping mutes, listeners’ judgments of the quality of sound, intonation and volume of the horn playing with three different stopping mutes in the bell, showed a large amount of variation across players. Listeners’ responses to quality of sound were quite similar across players for stopping mutes 1 and 3 (Figure 4.23). Stopping mute 2 received a greater variation in responses with some players’ sound considered bright and some dark.

Stopping mute 1 was generally considered, by the listeners, as (nearly) in tune across all players (Figure 4.24). Both the other two stopping mutes were considered to range from very sharp to very flat depending on the player and listener. In general, Listener 1 rated the intonation of stopping mutes 2 and 3 as flat and Listener 3 rated them as sharp. Listeners’ ratings of the stopping mutes for volume were very similar to those for the practice mutes – responses varied widely with no clear consensus on either the volume of individual players or stopping mutes (Figure 4.25).
4.3. RESULTS

Figure 4.21: Players’ responses to the accuracy of playing the horn with four different practice mutes in the bell.

Figure 4.22: Players’ responses to the volume of playing the horn with four different practice mutes in the bell.
Figure 4.23: Listeners’ responses to players’ quality of sound of playing the horn with three different stopping mutes in the bell, showing breakdown by listener (left) and player (right).

Figure 4.24: Listeners’ responses to players’ intonation of playing the horn with three different stopping mutes in the bell, showing breakdown by listener (left) and player (right).
4.3. RESULTS

4.3.2.2 Practice mute

For all the subjective rating scales (quality of sound, intonation, and volume), listeners' ratings of the horn playing with the four different practice mutes in the bell were quite varied (Figures 4.26 to 4.28). Most players were judged as having a dark quality of sound for all four practice mutes, with practice mute 2 receiving both the brightest and darkest rating for quality of sound (Figure 4.26). Listeners' rated Practice mute 1 as the most in tune across all players (Figure 4.27). Practice mute 2 had the widest range of listeners’ responses, ranging from very sharp to quite flat on the intonation scale.

Judgments of volume had the largest variation of the three scales rated by the listeners across all four practice mutes. It is apparent from Figure 4.28 that each listener rated the volume of the same player with the same mute quite differently. There appears to be no clear consensus as to which mute is considered the softest by the listeners and also no pattern as to the volume of the sound produced by any particular player.
Figure 4.26: Listeners’ responses to players’ quality of sound of playing the horn with four different practice mutes in the bell, showing breakdown by listener (left) and player (right).

Figure 4.27: Listeners’ responses to players’ intonation of playing the horn with four different practice mutes in the bell, showing breakdown by listener (left) and player (right).
Figure 4.28: Listeners’ responses to players’ volume of playing the horn with four different practice mutes in the bell, showing breakdown by listener (left) and player (right).

### 4.3.3 Player versus listener subjective feedback

A comparison of a player’s ratings of the practice and stopping mutes with listeners’ ratings of the mutes played by that particular player are presented in Figures 4.29 to 4.31. As can be seen there is generally not a good correlation between a particular player’s ratings (for either quality of sound, intonation or volume) and listeners’ ratings of that same player, for any of the mutes. No clear trends are apparent for any of the rating scales except for the volume of practice mutes. Players tended to consistently rate all of the practice mutes to be louder than did the listeners.
Figure 4.29: Comparison of listeners’ responses and players’ responses to quality of sound of playing the horn with four different practice mutes and three different stopping mutes in the bell. Note small number of data points is due to lack of responses for this question.
Figure 4.30: Comparison of listeners’ responses and players’ responses to intonation of playing the horn with four different practice mutes and three different stopping mutes in the bell.
Figure 4.31: Comparison of listeners’ responses and players’ responses to volume of playing the horn with four different practice mutes and three different stopping mutes in the bell.
4.3.4 Recordings

The energy distribution in the sound spectrum is clearly affected by playing with a stopping or practice mute instead of a hand in the bell (Figure 4.32). As can be seen, the amplitudes of low frequency harmonics are lowered for the stopping mute and the high frequency components are increased, compared to those for the hand. The amplitudes of the harmonics for the practice mute are greatly reduced compared to those for the hand.

The stopping mutes showed a strong correlation ($R^2 = 0.8$) and the hand showed a moderate correlation ($R^2 = 0.5$) between spectral centroid and spectral power (Figure 4.33). Sound spectra for the practice mute did not exhibit the same trend, instead showing a very small negative correlation between spectral centroid and spectral power.

The spectral centroid and spectral power for each hand and mute, averaged across all players, is given in Figures 4.34 and 4.35, respectively. As can be seen, the use of a stopping mute increases the average spectral centroid by more than 2 kHz, without much changing the spectral power. The use of a practice mute decreases the average spectral power by approximately 10 dB, but does not affect the spectral centroid to a large extent.
Figure 4.32: Sound spectra for chromatic scale (F4-C5, written horn pitch) played on the horn with hand (top), stopping mute (middle) and practice mute (bottom) in the bell. (Magnitude is linear scale with respect to same arbitrary reference.)
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Figure 4.33: Spectral centroid versus spectral power for all playings of the chromatic scale segment.

Figure 4.34: Average spectral centroid for the three hands, three stopping mutes and four practice mutes. Error bars show +/- standard deviation.
4.4 Discussion

When evaluating the playability of different mutes, the most important aspects were considered to be the effect on the quality of sound produced, intonation, ease of playing, level of sound output and accuracy of placing notes. The subjective rating scales used in this study were designed to cover these aspects. The scale relating to accuracy and ease of playing had a high correlation, but no statistical correlation was found between any other pairs of ranked qualities.

4.4.1 Player subjective feedback

4.4.1.1 Hand

Ratings for the three hands on the quality of sound scale yielded significant results. Hand 3 was considered, by players, to have a significantly darker quality of sound than Hand 1. Hand 3 was larger than Hand 1 and took up more space in the bell. The shape of Hand 3 was also less open than that of Hand 1. As more of the bell opening was covered for Hand 3, more of the high frequency components in the sound would be reflected back into the instrument and less would be radiated from the bell. This would result in a higher low frequencies to high frequencies ratio for Hand 3 than for Hand 1 and hence a darker sound.

Data collected for the two scales relating to intonation and ease of playing did not show any significant differences between the three hands. Several factors may have contributed to this: playing with a hand other than one’s own, is very unnatural.
and would not occur outside of an experimental setup. As a result, players may have had difficulty judging differences between the three hands because of the lack of relevant context; the differences between the three different hands are subtle compared to differences between different instruments or the effect of playing with different mouthpieces. Previous studies have shown that it is difficult for players to reliably differentiate between different instruments or mouthpieces on certain subjective rating scales (Pratt and Bowsher, 1978, Plitnik and Lawson, 1999, Bertsch and Waldherr, 2005 and Bertsch et al., 2005); and the mouthpiece and horn were kept constant across players and thus were not familiar to the players. This may have resulted in some of the judgements relating to the player/mouthpiece/instrument coupling rather than judgements specifically on the effect of the different hands.

4.4.1.2 Stopping mute

No significant differences were found between the three different stopping mutes on any of the five subjective scales relating to quality of sound, intonation, ease of playing, accuracy and volume. Players’ responses varied considerably on all scales except ratings of intonation. It is surprising that no differences were found between the stopping mutes as the three models were very different. Stopping mute 1 was representative of a ‘normal’ stopping mute which all the players would previously have used. Stopping mutes 2 and 3 however, had not previously been used by any of the players in the study.

Stopping mute 2 had an extended length of cylindrical tubing between the body and the bell of the mute (see Figure 3.97) and stopping mute 3 was made of wood, rather than brass. As players found no consistent differences between these different models, this would suggest that ultimately the model of stopping mute chosen by a particular player is due to personal preference and not an inherent difference in quality between different models.

4.4.1.3 Practice mute

Six of the seven players owned a practice mute and two of those owned two different models of practice mutes. Three players owned one of the models of practice mute used in this study (two owned a Yamaha Silent Brass and one owned a Trumcor Stealth). Interestingly, all three players who owned one of these mutes also rated that particular mute as the quietest, most in tune and easiest to play of the four mutes. This strongly suggests that familiarity with the mute influenced players’ judgements of its playability or alternatively, that those players had chosen to buy that particular model of mute because they thought it quiet, in tune and playable.

For players’ ratings of the practice mutes, only the subjective scales relating to ease of playing and accuracy showed any significant differences between mutes. Practice mute 2 was found to be significantly more difficult to play and centre
CHAPTER 4. EFFECT OF HAND AND MUTE ON PLAYING

pitch than practice mute 1. This is not surprising as practice mute 2 is generally considered to be of poor quality, mainly due to the fact that it is impossible to play notes below C4 (HP) using the mute. Practice mute 1 is also generally considered to be of high quality (by brass instrument players) and is considerably more expensive than practice mute 2.

There were some correlations between players’ judgements of the four practice mutes and the subjective assessment of trumpet practice mutes (Dishman, 2005). Four of the trumpet practice mutes assessed were the trumpet equivalents of the four horn practice mutes used in this study. The two scales used by Dishman (2005) relating to tone quality (brittle–covered) and volume (loud–soft) were similar to the scales of sound quality (dark–bright) and volume (soft–loud) used in this study and general ratings are similar for the two instruments on these scales. The variation in player ratings present in this study was absent in Dishman’s study as the assessment of the mutes was carried out by only one player.

4.4.2 Listener subjective feedback

There was very poor listener consensus between ratings of the stopping and practice mutes on any of the three scales relating to quality of sound, intonation and volume. Due to the low numbers of listeners, statistical analyses were not conducted on this data. However, it is clear that no differences were found between any of the mutes on any of the subjective rating scales and that individual listener’s ratings depended as much on the player as the mute. It is expected that the player would have a greater influence, than the mute, over the sound. However, due to the low numbers of listeners for each player in this study, it was not possible to investigate this. Interestingly, listener ratings did not correlate well with player ratings for the same playing on any of the subjective rating scales.

4.4.3 Recordings

Playing with a stopping or practice mute in the bell, instead of a hand, greatly affects the energy distribution in the sound spectra. The increase in amplitudes of the high harmonics due to the stopping mute was comparable to that demonstrated by Meyer (1967) (Figure 4.36; see Figure 1.15 for comparison with Meyer (1967)). Compared to a hand in normal playing position, a stopping mute caused the average spectral centroid to increase greatly (over 2 kHz) without much changing the intensity of the sound. In comparison, the practice mute decreased the power of the sound by approximately 10 dB without significantly changing the spectral centroid.

No significant differences in the average spectral centroid were found between the three different hands, three different stopping mutes or four different practice mutes. Across players, the sound produced by practice mute 1 was of considerably
4.4. DISCUSSION

Figure 4.36: Sound spectra for E4 played normally (top) and stopped (bottom) on the horn. (dB with respect to same arbitrary reference.)

lower power than practice mute 2. This correlates well with players’ ratings in which practice mute 2 was judged as being significantly louder than practice mute 1.

4.4.4 Limitations

Several limiting factors may have contributed to the lack of statistically significant results obtained. Ideally, this study would have included a much larger sample size to enable more statistical analyses. However, this was not possible and similar studies have been conducted with even fewer participants. It was not possible to make this experiment semi-blind as the mutes had different shapes and the makers’ labels were attached. Player bias was limited by the placement of the mutes in the bell of the horn by the researcher, without the player having a chance to visually or tactiley examine the mutes. However, players were free to look at the mutes if they chose and also observed other players playing with the mutes in their capacity as listeners. Three players also owned a model of practice mute used in this experiment and results suggest that this did affect those players ratings of the mutes. Thus, it is evident that player (and possibly listener) bias was present.

Players only had the opportunity to play one chromatic scale and short excerpt with each of the hands and mutes and thus, had only a limited playing time in which to form their impressions of the hand or mute. If players had been able to spend longer playing with each and had been able to play whatever they liked, ratings may have been different. Player ratings for the mutes may have been affected by the running order of the experiment (Table 4.1). Playings on each of the stopping and
practice mutes were completed by the player before they were able to complete the
player survey. Thus, ratings were completed in retrospect and relied on the player’s
memory of each of the mutes. This likely resulted in slightly different ratings from
if the survey had been completed after playing with each mute.

Unfortunately, due to an error in the final printing, three of the surveys were
missing the ‘dark’ and ‘bright’ labels on the quality of sound scales for the mutes. As
a result, these data had to be discarded as it could not be determined what labels
these three players used to rate this scale. Consequently, there were fewer data
points available for comparisons of the quality of sound for the mutes (all labels on
the hands survey were correct).

The same mouthpiece was used for each player as a control, however, this meant
that players were unfamiliar with the mouthpiece/player coupling. Indeed, the
mouthpiece would not have suited each player due to individual lip size. This re-
resulted in several players commenting on the effect of the mouthpiece rather than
the hand in the bell. It would have been a better experimental design if each player
had first played with their own hand and this mouthpiece, rather than their own
mouthpiece, for comparative purposes. This would also have given them more time
to get used to playing with the test mouthpiece and allowed for greater focus on the
differences between the three hands.

4.4.5 Summary of findings

- The scales relating to accuracy and ease of playing were found to have high
  levels of correlation, but no statistical correlation was found between any other
  pairs of ranked qualities.

- Significant differences were found between players’ ratings of the three hands
  on the dark–bright scale relating to quality of sound.

- Significant differences were found between players’ ratings of the four practice
  mutes on the difficult–easy scale relating to ease of playing and accuracy of
  centring pitch.

- No significant differences were found between players’ ratings for the three
  stopping mutes.

- Players’ ratings varied greatly for all of the subjective rating scales across
  hands, stopping mutes and practice mutes.

- Player bias was exhibited for mutes owned by the player.

- Listeners’ ratings showed poor consensus and varied greatly for all of the sub-
  jective rating scales across stopping and practice mutes and ratings depended
  on the player as well as the mute.
• Listener ratings did not correlate with player ratings for the same playing.

• Stopping mutes greatly increased the spectral centroid of the sound and practice mutes decreased the intensity of the sound. The average power output with practice mute 1 was significantly lower than with practice mute 2.
Chapter 5

Effect of auditory feedback on playing the horn

5.1 Background

Auditory feedback is very important to playing a musical instrument as it is used to monitor the pitch, tuning, loudness and timbre of the sound produced. The importance of various aspects of auditory feedback to the playing of musical instruments has been investigated through the manipulation of the heard sound (e.g. delayed auditory feedback, absence of auditory feedback, addition of masking noise, volume altered auditory feedback and pitch manipulated auditory feedback; see section 2.3). The majority of this research has focused on singers and keyboard players and few studies have investigated the effect that auditory feedback has on brass players: Havlicek (1968) included brass instruments in his study on delayed auditory feedback and Cook (1996) investigated the effect of masking noise on players’ abilities to play the trombone.

The main factor affecting the auditory feedback received by a classical musician, is the acoustics of the room. Much research has been undertaken in the area of room acoustics and musicians’ preferences for particular room acoustics have been investigated. However, preferences depend on the role of the musician (soloist or ensemble player), the methodology used (real or simulated rooms), personal preferences and the instrument played (Gade, 1989a and b). For a review of the literature relating to musicians’ preferences of room acoustics and methodologies used, see Gade (2010).

The acoustics of the room is especially important to the sound of the horn, as the bell of the horn points behind the player and the direct sound is quite strong at some frequencies (see section 1.1.2.2). Thus, the sound heard by the player has a substantial component of reflected sound and the reflecting (or absorbing) surface behind the player affects this reflected sound. As a result, playing the horn in different acoustic conditions will change the frequency components present in the reflected sound and thus, the timbre of the auditory feedback to the player.
Horn players note that it is uncomfortable playing the horn with the bell pointing directly towards a wall or reflecting surface as the sound produced is ‘bad’. However, the actual sound produced by the player would be the same regardless of the acoustic conditions, unless the player alters their playing as a result of the auditory feedback received. Several horn players have commented on finding it difficult to play well in different acoustic environments and that they have made an effort to subtly change various aspects of their playing in order to produce their ‘normal’ sound.

In a survey of professional musicians, Ueno and Tachibana (2005) found that players consciously changed their playing to suit the acoustic venue and deliberately tried to ‘hear’ their sound from the audience’s position, whilst on stage. Ueno et al. (2010) investigated the ways in which players deliberately changed their playing in response to different acoustic environments through the use of a simulation system to produce sound-fields corresponding to five different acoustic room conditions (ranging in size from an anechoic room to a large church). After playing in the different conditions, players were questioned on the changes they had made to their playing style. Although most of the adjustments were made in the areas of tempo, vibrato and note length, several comments also referred to changing the sound produced.

Another cause of altered auditory feedback is that of practising with a practice mute. The sound spectra produced when playing with a practice mute is different from that of the horn played with a hand in the bell and consequently, the auditory feedback received by the player will be different. Given that many brass players practise for extended periods with these mutes, it is surprising that the effect of the change in sound has not been previously investigated. Table 5.1 shows several comments on the effect (relating to sound) of practising a brass instrument with a practice mute noted by various brass players.

Thus, changes in the auditory feedback received by horn players are either caused by changes in the reflected sound or changes in the sound produced due to the insertion of a mute in the bell, both of which result in a change in the spectral envelope (see sections 2.1.2.2 and 2.3.1.5) of the heard sound. The effect of manipulating the spectral envelope of the auditory feedback received by musicians, has not been previously investigated. However, Garber and Moller (1979) studied a similar effect with speech and found that filtering the auditory feedback to the speaker resulted in a change in nasalisation (tone quality) of the speech.

In much of the research on auditory feedback, it is necessary to present the sound via headphones. Ideally, head-related transfer functions (HRTFs) would be taken into account so that the subject is presented with an accurate representation of the sound. HRTFs are “spectral cues which influence spacial hearing...and summarize the direction-dependent acoustic filtering a free field sound undergoes due to the head, torso, and pinna” (Cheng and Wakefield, 2001). Thus, when a sound originating at point $x$ is presented to a subject via headphones after being filtered with
Table 5.1: Comments relating to the effect (on sound) of practising brass instruments with a practice mute.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Comment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>I was playing very high on the pitch on the mute and I also discovered that my personal sense of pitch placement is very much tied up with tonal color. The feedback of tone I was used to relying upon was basically lost on the practice mute.</td>
<td>Ericson (2003)</td>
</tr>
<tr>
<td>Euphonium</td>
<td>I really don’t like to use the mute to practice because it makes the horn respond TOTALY differently and I think its almost impossible to work on my tone with it.</td>
<td>dfraser (2010)</td>
</tr>
<tr>
<td>Trumpet</td>
<td>mutes slow your development down compared to playing open. Your sound is created by what your ears tell your brain. If we mute that signal, the brain does not get as much info</td>
<td>rowuk (2010)</td>
</tr>
</tbody>
</table>

HRTFs, the subject should be able to locate the point of origin.

As HRTFs are unique to an individual, the use of general HRTFs may not, according to Cheng and Wakefield (2001), result in correct spatial perception.\(^1\) As a result, HRTF data would need to be collected for each subject involved in the experiment, which is simply not possible with the time and resources available to most researchers in the area of auditory feedback and none of the studies mentioned in section 2.3 that presented sound via headphones made use of HRTFs. This is likely justified by the fact that the sound that is intended for the subject to hear, is simply a manipulation of the auditory feedback (i.e. the sound they would be hearing at the ear) and thus, the sound is spatially located at the ears anyway. However, this then requires that the sound (pre-manipulation) actually be collected at each ear separately, to ensure that the manipulated sound is accurately represented through the headphones.

The characteristic headphone transducer also affects the sound heard by the subject which can be compensated for by the use of a headphone transfer function. Kulkarni and Colburn (2000) report that the magnitude of the spectral features in headphone transfer functions are as large as those for HRTFs, but that the headphone transfer function varies greatly with small changes in placement of the headphone cushions over the ears. Thus, an appropriate transfer function that takes into account the headphones and subject is actually only valid for one particular placement of the headphones and hence, even if the HRTFs were used for individual subjects, it would be virtually impossible to compensate for the effects of the headphones, which are of equal magnitude to those of HRTFs.

This study aims to investigate whether or not horn players change their produc-

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\(^1\)Interestingly, Usher and Martens (2007) demonstrated that sounds filtered using the subject’s own HRTFs were not necessarily judged as sounding the most natural compared to sound filtered using other peoples’ HRTFs.
tion of sound depending on the auditory feedback received. Through manipulating the spectral envelope of the heard sound, a simulated acoustic environment will be created with the aim of presenting horn players with changes in auditory feedback that could realistically be received whilst playing in different situations due to changes in the reflected sound. Thus, the purpose of this study is not to show how horn players respond to playing in different room acoustics, but to investigate the more subtle effect of spectrally altered auditory feedback on the horn player’s production of sound.

Auditory feedback was presented via headphones and the horn player’s sound recorded for analysis. HRTFs and headphone transfer functions were not available and were not deemed essential to the success of the experiment. Three different levels of players were included in the study (professional, advanced student and student), in order to determine if experience in horn playing has an effect on the response to changes in auditory feedback. It is expected that there will be a difference between the groups which could be due to two opposing hypotheses:

1. Professional players have highly developed listening skills which are used to constantly monitor intonation, loudness and tone (e.g. blending with other instruments in an orchestra). Student players are more concerned with producing the correct note and developing their technical skills and thus, may not be as focused on the auditory feedback. This hypothesis suggests that professional players will be more influenced by changes in the heard sound than student players.

2. Professional players have more experience in playing (muscle memory) and likely have a more developed sense of their sound production. Whereas, student players may not have as much confidence in their ability to produce a ‘correct’ or ‘good’ sound without being able to hear it. This hypothesis suggests that professional players will be less influenced by changes in auditory feedback than student players.

It is also possible that both of these hypotheses are true, which would result in no difference between the groups due to a cancellation effect.

5.2 Methods

5.2.1 Materials

5.2.1.1 Equalizer

Preliminary measurements showed that playing directly into a reflecting surface (distance \( \approx 0.4 \text{ m} \)) greatly increased the amplitudes of frequency components in the sound spectra (measured just above the player’s head) in the region 400 to
500 Hz. Playing directly into an absorbing surface (distance \( \approx 0.4 \text{ m} \)) decreased the amplitudes of frequency components in the sound spectra between 700 Hz and 1 kHz, and very few harmonics were present above 1 kHz. As the player’s hand has the greatest effect on the resonance peaks of the horn above the cutoff frequency of the bell (around 500 Hz), decreased amplitudes of the frequency components between 450 and 600 Hz were also used.

A 31-channel graphic equalizer (model dbx 131) was used to manipulate the sound. Four different settings were employed with the aim of filtering the following:

1. flat response (Flat).
2. increasing amplitudes of frequencies 400-500 Hz (Narrowboost).
3. decreasing amplitudes of frequencies 450-600 Hz (Notch).
4. greatly decreasing amplitudes of frequencies above 1 kHz (Lowpass).

Frequency responses for each of the four settings are shown in Figure 5.1 of the EQ with an added 56 Ω resistor used to compensate for the 64 Ω impedance load rating of the headphones. The effect of the resistor on the frequency response of the EQ is shown in Figure 5.2. In order to accurately reproduce the settings during experiments, wooden cutouts were used (Figure 5.3) to indicate the minimum position of each slider.

### 5.2.1.2 Musical excerpts

Two musical excerpts were used:

1. Descending chromatic scale from F5 to F3 (HP; Figure 5.4a).
2. Excerpt from Tchaikovsky’s Symphony No. 6, IV. – Horn 2 in F (Figure 5.4b). This excerpt is a well known horn solo in the orchestral repertoire and was expected to be familiar to all players (only one of the student players was unfamiliar with the piece and she was given the opportunity to practise it before the experiment began). The piece focuses on the middle range of the horn and requires a good tone and intonation.

### 5.2.2 Recordings

#### 5.2.2.1 Participants

Twelve horn players (P1 - P12) were recorded playing the horn using their own horn and mouthpiece. Players ranged in age (details were not collected), gender and experience. After the experiments, players were categorised into three different groups based on their proficiency on the instrument (Table 5.2).
Figure 5.1: Frequency response of EQ (with added resistor) for the four different settings.

Figure 5.2: Effect of added 56 Ω resistor on the frequency response of the EQ for settings 1 and 4.
5.2. METHODS

Figure 5.3: Wooden cutouts used to accurately reproduce each of the EQ settings by indicating the minimum position of each slider.

Table 5.2: Categorisation of horn players (P1-P12) based on proficiency in playing the horn.

<table>
<thead>
<tr>
<th>Professional</th>
<th>Advanced student</th>
<th>Student</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
<td>P3</td>
</tr>
<tr>
<td>P7</td>
<td>P5</td>
<td>P4</td>
</tr>
<tr>
<td>P11</td>
<td>P6</td>
<td>P10</td>
</tr>
<tr>
<td></td>
<td>P8</td>
<td>P12</td>
</tr>
<tr>
<td></td>
<td>P9</td>
<td></td>
</tr>
</tbody>
</table>
5.2.2.2 Setup

Recordings were carried out in three small to medium sized rooms (Table 5.3) in the School of Music, UWA and WAAPA, ECU. The horn player was seated and the sound was recorded using two Røde NT3 microphones. Microphone 1 was placed behind the player at a distance of approximately one radius from the bell of the horn and microphone 2 was placed centrally just above the player’s head (Figure 5.5a). Microphone 1 routed to channel 1 of the soundcard (Motu Traveler) and microphone 2 routed to channel 2 of the soundcard and the equalizer (dbx 131). The output of the equaliser routed to channel 3 of the soundcard and the headphones (Sennheiser HD280). A digital video camera (Canon MVX4i) was placed behind the player to capture the player’s hand position in the bell. Figure 5.5b shows the equipment used and a diagram of the setup is given in Figure 5.6.

5.2.2.3 Feedback conditions and Running order

Six feedback conditions were included: normal playing with no headphones (Normal); normal feedback through headphones (Flat); increased amplitudes of frequencies between 400 and 600 Hz (Narrowboost); decreased amplitudes of frequencies between 450 and 600 Hz (Notch); decreased amplitudes of frequencies above 1 kHz (Lowpass); and no feedback through headphones (Headphones). Each feedback condition was presented to the player twice (except Headphones) in an order chosen so that each condition did not precede or proceed the same condition twice. The running order of the experiment is given in Table 5.4. Participants were instructed to play the chromatic scale at a constant tempo and \textit{mf} dynamic. No instructions were given on how to play the excerpt, except that it should be played consistently across all playings. Players did not use vibrato.

5.2.3 Analysis of recordings

Two main analyses were undertaken on the collected data – observation of hand position from the video data and FFT analysis of the sound data. The sound recordings were cut and any split or missed notes identified and partially or fully removed. A single FFT was done for each scale and excerpt for sound spectra analysis (spectral centroid, spectral power and spectral slope). FFTs were also done of individual notes in the scales and excerpts for frequency and intonation analysis.

Table 5.3: Approximate dimensions of the experiment rooms used.

<table>
<thead>
<tr>
<th>Room</th>
<th>Width (m)</th>
<th>Length (m)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensemble room (UWA)</td>
<td>4.5</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Green room (WAAPA)</td>
<td>7.5</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Ensemble room (WAAPA)</td>
<td>6</td>
<td>9</td>
<td>4</td>
</tr>
</tbody>
</table>
5.2. METHODS

Figure 5.5: Setup of recording showing the microphone placement (a) and equipment (b).

Figure 5.6: Diagram of recording setup.

Table 5.4: Experiment running order.

<table>
<thead>
<tr>
<th>Feedback condition</th>
<th>Headphones</th>
<th>Music played</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (N)</td>
<td>no</td>
<td>3 x scale, 2 x excerpt</td>
</tr>
<tr>
<td>Headphones (H)</td>
<td>yes, unplugged</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Set EQ level</td>
<td>yes</td>
<td>player’s choosing</td>
</tr>
<tr>
<td>Flat (F)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Narrowboost (NB)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Lowpass (LP)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Notch (NT)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Lowpass (LP)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Flat (F)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Notch (NT)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Narrowboost (NB)</td>
<td>yes</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
<tr>
<td>Normal (N)</td>
<td>no</td>
<td>1 x scale, 1 x excerpt</td>
</tr>
</tbody>
</table>
Methods of analysis are outlined below:

- Spectral centroid ($S_c$) was calculated for the scale and excerpt from the FFT data over the frequency range 0 to 5 kHz (DC component is insignificant):

$$S_c = \frac{\sum_{n=0}^{n-1} f(n)x(n)}{\sum_{n=0}^{n-1} x(n)} \quad (5.1)$$

where $x(n)$ is the magnitude for the frequency corresponding to bin number $n$ and $f(n)$ is the centre frequency of that bin, with both $x(n)$ and $n$ being linear.

- Spectral power in dB ($S_p$) was calculated for the scale and excerpt from the FFT data by doing a trapezoidal integration over the frequency range 0 to 5 kHz:

$$S_p = 20 \log\left(\frac{1}{2} \sum_{n=0}^{n-1} (x(n+1) + x(n))(f(n+1) - f(n))\right) \quad (5.2)$$

where $x(n)$ is the magnitude for the frequency corresponding to bin number $n$ and $f(n)$ is the centre frequency of that bin, with both $x(n)$ and $n$ being linear.

- Spectral slope ($S_s$) was calculated for the scale by fitting a line to the log-log FFT plot over the frequency range 1 to 3 kHz. This was then converted to dB/8ve by using the line fit formula to calculate the difference in amplitude between 1 and 2 kHz.

- The frequency of individual notes was calculated by fitting a parabola to the peak of the first harmonic. Individual notes (and intervals) analysed are indicated in Figure 5.7.

![Figure 5.7: Individual notes and intervals analysed in the scale and excerpt.](image)
• The intonation between two notes was calculated in cents:

\[
\text{Intonation} = 1200 \log\left(\frac{F_2}{F_1}\right) / \log(2) \tag{5.3}
\]

where \( F_1 \) and \( F_2 \) are the two frequencies being compared.

## 5.3 Results

Results (other than the channel comparison) have been colour coded to enable easy identification of players’ proficiency levels (Table 5.5).

### 5.3.1 Channel comparison

Three separate channels were recorded for each player: channel 1 was the direct sound from the horn and was the channel used for all analysis; channel 2 was the sound from above the player’s head (i.e. the sound the player would normally hear); and channel 3 was the auditory feedback presented to the player (channel 2 routed through the EQ). Figures 5.8 to 5.15 show the differences in waveform and sound spectra, produced by player 11, between the three different channels for the four different feedback conditions involving feedback through headphones (Flat to Low-pass). Differences in spectral centroid, spectral power and spectral slope are also indicated.

As can be seen, channels 2 and 3 have lower sound levels than channel 1 due to the distance of the microphone from the bell. The difference in waveform shape and spectral envelope of channel 2 compared to channel 1 is due to the room acoustics. Channel 1 is recorded with the microphone placed at approximately one radius from the bell of the horn, and is thus dominated by near sound. However, Channel 2 is recorded above the player’s head and thus includes components due to first reflections from walls, floor and ceiling, and to reverberant sound. As three different rooms were used over the duration of the study (approximate dimensions are given in Table 5.3), figures showing the differences in waveform and sound spectra between the three channels are also presented in Appendix J for two other players to enable comparisons of the effects of the rooms’ reflections on the sound. Note that differences in sound level between channels 2 and 3 are different for each player, as the level on channel 3 was adjusted for each player so that the sound they received

<table>
<thead>
<tr>
<th>Proficiency group</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professional</td>
<td>Blue</td>
</tr>
<tr>
<td>Advanced student</td>
<td>Black</td>
</tr>
<tr>
<td>Student</td>
<td>Pink</td>
</tr>
</tbody>
</table>

Table 5.5: Colour coding for player proficiency groups.
Figure 5.8: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of scale played in Flat. (Magnitude has same linear arbitrary units.)

Figure 5.9: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of scale played in Narrowboost. (Magnitude has same linear arbitrary units.)
5.3. RESULTS

Figure 5.10: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of scale played in Notch. (Magnitude has same linear arbitrary units.)

Figure 5.11: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of scale played in Lowpass. (Magnitude has same linear arbitrary units.)
CHAPTER 5. EFFECT OF AUDITORY FEEDBACK

Figure 5.12: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of excerpt played in Flat. (Magnitude has same linear arbitrary units.)

Figure 5.13: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of excerpt played in Narrowboost. (Magnitude has same linear arbitrary units.)
5.3. RESULTS

Figure 5.14: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of excerpt played in Notch. (Magnitude has same linear arbitrary units.)

Figure 5.15: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 11 showing FFT (above) and waveform (below) of excerpt played in Lowpass. (Magnitude has same linear arbitrary units.)
through the headphones sounded a 'normal' level.

Channel 3 shows the effect on the sound of the four different feedback conditions: Flat – channel 3 is very similar to channel 2 (Figures 5.8 and 5.12); Narrowboost – channel 3 has increased amplitudes for frequencies between 400 and 600 Hz (Figures 5.9 and 5.13); Notch – channel 3 has decreased amplitudes for frequencies between 450 and 600 Hz (Figures 5.10 and 5.14); and Lowpass – channel 3 has decreased amplitudes for frequencies above 1 kHz (Figures 5.11 and 5.15).

5.3.2 Repeatability

Each experiment run through involved four repetitions of the scale and three repetitions of the excerpt played under normal playing conditions (no headphones). Figures 5.16 to 5.22 show the repeatability (average ± the maximum and minimum) of several different measures (spectral centroid, spectral power, spectral slope and the intonation of various intervals) for these repeated playings by each player.

As these figures show, intraplayer differences are quite large for repeated playings under normal playing conditions and there appear to be no consistent patterns within players. That is, one player may have a large range in one measure, but not in another. The range of intraplayer differences also varies considerably across players.

5.3.3 Sound spectrum

Figures showing the sound spectra and spectral envelopes for playings of the scale and excerpt by each player can be found in Appendix K. Results from three measures of the sound spectrum (spectral centroid, spectral power and spectral slope) are presented below.

![Figure 5.16: Average spectral centroid across 4 playings of scale in Normal for Players 1 to 12. Error bars show maximum and minimum values.](image-url)
Figure 5.17: Average spectral power across 4 playings of scale in Normal for Players 1 to 12. Error bars show maximum and minimum values.

Figure 5.18: Average spectral slope across 4 playings of scale in Normal for Players 1 to 12. Error bars show maximum and minimum values.

Figure 5.19: Average spectral centroid across 3 playings of excerpt in Normal for Players 1 to 12. Error bars show maximum and minimum values.
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Figure 5.20: Average spectral power across 3 playings of excerpt in Normal for Players 1 to 12. Error bars show maximum and minimum values.

Figure 5.21: Average interval between D4 (#3) and G4 across 3 playings of excerpt in Normal for Players 1 to 12. Error bars show maximum and minimum values.
Figure 5.22: Average intervals between octave notes (Bb4-Bb3, Bb3-Bb2 and Bb4-Bb2) across 4 playings of scale in Normal for Players 1 to 12. Error bars show maximum and minimum values.

5.3.3.1 Spectral centroid

Figures 5.23 and 5.24 show the calculated spectral centroid as a function of the corresponding spectral power across all players and conditions for the scale and excerpt, respectively. There is a moderate correlation between spectral centroid and spectral power for the scale ($R^2 = 0.51$), but only a weak correlation for the excerpt ($R^2 = 0.13$). Within individual players, there is a strong to very strong correlation between spectral centroid and spectral power – seven players for the scale (Figure 5.25) and three players for the excerpt (Figure 5.26).

Considering this same data broken down into feedback conditions (Figures 5.27, 5.28, 5.29 and 5.30), no trends are apparent across all players. However, some general observations can be made for the scale (Figures 5.27 and 5.28): Player 12 consistently played louder with headphones (Flat, Narrowboost, Notch, Lowpass, Headphones) than without (Normal); Player 4 consistently played softer with headphones than without; two players (P10 and P11) tended to have higher spectral centroids for Lowpass than Normal without an increase in spectral power; and Player 1 tended to play Lowpass louder than Normal without increasing the spectral centroid. Similar comments can be made for the excerpt (Figures 5.29 and 5.30): two players (P3 and P12) consistently played louder with headphones than without; two players (P4 and P7) tended to play softer with headphones than without; and Player 2 tended to have higher spectral centroids for Lowpass than Normal without
Figure 5.23: Spectral centroid vs. spectral power for all playings of scale across players and feedback conditions.

Figure 5.24: Spectral centroid vs. spectral power for all playings of excerpt across players and feedback conditions.
Figure 5.25: Spectral centroid vs. spectral power of scale for all feedback conditions and Players 1 to 12.
Figure 5.26: Spectral centroid vs. spectral power of excerpt for all feedback conditions and Players 1 to 12.
Figure 5.27: Spectral centroid for scale across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1 to 12.
Figure 5.28: Spectral power for scale across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1 to 12.
Figure 5.29: Spectral centroid for excerpt across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1 to 12.
Figure 5.30: Spectral power for excerpt across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1 to 12.
an increase in spectral power.

5.3.3.2 Spectral slope

There is a small negative correlation between spectral slope and the corresponding spectral power for the scale across all players and conditions ($R^2 = 0.09$; Figure 5.31). However, two players showed a moderate negative correlation between spectral slope and spectral power (that is, the lower the spectral slope, the higher the spectral power; Table 5.6). Figure 5.32 shows the average spectral slope for Normal along with the spectral slopes for each of the playings for the other feedback conditions for each player. As can be seen, the majority of spectral slope values lie within the intraplayer repeatability, regardless of the feedback condition. Thus, no trends are apparent in the spectral slope for different feedback conditions.

From Figure 5.32 some general observations can be made for different players: Player 2 had lower (outside of repeatability) spectral slopes for conditions involving headphones (Flat, Narrowboost, Notch, Lowpass, Headphones) than for Normal, without playing more quietly; Four players (P2, P3, P9 and P11) had at least one repetition for all conditions, other than Normal, lie outside of repeatability; three players (P2, P6 and P11) had both repetitions for at least one feedback condition lie outside of repeatability; Player 7 had all repetitions for all feedback conditions lie within repeatability.

5.3.4 Intonation

For both the scale and excerpt, there is large variation in repeatability for most players on all of the intervals measured (see Figure 5.7) as shown for four of the intervals in Figures 5.21 and 5.22. There were no consistent differences in the intonation of intervals due to feedback condition by any of the players (see Appendix L for figures). However, several players showed specific differences between Normal and the conditions with headphones (Flat, Narrowboost, Notch, Lowpass, Headphones).

For the upper octave interval Bb4-Bb3, five players (P2-P5, P6 and P8) had consistently small intervals (less than 1200 cents) and Player 10 had consistently large octaves (greater than 1200 cents) across all conditions (Figure 5.33). Figure 5.34 shows that for the lower octave interval Bb3-Bb2, three players (P1, P2 and P4) played consistently more in tune (up to 40 cents closer to 1200 cents) with headphones (Flat, Narrowboost, Notch, Lowpass, Headphones) than without (Normal) and three players (P5, P6 and P8) played consistently less in tune (up to 50 cents further from 1200 cents). Four players (P1, P3, P4 and P6) also played consistently less in tune (further from 500 cents for equal tempered tuning or 498 cents for just intonation) with headphones, than without, for the perfect fourth interval in the excerpt D4#1-G4 (Figure 5.35).
Figure 5.31: Spectral slope vs. spectral power for all playings of scale across players and feedback conditions.

Table 5.6: Slope and $R^2$ value of correlation for line fit to spectral slope vs. spectral power for all players.

<table>
<thead>
<tr>
<th>Player</th>
<th>Slope</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.236</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>-0.233</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>0.374</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>-0.807</td>
<td>0.54</td>
</tr>
<tr>
<td>5</td>
<td>0.184</td>
<td>0.36</td>
</tr>
<tr>
<td>6</td>
<td>-0.648</td>
<td>0.66</td>
</tr>
<tr>
<td>7</td>
<td>-0.286</td>
<td>0.40</td>
</tr>
<tr>
<td>8</td>
<td>-0.427</td>
<td>0.86</td>
</tr>
<tr>
<td>9</td>
<td>-0.503</td>
<td>0.75</td>
</tr>
<tr>
<td>10</td>
<td>-0.053</td>
<td>0.03</td>
</tr>
<tr>
<td>11</td>
<td>-0.431</td>
<td>0.68</td>
</tr>
<tr>
<td>12</td>
<td>-0.673</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Figure 5.32: Spectral slope for scale across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1 to 12.
Figure 5.33: Interval between Bb4 and Bb3 in scale across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 2, 3, 5, 6, 8 and 10.
Figure 5.34: Interval between Bb3 and Bb2 in scale across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1, 2, 4-6 and 9.
Figure 5.35: Interval between D4#1 and G4 in excerpt across feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) for Players 1, 3, 4 and 6.
5.3.5 Professional vs. student

Figures 5.36, 5.37 and 5.38 show the average measure for Normal versus the measures for each of the other feedback conditions (Flat, Narrowboost, Notch, Lowpass, Headphones) for spectral centroid, spectral power and spectral slope of the scale, respectively. Players are grouped (in colour) by level of proficiency and the dotted line indicates equality in measures between the feedback conditions. It is clear from the figures that although there is considerable variation from equality, especially for some players, there is no systematic difference between the three groups for any of the measures. Results were similar for the spectral centroid and spectral power of the excerpt (Figures 5.39 and 5.40).

The average spectral centroid, spectral power and spectral slope for each of the groups across Normal (repeatability) and all feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) are shown in Figure 5.41. The student group had the smallest standard deviation for spectral centroid and the professional group had the smallest standard deviation for spectral power. Both the average value and size of standard deviation were largely unaffected by the addition of manipulated auditory feedback across all three groups. The advanced student group had a large standard deviation for spectral slope compared to the other two groups.

A comparison of the correlations between spectral centroid and spectral power for the three groups of players (average slope and $R^2$ value) are shown in Figure 5.42. The professional group had the lowest correlation between spectral centroid and spectral power for the scale, but also had the largest standard deviation. For the excerpt, average correlation values were very similar between the three groups and all were quite low. The standard deviation was large for the student group compared to the other two groups.

Figure 5.43 shows the average intonation for six of the intervals measured. As can be seen, there is no clear pattern between the three groups (professional, advanced student and student) across the different intervals. In general, the professional group has the smallest standard deviation and the student group has the largest. No one group appears to play more in tune than any other (closer to the equal temperament or just intonation value) for either the scale or excerpt intervals.

5.3.6 Hand position

The position of the right hand in the bell of the horn varied across all twelve players (Figure 5.44). Player 1 changed her hand position part of the way through the playing of the scale for two of the feedback conditions (Narrowboost and Lowpass). The hand position became more open and remained in the new position for the subsequent playing of the excerpt (during the same feedback condition). Figures 5.45 and 5.46 show the change in hand position for Narrowboost and Lowpass, respectively.
Figure 5.36: Average spectral centroid for Normal vs. spectral centroid for Flat, Narrowboost, Notch, Lowpass, and Headphones across players for scale. Players are grouped by colour: Professional (blue), Advanced student (black) and Student (Pink).
Figure 5.37: Average spectral power for Normal vs. spectral power for Flat, Narrow-boost, Notch, Lowpass, and Headphones across players for scale. Players are grouped by colour: Professional (blue), Advanced student (black) and Student (Pink).
Figure 5.38: Average spectral slope for Normal vs. spectral slope for Flat, Narrow-boost, Notch, Lowpass, and Headphones across players for scale. Players are grouped by colour: Professional (blue), Advanced student (black) and Student (Pink).
Figure 5.39: Average spectral centroid for Normal vs. spectral centroid for Flat, Narrowboost, Notch, Lowpass, and Headphones across players for excerpt. Players are grouped by colour: Professional (blue), Advanced student (black) and Student (Pink).
Figure 5.40: Average spectral power for Normal vs. spectral power for Flat, Narrowboost, Notch, Lowpass, and Headphones across players for excerpt. Players are grouped by colour: Professional (blue), Advanced student (black) and Student (Pink).
Figure 5.41: Average spectral centroid, spectral power and spectral slope across all feedback conditions (A) and repeatability of Normal (R) for professional, advanced student and student player groups. Error bars show +/- standard deviation.
Figure 5.42: Average $R^2$ and slope values of fit to spectral centroid vs. spectral power for professional, advanced student and student player groups. Error bars show +/- standard deviation.
Figure 5.43: Average intervals for professional, advanced student and student player groups. Error bars show +/- standard deviation. Scale octaves intervals are shown on the left and intervals from the excerpt are shown on the right.
Figure 5.44: Position of right hand in bell for the twelve players.
Figure 5.45: Change in hand position of P1 during playing of scale in Narrowboost.
The change in position was greater for Lowpass than for Narrowboost. The second presentation of Lowpass also resulted in a change in hand position, although smaller than the first. The second presentation of Narrowboost did not elicit a change in the hand position.

Three players (P3, P5 and P6) made small changes to their hand position for certain notes during the experiment and these changes only occurred during the feedback conditions containing manipulated auditory feedback and not during playing under normal conditions (Normal or Headphones). Changes in hand position by these players only lasted for one or two notes within the scale or excerpt in particular feedback conditions: Player 3 opened her hand slightly for several notes in the scale during the first playing of Lowpass (Figure 5.47) and for the repeated G4s in the excerpt during the second playing of Notch; Player 5 opened his hand slightly for the repeated G4s in the excerpt during the first playing of Narrowboost (Figure 5.48); and Player 6 opened her hand slightly for the excerpt (after playing the scale) during the first playing of Lowpass (Figure 5.49).

Players 7 and 9 exhibited changes in hand position during playing that did not correspond to different feedback conditions (i.e. they were also present during normal playing). Player 7 consistently closed his hand position slightly from D4#3 in the excerpt (Figure 5.50). This movement was present in all playings of the excerpt. Player 9 moved her hand several times during playing (usually whilst breathing in). The movement was rotational in action and appeared to be a repositioning of the hand (Figure 5.51), which often ended up in a slightly more closed position before being moved back to the original position. The rotational movement usually occurred during a pause in playing, but the final adjustments occurred during the proceeding playing. The other six players did not exhibit any visual change in hand position during the experiment.
Figure 5.46: Change in hand position of P1 during playing of scale in Lowpass.
Figure 5.47: Change in hand position of P3 during playing of scale in Lowpass.
Figure 5.48: Change in hand position of P5 during playing of excerpt in Narrow-boost.
Figure 5.49: Change in hand position of P6 during playing of excerpt in Lowpass.
Figure 5.50: Change in hand position of P7 during playing of excerpt.
Figure 5.51: Change in hand position of P9 during repositioning of hand.
5.4 Discussion

Frequency analysis of the recordings showed that the four different equalizer settings did produce the expected change in sound spectra (Table 5.7). It was important that the manipulations in the auditory feedback be subtle so that changes would be perceived as natural and could be reasonably expected to occur in situations where the acoustic environment was varied (either by change of venue, change of positioning within the same venue, or change of reflecting/absorbing surface behind the player). It was also vital that the subtle manipulations were able to be heard by the player. Due to time constraints, it was not possible to interview the participants after completion of the experiment and thus player responses to what they heard were not investigated. However, an unsolicited comment by one of the players, It was bizarre, it was like playing in, you know, ten different rooms all with just slightly different acoustics, indicates that the differences were indeed audible and gave the desired impression (at least to one player).

5.4.1 Repeatability

There were large intraplayer differences in all measures analysed (spectral centroid, spectral power, spectral slope, frequencies and intervals) for the repeated playings of the scale and excerpt under the normal auditory feedback condition (Normal). The range of intraplayer differences varied across players and measures, with some being as large as the differences between players. This is comparable to the study by Lehman (1964), in which intraplayer differences were found to be up to 75% of interplayer differences.

There were a couple of unusual intraplayer differences. For example, Player 12 showed a very small range in spectral centroid, spectral power and spectral slope. This player was the least advanced in terms of quality of tone produced and accuracy in playing. Several playings of the scale, over the whole experiment, had to be disregarded due to inaccurate playing. Thus, the average and range for the repeatability of the scale by Player 12 was calculated on three, rather than four, playings. This could possibly have influenced the size of the range, but it is probably more likely

Table 5.7: Change in sound spectra for feedback conditions 1 to 4, compared to normal playing (Normal).

<table>
<thead>
<tr>
<th>Feedback condition</th>
<th>Change in sound spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>no change</td>
</tr>
<tr>
<td>Narrowboost</td>
<td>increased amplitudes: 400-600 Hz</td>
</tr>
<tr>
<td>Notch</td>
<td>decreased amplitudes: 450-600 Hz</td>
</tr>
<tr>
<td>Lowpass</td>
<td>decreased amplitudes: above 1 kHz</td>
</tr>
</tbody>
</table>
that small changes in tone colour produced by other players over multiple playings were not present in this player’s sound due to its poor quality. It is interesting to note that this player also had the largest intraplayer differences for the intonation measure, indicating that her intonation was very inconsistent.

Player 7 had one of the largest intraplayer differences for the spectral centroid, spectral power and spectral slope repeatability measures for the scale. This was due to an unusual sound spectrum for the fourth repetition (Figure 5.52). In the unusual spectrum, the frequency components between 1200 and 1400 Hz are absent and there are also stronger frequency components present between 1500 and 1800 Hz.

5.4.2 Sound spectrum

5.4.2.1 Spectral centroid and spectral power

Across all players and conditions, there was a moderate correlation ($R^2 = 0.51$) between spectral centroid and spectral power for the scale, but only a very weak correlation ($R^2 = 0.13$) for the excerpt. The weaker correlation for the excerpt is interesting, and perhaps surprising, as spectral centroid was found to correlate strongly with intensity for individual trumpet and saxophone notes by Beauchamp (1982). Individual players did show moderate to very strong correlations between spectral centroid and spectral power, but mainly for the scale. The differences in correlation found between this study and those previously found in the literature may be due to the fact that previous studies have calculated the spectral centroid of a single note and correlated it with the intensity of that note, whereas in this study, the spectral centroid was calculated for the sound spectrum of a two octave chromatic scale (minus the final octave note) and correlated with the spectral power of the same spectrum. The weaker correlation for the excerpt could be related to the length of note (generally longer in the excerpt than in the scale), narrower range of pitch in the excerpt, or perhaps to a deliberate attempt by the players to determine the timbre in a musical context.

For the different feedback conditions, there were no trends apparent across players for spectral power, spectral centroid or spectral slope. This indicates that there were no measurable differences in spectral centroid or spectral power which varied consistently due to the different feedback conditions across players. Players were asked to adjust the sound level heard through the headphones so that it sounded like ‘normal’ playing. Table 5.8 shows the resulting gain setting on the equalizer for each player. The purpose of adjusting the gain to suit each individual player was to encourage the player to play at the same dynamic level with and without headphones and to enable any differences in playing intensity due to the manipulation of the auditory feedback to be observed. However, several players consistently played either louder or softer with headphones than without, regardless of the feedback
5.4. DISCUSSION

Figure 5.52: Representative ‘normal’ sound spectrum for scale (left) and unusual spectrum (right) for Player 7 in Normal. (Magnitude is linear scale with respect to same arbitrary reference.)

Table 5.8: Gain setting for each player.

<table>
<thead>
<tr>
<th>Player</th>
<th>Gain setting (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+4.2</td>
</tr>
<tr>
<td>2</td>
<td>+3.6</td>
</tr>
<tr>
<td>3</td>
<td>+1.2</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>+1.2</td>
</tr>
<tr>
<td>7</td>
<td>+1.2</td>
</tr>
<tr>
<td>8</td>
<td>+1.8</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>+2.4</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>+1.2</td>
</tr>
</tbody>
</table>
CHAPTER 5. EFFECT OF AUDITORY FEEDBACK

5.4.2.2 Spectral slope

There was a slight negative correlation ($R^2 = 0.09$) between spectral slope and spectral power calculated from the sound spectra of a two octave scale (minus the third octave note). This is perhaps surprising as Luce and Clark (1967) showed a dependency on intensity for the value of spectral slope. They found that as the intensity increased, the rolloff rate decreased (see Figure 1.8). Two players showed a moderate correlation ($R^2 = 0.75$ and $0.86$) between spectral slope and spectral power which agreed with the findings by Luce and Clark (1967) – the greater the spectral power, the slower the rate of rolloff of the spectrum. The values obtained in this study were also much higher than the $15 \text{ dB/8ve}$ that Luce and Clark quoted. However, this is likely due to the range of frequencies used to calculate the spectral slope. Luce and Clark (1967) do not specify the range used, but they indicate that the amplitudes of spectral components begin to decrease above 500 to 600 Hz. If the spectral slopes in the present study are calculated using a range of frequencies starting at 600 Hz (rather than 1 kHz), the resulting spectral slope values are more similar to the $15 \text{ dB/8ve}$ found by Luce and Clark (Table 5.9). As with the spectral centroid, there were no consistent differences between any of the feedback conditions across players.

5.4.3 Intonation

A comparison of important intervals, such as the octaves in the scale, and the repeated unisons and perfect fourth in the excerpt also showed no apparent differences due to feedback condition across players. However, several players tended to play the intervals consistently either more in tune or less in tune with headphones than without. Thus, manipulating the auditory feedback did not have a measurable effect on the intonation of either the scale or the excerpt.

5.4.4 Professional vs. student

It was expected that differences may be apparent between professional, advanced student, and student players in the sound produced as a result of the manipulated auditory feedback. As discussed above, no systematic differences, due to the feedback condition, were found across players for any of the measures of the sound spectrum or intonation. Thus, players were grouped into the categories of professional, advanced student, and student based on their playing abilities, as judged during the experiment. Results showed that there were no consistent differences in spectral centroid, spectral power or spectral slope between Normal and the other conditions (Flat, Narrowboost, Notch, Lowpass, Headphones) across the three groups.
A comparison of the average, across players, for spectral centroid, spectral power and spectral slope for each of the three groups produced a surprising result. The student group had the smallest standard deviation for spectral centroid in both the scale and excerpt. This possibly suggests that the student group was less affected by the manipulated auditory feedback than the other two groups and consequently changed their sound the least. However, this cannot be substantiated from the data and the small sample sizes for each group make it difficult to draw any strong conclusions from the data. The student group also had the highest average rolloff rate (spectral slope). This indicates that either their higher notes were played weaker due to lower ability or their sound was generally lacking in high frequency components.

On average, the professional group had a lower correlation between spectral centroid and spectral power of the scale, than the other two groups. A lower correlation suggests that the player is able to change the distribution of frequency components in the sound (tonal colour) without altering the intensity of the sound, or alternatively, they are able to change the intensity of the sound without much changing the brightness. Thus, it could be expected that professional players would have greater control over this aspect of playing than student players. This trend is not evident for the excerpt as all three groups showed very low correlation between the spectral centroid and spectral power, when averaged over players.

It was expected that the professional group would generally play with the most accurate intonation and that the student group would exhibit the worst intonation. However, this was not observed in this study with all three groups showing averages that were sharp for some intervals and flat for others. The standard deviation is smaller for the professional group on nearly all intervals which indicates that the intonation of the professional players was more consistent across playings. This is
confirmed in Table 5.10 which shows that the professional group played all intervals within a smaller range than the other two groups and suggests that the variation from equal temperament by the professional players may have been intentional.

The perfect fourth interval D4#3-G4 was generally played slightly flatter than the equal temperament value of 500 cents. The note G4 is naturally a sharp note on the horn when played using valves 1 and 2 on the Bb horn. However, if the note is played using valve 3 on the Bb horn, then it will be naturally flat in this context. The fingerings used by each player were not investigated, but it is interesting to see that across all playings, the professional players played this interval sharp (503.9 ± 4.6 cents) whereas nearly all of the playings by the advanced students produced a flat interval (494.1 ± 8.6 cents). Playings by the students were mainly sharp (503.6 ± 8.2 cents), but ranged equally (about 20 cents) above and below the perfect fourth interval.

Overall, no systematic differences between the three different groups have been observed. Thus, it is possible that both the hypotheses stated at the start of this chapter are true and a cancellation effect has occurred. However, no systematic differences, due to feedback conditions, were found across any of the players and hence the lack of differences between groups is more likely due to the inability to measure possible differences with the methodology employed in this study. It is also possible that players have a limited ability to control timbre at constant power or, alternatively, that they can change timbre at constant power, but did not because they were instructed to play in a normal, consistent style. Thus, an experiment in which players are asked to vary the loudness or timbre of the sound may produce very different results.

### 5.4.5 Hand position

Variation in hand position between players was expected and has previously been shown in two surveys of principal horn players in major European orchestras. Hand positions of the players surveyed by Exline (1964-65) are shown in Figure 5.53. As can be seen, the hand shape and position in the bell varies widely and indeed the majority of these positions would be considered ‘wrong’ by many pedagogues, even at that time (e.g. Farkas, 1956). Variations in hand position between players in the recent survey by Phillips (2010) are much more subtle (Figure 5.54) and are more similar to the variations exhibited between players in this study.

In half of the players, movement of the hand in the bell was visible in the video recordings taken from behind the player on the axis of the bell. The different types of movement can be separated into four different categories: 1. Normal movement associated with tuning of specific notes. This type of movement occurred during all feedback conditions (Normal, Flat, Narrowboost, Notch, Lowpass, Headphones) and was exhibited by one player; 2. Abnormal movement associated with repositioning
Figure 5.53: Hand positions for eleven European principle horn players surveyed in 1964-65. (Exline (4 65))
Figure 5.54: Hand positions for twelve European principle horn players surveyed in 2010. (Phillips (2010))
Table 5.10: Range of intonation for different intervals and player groups showing the maximum number of cents sharp (range sharp) and the maximum number of cents flat (range flat) across all playings in each of the three player groups (professional, advanced student and student).

<table>
<thead>
<tr>
<th>Interval</th>
<th>Perfect interval (cents)</th>
<th>Range sharp (cents)</th>
<th>Range flat (cents)</th>
<th>Total range (cents)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pro</td>
<td>Adv</td>
<td>Stu</td>
</tr>
<tr>
<td>Bb4-Bb3</td>
<td>1200</td>
<td>20</td>
<td>57</td>
<td>24</td>
</tr>
<tr>
<td>Bb3-Bb2</td>
<td>1200</td>
<td>34</td>
<td>30</td>
<td>69</td>
</tr>
<tr>
<td>Bb4-Bb2</td>
<td>2400</td>
<td>35</td>
<td>45</td>
<td>67</td>
</tr>
<tr>
<td>D4#1-D4#2</td>
<td>0</td>
<td>16</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>D4#2-D4#3</td>
<td>0</td>
<td>11</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>D4#3-G4</td>
<td>500</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

of hand during playing. This type of movement usually occurred during pauses in playing (such as breathing) and was exhibited by one player. This type of movement could be indicative of a poorly formed or uncomfortable hand position; 3. Movement which occurred only for certain notes in particular feedback conditions. This type of movement generally consisted of a slight opening in hand position, most often for the repeated G4s in the excerpt. However, the movement was only visible during one or two different feedback conditions and not in normal playing (Normal). This type of movement was exhibited by four players; and 4. Change in hand position due to different feedback conditions. This movement of the hand consisted of an opening of the hand position which continued throughout that feedback condition. This was exhibited by one player who also made the following comment afterwards – “I wanted to open my hand a lot more”.

The above comment suggests that this player was aware that she changed her hand position in response to the auditory feedback. However, there is no evidence for the other players to suggest whether the hand movement was conscious or sub-conscious. Surprisingly, no correlations were found between the changes in hand position and the resulting intonation. However, it must be emphasised that all the hand movements exhibited in this study were very small and probably resulted in a small change in tonal colour of the sound which could not be measured. It is also possible that other hand movements occurred during playing which were not able to be captured by the video camera. An interesting study to consider in the future would be a thorough analysis of the hand movement using motion capture which has been previously used to investigate movements related to expression (e.g. Palmer et al., 2009), movements involved in playing an instrument (e.g. Schoonderwaldt and
Demoucron, 2009), and movements due to manipulations in auditory feedback (e. g. Goebel and Palmer, 2009).

5.4.6 Limitations

There were several limitations to this study which could potentially have contributed to the apparent lack of effect due to spectral alterations of the auditory feedback. Firstly, the problems associated with the use of headphones are inherent in most studies involving altered auditory feedback. The inclusion of individualised HRTFs would make the sound location more accurate, but this was not considered necessary as the sound heard was the sound produced by the player (although rerouted through an equalizer) and recorded above the player’s head. Ideally, the sound would have been recorded at the player’s ears, but this was expected to cause interference with the presented sound through the headphones. Thus, a microphone placed just above the centre of the player’s head, was used and then presented in stereo to the player. The use of a monaural recording instead of binaural may have reduced the sound information available to the player.

In the equalizer settings used for each feedback condition, compensation was made for the headphones’ poor response in the low frequencies. However, as Gade (1989a) discusses, the sound heard through headphones can sound unnatural. This unnaturalness was commented upon by one of the players in this study who complained of the sound ‘echoing’ with the headphones on. If the sound was perceived as unnatural by the players, this could result in them ignoring the auditory feedback and focusing on other aspects of their playing, such as muscle memory and bone conducted sound. Of course, it is impossible to remove the direct sound of the instrument, as recognised by Gade (1989a), and thus the effect of manipulating the auditory feedback via headphones may be significantly weakened by the player’s ability to still hear the direct sound. This is especially problematic with loud instruments, such as those in the brass instrument family.

Other limitations due to size of participant group and experiment time restrictions may have impacted the results obtained. Clearly, the larger the sample size, the greater the chance of making statistically significant measurements of small effects. However, more importantly, the necessarily short experiment time needed in order to recruit participants meant that only the bare minimum number of runs could be carried out. Ideally, each feedback condition would have been repeated numerous times, but only two repetitions (and four repetitions for normal playing) were possible. Due to the large intraplayer differences, a greater number of repetitions may have shown trends in the data across feedback conditions that lay outside of normal intraplayer differences.

As mentioned in section 5.4.5, the use of a digital video camera was sufficient to pick up small movements in hand position. However, the use of motion capture
5.4. DISCUSSION

Technology would allow a more detailed analysis of the movement of horn players’ hand positions, even during normal playing.

5.4.7 Summary of findings

- The manipulations in auditory feedback appear to have produced the desired audible effect of subtle changes in acoustic environment for at least one player.

- Intraplayer differences were generally quite large and varied between players. Intraplayer differences were almost as large as interplayer differences for some measures and players.

- Results suggest that players do not make large adjustments to their sound in order to compensate for changes in the acoustic environment. No consistent differences were found for spectral centroid, spectral power, spectral slope or intonation due to the feedback conditions.

- Several players appeared to show changes in spectral centroid and spectral slope due to the wearing of headphones, rather than the auditory feedback received, and these changes were independent from the intensity of the sound.

- Several players increased or decreased the intensity of the produced sound when wearing headphones and this was independent of the received auditory feedback.

- Strong correlations between spectral centroid and spectral power were seen only in some players.

- No systematic differences were found between the professional, advanced student, and student groups. Although, the professional group played all intervals within a smaller range than either of the other two groups.

- Changes in hand position were visible and could be categorised into four types: normal movement associated with tuning of specific notes; abnormal movement associated with repositioning of hand during playing; movement which occurred only for certain notes in particular feedback conditions; and a change in hand position due to different feedback conditions.
Chapter 6

Conclusions and future work

6.1 Overview of findings

Three experiments were carried out over the course of this study on factors affecting the acoustics and playability of the horn, as well as the effect that auditory feedback has on the playing of the horn. In the first experiment, extensive acoustic impedance measurements were made for two horns with various combinations of mouthpieces (3), hands (3), mutes (10) and valve combinations (16). A total of 500 impedance spectra were measured and will form a useful database for horn players seeking explanations of various playing oddities. For this reason, the database will be published on the web. Horn players’ ratings of playability were collected, in the second experiment, for the different hands (3) and mutes (7) on subjective rating scales relating to quality of sound, intonation, ease of playing, accuracy and volume. The third experiment investigated horn players’ responses to playing under conditions of spectrally altered auditory feedback.

Findings from these three experiments have provided new insights into the three research questions raised at the beginning of this study – How does the size, shape and position of the hand affect the acoustics and playability of the horn? What affects the playability of different models of mute? Does the auditory feedback received affect horn playing? Important findings relating to these questions are outlined below.

6.1.1 Hand

Although the importance of ‘correctly’ positioning the right hand in the bell of the horn has been acknowledged by horn players since the advent of hand horn playing several hundred years ago, little research has investigated the effect that different hand shapes and positions have on the acoustics and playability of the horn. The variation in right hand shape and placement in the bell appears to have reduced somewhat between the 1964/5 survey of horn players (Exline, 1964-65) and the
The 2010 survey (Phillips, 2010). The variation in hand position of players involved in this research are comparable to that found in the 2010 survey.

The three different replica hands, used in the impedance and playability studies, produced measurable changes in the input impedance of the horn. These changes correlated well with players’ ratings of quality of sound and intonation. Impedance results showed that Hand 3 tended to have higher amplitude resonance peaks above the ninth resonance, than either of the other two hands. This was considered to be a consequence of Hand 3 being larger and having a more closed shape. Thus, when playing the horn with Hand 3 in the bell, it would be expected that the higher frequency harmonics would be reflected back into the instrument more than when playing with either of the other two hands. If the ratio of high frequency to low frequency harmonics in the radiated sound is lower (as expected for Hand 3), the sound should be considered less bright. This was indeed the case in the playability study which showed that players rated Hand 3 as significantly darker in sound quality than Hand 1.

A qualitative explanation may also be offered for intonation. Although not statistically significantly different, players’ ratings for the intonation of the three hands showed the general tendency for Hand 3 to be considered flatter than either Hand 1 or Hand 2. Several of the notes in the excerpt used for assessing the hands, are normally played on the open Bb horn (Figure 6.1) and a comparison of the resonance peaks corresponding to these notes indicated that Hand 3 produced somewhat lower resonance frequencies (between 5 and 15 cents depending on the resonance) than the other two hands. As this hand belongs to and is used by a horn player

![Notes in excerpt usually played on open Bb horn.](image)

(who presumably does not play flat), it is likely that either he has a different lip property which causes the playing frequency to be higher, or his horn is set up with the tuning slide pushed in further than in this experiment.
Thus, different hands in the bell affect both the frequency and amplitudes of the resonance peaks and players’ ratings of the playability of the horn in terms of quality of sound and intonation. The changes in the impedance spectra can be related to differences in the size, shape and position of the hands in the bell. This is also somewhat the case for the perceived playability of the horn and hand combination.

As observed in the auditory feedback study in which four different types of hand movement were identified, a player’s hand position does not necessarily remain constant whilst playing. Two of these types occurred during normal playing and two appeared to be in response to the auditory feedback heard. The four different types can be classified as:

1. Tuning movement I – a deliberate movement to flatten or sharpen particular notes that are normally out of tune on the instrument or in the context of the music.

2. Extra-musical movement – a systematic repositioning of hand through either habit or discomfort. This type of movement occurs during pauses in the music, but can extend into the playing.

3. Position movement – a subconscious or conscious extended change in hand position in response to the heard sound. This occurred during particular feedback conditions in which the spectral envelope of the sound was manipulated.

4. Tuning movement II – a subconscious or conscious brief change in hand position in response to the heard sound. This only occurred during particular feedback conditions in which the spectral envelope of the sound was manipulated.

Hand movement was not visible in all players and movement did not appear to depend on the level of proficiency of the player.

6.1.2 Mouthpiece

The effect of different shapes and dimensions of horn mouthpieces on the playability and acoustical properties of horn mouthpieces has previously been investigated in detail by Plitnik and Lawson (1999). In the present study, the input impedance of three different mouthpieces, alone and coupled to the horn, were measured. Differences in resonance peak amplitude and frequency between the three mouthpieces related to differences in the impedance spectra when each mouthpiece was coupled to the horn. For example, Mouthpiece 2 had the highest amplitude resonance peak and also tended to have the highest peak amplitudes when coupled to the horn.

The cleanliness of the mouthpiece was found to have a measurable effect on the impedance spectrum. The presence of dirt buildup in the throat and bore of the
mouthpiece tends to decrease the amplitudes of resonance peaks when coupled to the horn. This finding was similar to that by Pratt and Bowsher (1979) for the cleanliness of trombone tubing. The decrease in amplitude of resonance peaks could explain why player’s can notice an improvement in response of the instrument after cleaning of the mouthpiece or instrument’s tubing.

Although the playability of different mouthpieces was not investigated, the use of a single mouthpiece in the playability study meant that none of the players were familiar with the mouthpiece. As a result, players’ ratings were somewhat influenced by the mouthpiece, rather than purely focused on the playability of each of the three replica hands. As Plitnik and Lawson (1999) noted, the mouthpiece is “the single most important component of the instrument.”

6.1.3 Mute

Previous research on horn mutes has been limited to descriptive analyses of different models of mutes (Smith, 1980) or measurements on a single mute (Kurka, 1961, Backus, 1976 and Wachter, 2008). The present study appears to be unique as it investigates the effect of several different models and types of horn mutes on the acoustics and playability of the horn. Large differences were found in the horn impedance spectra when different models of straight mutes and practice mutes were fitted. However, differences between the spectra for the four different models of stopping mute, were very small.

No significant differences in playability were found between any of the stopping mutes. This is consistent with the measured similarities in their impedance spectra. The shape of the stopping mute was found to be of greater influence to the resonance peaks than the material from which the mute was made. For example, the stopping mute which had an added length of cylindrical tubing between the body and bell of the mute, produced a greater difference in the impedance spectrum of the horn than the two geometrically similar mutes made of different materials (wood and brass). The stopping mute introduces an extra resonance into the impedance spectra, so that the third resonance of the horn with stopping mute corresponds to the second resonance of the horn with hand. The difference in frequency of resonance peaks with the stopping mute and the corresponding resonance peaks with the hand were found to differ, from the nominal semitone, depending on the resonance number and the valve combination used.

Results from impedance measurements show that the resonance peaks for the horn with Practice mute 1 were closest in harmonicity to those for the hand. Practice mute 2 had the least harmonic resonance peaks, with low frequency resonances sharper (up to 50 cents) than for the other practice mutes and high frequency resonances flatter (at least 50 cents). Players’ ratings of the intonation of these two practice mutes correlate well with these results. Nearly all players rated Practice
mute 1 as ‘in tune’, whereas some players rated Practice mute 2 as sharp and some rated it as flat. Players also rated Practice mute 2 as significantly more difficult to play and centre pitch than Practice mute 1.

Thus, differences in acoustic properties of mutes, due to different models, are measurable in the input impedance of the horn coupled to the mute and correlate to various subjective ratings of playability.

Stopping mutes greatly increased the spectral centroid of the played sound, without affecting the spectral power. This occurred due to a redistribution of the energy to higher harmonics. Conversely, practice mutes decreased the spectral power of the sound, without much changing the spectral centroid.

6.1.4 Valves

The addition of increasing lengths of valve tubing was found to affect both the amplitudes and harmonicity of resonance peaks. The overall harmonicity of the impedance spectra appear to decrease with increasing length of valve tubing. However, on closer examination, it is found to be only the inharmonicity of the second resonance which is greatly affected. The inharmonicity of the second resonance has previously been illustrated by Chick et al. (2004), but only for selected valve combinations and the phenomenon was not commented upon. If the inharmonicity of the second resonance is excluded, the overall harmonicity of the impedance spectra actually increases slightly with increasing valve tubing length. The second resonance on the open Bb horn is commonly used, but the second resonance for other valve combinations on the Bb horn and F horn is not used in general playing. Thus, the large decrease in harmonicity of the second resonance with increasing valve length is not of great consequence to normal horn playing. However, it may explain the fact that it is very difficult to produce stable notes in the extreme low register using valve combinations other than open Bb horn, as the higher resonances are not harmonically aligned with the second resonance.

6.1.5 Sound spectra

Altering the spectral envelope of the horn player’s auditory feedback did not produce any systematic measurable changes in the sound produced by the players. There were large intraplayer differences which largely obscured differences between players and any potential differences due to changes in the auditory feedback. Not all players showed a strong correlation between spectral centroid and spectral power in their individual playings which suggests that some players may have control over the spectral content of the sound independently to the intensity of the sound produced. This would need to be confirmed in a study involving deliberate variations in sound intensity. The wearing of headphones appeared to affect the sound produced by
several players, but the changes in the spectral envelope of the feedback played through them did not.

6.1.6 Professional vs. student players

The effect of different hands and mutes on the playability of the instrument for professional versus student players was not investigated as all participants in this part of the study were professional horn players. No differences were found between the professional, advanced student and student groups in the sound produced as a result of altering the spectral envelope of the auditory feedback. However, across all playings in all feedback conditions, the variation in size of each interval played by the professionals was smaller than the variation when played by the students.

6.2 Implications for horn playing

The hand shape and position in the bell is of vital importance to the resonances and playability of the horn. As each player’s hand is a different size, each player’s hand will also have a slightly different shape and position in the bell. However, it can be seen that even small differences produce measurable changes in the resonance peaks and thus, it is important to emphasise the development of a suitable hand position, especially in beginning horn players. Small changes in hand position occur during normal playing, usually for intonation purposes, but large extra-musical movements should be discouraged as they can affect the sound produced.

Mouthpiece cleanliness was found to measurably affect the resonance peaks. A dirty mouthpiece caused resonance peaks to decrease in both amplitude and frequency. Thus, a mouthpiece with a lot of built up dirt could result in playing flat and having difficulty centering notes.

Different models of straight and practice mutes have measurably different effects on the resonances of the horn and these can be related to certain aspects of their perceived playability. Possibly the most useful information (to the horn player) is exhibited in the example of how to change the frequencies of resonance peaks on a poor quality mute which has a frequency region around which it is impossible to produce a stable note. As the impedance spectra demonstrate, this unstable playing frequency region is caused by an extra peak interfering with the corresponding resonance. By holding the mute out from the throat of the bell at varying distances, it is possible to change the frequency of the extra peak and thus change the region of playing instability.

Horn players often worry about their acoustic environment – whether they are too close, or too far from the reflecting wall. Do they spontaneously adjust their sound to compensate for changes in the sound due to differences in acoustic environment? The suggestion from this study is that horn players don’t change their sound much,
6.3 Future work

Given that small changes in hand shape or position produce measurable changes in the acoustic response (input impedance) of the horn, further investigation into these variations in hand position over time is warranted. A potential future study might include motion capture of the player’s right hand movement in relation to the bell of the horn. This would allow for a detailed characterisation of the movement of individual horn players’ hands and enable comparisons to be made across different proficiency levels. It would be interesting to carry out a similar study on natural horn players who necessarily change their hand position in order to produce the notes that are not part of the harmonic series.

A detailed acoustic impedance study of the natural horn measured with the different hand positions was attempted in the present study, but inconsistencies in the positioning of a real hand gave unreliable results. As the different hand horn positions are very subtle and the bell is smaller than that of a modern horn, it is difficult for a horn player to accurately reproduce the correct hand position in an unnatural situation. However, if replica hands could be made which accurately reproduce the different hand positions, it would be interesting to compare the harmonicity of different hand positions for the hand horn as a comparison to the harmonicity of different valve tubing lengths.

Unfortunately, due to time and equipment constraints, it was not possible to measure the input impedance of the mutes alone (without being coupled to the horn), but this would provide valuable information that could possibly aid in explaining the presence and frequency of extra peaks which are detrimental to its playability when coupled to the horn.

An investigation into the changes in the sound of the horn when played with a practice mute instead of a hand is of importance to the horn player as it is acknowledged by horn players that extended practising with a practice mute can be detrimental to normal playing. A study involving altered auditory feedback in which
the feedback received is spectrally altered to match that of playing with a practice mute could determine whether practising with a practice mute affects normal playing due to what the player hears, or whether it is purely the difference in feel of playing with a mute which affects the playing.

6.4 Final conclusions

- Replica hands were successfully made which accurately reproduced the size, shape, and playing position of actual horn players’ right hands. Measurable differences were found in the amplitudes and frequencies of resonance peaks due to the different hands and these differences correlated somewhat with players’ ratings of playability for each of the hands.

- Hand position was found to vary during playing for some horn players and four different types of movement were identified. Two types of movement occurred during normal playing and two in response to changes in the auditory feedback received by players.

- The cleanliness of the mouthpiece had a measurable effect on the impedance spectra of the horn, although not as large as the effect of different mouthpieces. Features of the mouthpiece resonance are also apparent in the impedance spectra of the horn coupled to the mouthpiece.

- Measurable differences in the impedance spectra were shown for different models of straight and practice mutes and these differences correlated with players’ ratings of playability for the practice mutes.

- The shape of the stopping mute was found to have a greater effect on the impedance spectrum than the material from which the mute was made, but no consistent differences in playability were evident across players’ ratings.

- Increasing the length of added valve tubing does not decrease the harmonicity of all resonance peaks proportionally. The harmonicity of the second resonance decreases greatly (up to 200 cents) with increasing valve length, whilst the overall harmonicity (excluding the second resonance) actually increases slightly (approximately 8 cents). This increase is not surprising in a well designed instrument, because the average added length due to valves used is greater than zero.

- Sound spectra are greatly affected by playing with mutes rather than the hand in the bell. Stopping mutes increased the average spectral centroid from less than 1 kHz to more than 3 kHz, without greatly affecting the intensity of the sound. Practice mutes were found to decrease the intensity of the sound, but did not greatly change the spectral centroid.
6.4. FINAL CONCLUSIONS

- No systematic measurable differences were found in the sound produced by players when presented with spectrally altered auditory feedback. Although, some players showed differences due to the use of headphones *per se*. Similarly, no differences were found between players of different proficiency levels. However, the professional player group had a smaller variation in the size of all measured intervals than both the student and advanced student player groups.

This thesis has provided new insight into factors affecting the acoustics, playability and playing of the horn and through systematic enquiry has indicated a number of predicted and unpredicted outcomes that add significantly to the research literature on horn acoustics.
Bibliography


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Appendices
Appendix A

Pitch to frequency mapping
Table A.1: Concert pitch (A4=440 Hz), written horn pitch and corresponding frequencies in equal temperament to the nearest Hertz.

<table>
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<tr>
<th>Concert pitch</th>
<th>Written horn pitch</th>
<th>Frequency (Hz)</th>
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<tr>
<td>Bb2</td>
<td>F3</td>
<td>117</td>
</tr>
<tr>
<td>B2</td>
<td>Gb3</td>
<td>124</td>
</tr>
<tr>
<td>C3</td>
<td>G3</td>
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<td>C4</td>
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<td>D4</td>
<td>196</td>
</tr>
<tr>
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<td>Eb4</td>
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Appendix B

Complete set of impedance measurements
Table B.1: Impedance measurements collected for the Professional model horn showing sets of fingerings for various combinations of mouthpiece and hand or mute. See Table 3.1 for fingering notations.

<table>
<thead>
<tr>
<th>Mouthpiece 1</th>
<th>Mouthpiece 2</th>
<th>Mouthpiece 3</th>
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<tbody>
<tr>
<td><strong>Open bell (no hand)</strong></td>
<td>xxxF; xxxBb</td>
<td>xxxF; xxxBb</td>
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<tr>
<td><strong>Hand 1</strong></td>
<td>xxxF; 1xF; x2xF; xxx3F; 12xF; 1xF3; x2xF3; 12xF3; xxxBb; 1xFBb; x2xBb; xxxBb; 1xFBb; x2xBb; x23Bb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
</tr>
<tr>
<td><strong>Hand 2</strong></td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; 1xF; x2xF; 1xF3; x2xF3; 12xF; xxxBb; 1xFBb; x2xBb; xxxBb; 1xFBb; x2xBb; x23Bb; 1xFBb; x2xBb; x23Bb</td>
</tr>
<tr>
<td><strong>Hand 3</strong></td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
</tr>
<tr>
<td><strong>Real Hand 1</strong></td>
<td>xxxF</td>
<td></td>
</tr>
<tr>
<td><strong>Straight mute 1</strong></td>
<td>xxxF; 1xF; x2xF; 1xF3; x2xF3; xxxBb; x2xBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
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<tr>
<td><strong>Straight mute 2</strong></td>
<td>xxxF; 1xF; x2xF; x23F; xxxBb; 1xFBb; x2xBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
</tr>
<tr>
<td><strong>Stopping mute 1</strong></td>
<td>xxxF; 1xF; x2xF; xxx3F; 12xF; 1xF3; x2xF3; 12xF3; xxxBb; 1xFBb; x2xBb; xxxBb; 1xFBb; x2xBb; x23Bb; 1xFBb; x2xBb; x23Bb</td>
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<tr>
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<td><strong>Practice mute 1</strong></td>
<td>xxxF; 1xF; x2xF; 1xF3; x2xF3; xxxBb; x2xBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
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<td>xxxF; 1xF; x2xF; 1xF3; x2xF3; xxxBb; x2xBb; 1xFBb; x2xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
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<td><strong>Practice mute 4</strong></td>
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<td>xxxF; xxxBb; 1xFBb; x2xBb; x23Bb</td>
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</table>
Table B.2: Impedance measurements collected for the Professional model horn showing sets of fingerings for various combinations of mouthpiece and hand or mute. See Table 3.1 for fingering notations.

<table>
<thead>
<tr>
<th>Open bell (no hand)</th>
<th>Mouthpiece 1</th>
<th>Mouthpiece 2</th>
<th>Mouthpiece 3</th>
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<tr>
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<tr>
<td><strong>Hand 1</strong></td>
<td>xxxF; 1xxF; x2xF; xx3F; 12xF; 1x3F; x23F; 123F; xxxBb; 1xxBb; x2xBb; xx3Bb; 12xBb; 1x3Bb; x23Bb; 123Bb</td>
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<tr>
<td><strong>Hand 2</strong></td>
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<td>xxxF; 1xxF; x2xF; xx3F; 12xF; x23F; 123F; xxxBb; 1xxBb; x2xBb; xx3Bb; 12xBb; 1x3Bb; x23Bb; 123Bb</td>
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<tr>
<td><strong>Hand 3</strong></td>
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<td>xxxF; 1xxF; x2xF; xx3F; 12xF; x23F; 123F; xxxBb; 1xxBb; x2xBb; xx3Bb; 12xBb; 1x3Bb; x23Bb; 123Bb</td>
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<tr>
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<td>xxxF</td>
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<tr>
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<td>xxxF; xxxBb; 1xxBb; x2xBb; 12xBb; x23Bb</td>
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<td><strong>Practice mute 3</strong></td>
<td>xxxF; xxxBb; 1xxBb; x2xBb; 12xBb; x23Bb</td>
<td>xxxF; xxxBb; 1xxBb; x2xBb; 12xBb; x23Bb</td>
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<td><strong>Practice mute 4</strong></td>
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<td>xxxF; xxxBb; 1xxBb; x2xBb; 12xBb; x23Bb</td>
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Appendix C

Impedance spectra
Figure C.1: Representative impedance spectra for a hand, straight mute, stopping mute and practice mute in bell of horn for open F horn and all valve combinations.
Figure C.2: Representative impedance spectra for a hand, straight mute, stopping mute and practice mute in bell of horn for open Bb horn and all valve combinations.
Appendix D

Alternative fingerings: Student horn
Figure D.1: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of the student model horn with Hand 1 in bell with valve combinations xxxF and 1x3Bb.

Figure D.2: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of the student model horn with Hand 1 in bell with valve combinations xx3F and 12xF.
Figure D.3: Magnitudes (left) and variation in frequency from harmonicity (right) of resonance peaks of the student model horn with Hand 1 in bell with valve combinations xx3Bb and 12xBb.
Appendix E

Valves: Bb horn
Figure E.1: Magnitudes of resonance peaks for open Bb horn (xxxBb) and all valve combinations with Hand 1 in bell for professional model horn.
Figure E.2: Magnitudes of resonance peaks for open B♭ horn (xxxBb) and all valve combinations with Hand 1 in bell for student model horn.
Figure E.3: Variation in frequency of resonance peaks from harmonicity for open Bb horn (xxxBb) and all valve combinations with Hand 1 in bell for professional model horn.
Figure E.4: Variation in frequency of resonance peaks from harmonicity for open Bb horn (xxxBb) and all valve combinations with Hand 1 in bell for student model horn.
Appendix F

Valves: Straight and practice mutes
Figure F.1: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Straight mute M1 in bell of professional model horn.
Figure F.2: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Straight mute M2 in bell of professional model horn.
Figure F.3: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Practice mute P1 in bell of professional model horn.
Figure F.4: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Practice mute P2 in bell of professional model horn.
Figure F.5: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Practice mute P3 in bell of professional model horn.
Figure F.6: Variation in frequency of resonance peaks from harmonicity for open F horn (xxxF), open Bb horn (xxxBb) and various valve combinations with Practice mute P4 in bell of professional model horn.
Appendix G

Stopping mute: Comparison with Wachter (2008)
Figure G.1: Impedance spectra for open F horn (xxxF) with open bell and stopping mute in bell.

Figure G.2: Impedance spectra for open F horn (xxxF) with open bell and stopping mute in bell. (Wachter, 2008)
Figure G.3: Impedance spectra for open Bb horn (xxxBb) with open bell and stopping mute in bell.

Figure G.4: Impedance spectra for open Bb horn (xxxBb) with open bell and stopping mute in bell. (Wachter, 2008)
APPENDIX G. STOPPING MUTE: COMPARISON WITH?

Figure G.5: Impedance spectra for open F horn (xxxF) and all valve combinations with stopping mute in bell.

Figure G.6: Impedance spectra for open F horn (xxxF) and all valve combinations with stopping mute in bell. (Wachter, 2008)
Figure G.7: Impedance spectra for open Bb (xxxBb) horn and all valve combinations with stopping mute in bell.

Figure G.8: Impedance spectra for open Bb horn (xxxBb) and all valve combinations with stopping mute in bell. (Wachter, 2008)
Appendix H

Hand: Comparison with Wachter (2008)
Figure H.1: Impedance spectra for open F horn (xxxF) and all valve combinations with hand in bell.

Figure H.2: Impedance spectra for open F horn (xxxF) and all valve combinations with hand in bell. (Wachter, 2008)
Figure H.3: Impedance spectra for open Bb horn (xxxBb) and all valve combinations with hand in bell.

Figure H.4: Impedance spectra for open Bb horn (xxxBb) and all valve combinations with hand in bell. (Wachter, 2008)
Appendix I

Instructions to participants and surveys
Information Sheet: Setups

As a participant in this experiment, you will be asked to:

- Play a chromatic scale and an excerpt from Ravel’s Piano Concerto in G major, using six different setups (combinations of mouthpiece and hand).
- Play the scale and excerpt as you would normally (but without vibrato) and as consistently as possible across each playing.
- Provide written feedback after playing.

Information Sheet: Mutes

As a participant in this experiment, you will be asked to:

- Play chromatic scales, a stopped excerpt from Tchaikovsky’s Symphony No. 6, and an excerpt from Tchaikovsky’s Symphony No. 5 on the provided horn, mouthpiece and mutes.
- Play the scales and excerpts for each different mute, as indicated on the excerpt sheet.
- Play the scale and excerpt as you would normally (but without vibrato) and as consistently as possible across each playing.
- Provide written feedback after playing.
- Complete a listener survey (whilst the other participants are playing).

Sound recordings will be made for analysis.

Figure I.1: Instructions given to participants prior to playing with the different hands and mutes.
Player Survey: Setups

Your name

Please make a judgement on the quality of sound, intonation, and ease of playing of each of the setups and compare them to playing with your own mouthpiece and hand (setup 1).

Please place a line on the scale in the place which best indicates your response. Please feel free to also write comments.

Setup 2

Quality of sound:

- Brighter
- No Difference
- Darker

Intonation:

- Sharper
- No Difference
- Flatter

Ease of playing:

- Easier
- No Difference
- Harder

Figure 1.2: Player survey for hands (p. 1).
Listener/Player Survey: Mutes

Your name

Your email or mail address (if you would like us to send you results of this study)

As a listener to the other players, please make a judgement on the quality of sound, intonation, and volume of different mutes as they are played. You are NOT being asked to judge or comment on the player’s musicality or interpretation of the excerpts.

As a player, please make a judgement on the quality of sound, intonation, volume, accuracy and ease of playing of each of the different mutes.

For each mute (S1, S2, S3 for stopping mutes and P1, P2, P3, P4 for practice mutes), please write the mute number on the scale in the place which best indicates your response. Please feel free to also write comments.

Example: here is how someone might rate the stopping mutes for one player

Do you own a practice mute? If so, what is the make?

How often do you use a practice mute?
Player 1: Stopping Mutes (S1, S2, S3)

Quality of sound:
Dark ——> Bright

Intonation:
Flat ——> In tune ——> Sharp

Volume:
Soft ——> Loud

Accuracy (if you are the player):
Difficult to centre pitch ——> Easy to centre pitch

Ease of playing (if you are the player):
Difficult ——> Easy

Player 1: Practice Mutes (P1, P2, P3, P4)

Quality of sound:
Dark ——> Bright

Intonation:
Flat ——> In tune ——> Sharp

Volume:
Soft ——> Loud

Accuracy (if you are the player):
Difficult to centre pitch ——> Easy to centre pitch

Ease of playing (if you are the player):
Difficult ——> Easy
Appendix J

Channel comparisons
Figure J.1: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of scale played in Flat.

Figure J.2: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of scale played in Narrowboost.
Figure J.3: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of scale played in Notch.

Figure J.4: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of scale played in Lowpass.
Figure J.5: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of excerpt played in Flat.

Figure J.6: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of excerpt played in Narrowboost.
Figure J.7: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of excerpt played in Notch.

Figure J.8: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 1 showing FFT (above) and waveform (below) of excerpt played in Lowpass.
Figure J.9: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of scale played in Flat.

Figure J.10: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of scale played in Narrow-boost.
Figure J.11: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of scale played in Notch.

Figure J.12: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of scale played in Lowpass.
Figure J.13: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of excerpt played in Flat.

Figure J.14: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of excerpt played in Narrowboost.
Figure J.15: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of excerpt played in Notch.

Figure J.16: Comparison of channels 1 (direct sound), 2 (head), and 3 (head+EQ) for Player 7 showing FFT (above) and waveform (below) of excerpt played in Low-pass.
Appendix K

Sound spectra
Figure K.1: Sound spectra and spectral envelopes for all playings of the scale by Player 1.
Figure K.2: Sound spectra and spectral envelopes for all playings of the scale by Player 2.
Figure K.3: Sound spectra and spectral envelopes for all playings of the scale by Player 3.
Figure K.4: Sound spectra and spectral envelopes for all playings of the scale by Player 4.
Figure K.5: Sound spectra and spectral envelopes for all playings of the scale by Player 5.
Figure K.6: Sound spectra and spectral envelopes for all playings of the scale by Player 6.
Figure K.7: Sound spectra and spectral envelopes for all playings of the scale by Player 7.
Figure K.8: Sound spectra and spectral envelopes for all playings of the scale by Player 8.
Figure K.9: Sound spectra and spectral envelopes for all playings of the scale by Player 9.
Figure K.10: Sound spectra and spectral envelopes for all playings of the scale by Player 10.
Figure K.11: Sound spectra and spectral envelopes for all playings of the scale by Player 11.
Figure K.12: Sound spectra and spectral envelopes for all playings of the scale by Player 12.
Figure K.13: Sound spectra and spectral envelopes for all playings of the excerpt by Player 1.
Figure K.14: Sound spectra and spectral envelopes for all playings of the excerpt by Player 2.
Figure K.15: Sound spectra and spectral envelopes for all playings of the excerpt by Player 3.
Figure K.16: Sound spectra and spectral envelopes for all playings of the excerpt by Player 4.
Figure K.17: Sound spectra and spectral envelopes for all playings of the excerpt by Player 5.
Figure K.18: Sound spectra and spectral envelopes for all playings of the excerpt by Player 6.
Figure K.19: Sound spectra and spectral envelopes for all playings of the excerpt by Player 7.
Figure K.20: Sound spectra and spectral envelopes for all playings of the excerpt by Player 8.
Figure K.21: Sound spectra and spectral envelopes for all playings of the excerpt by Player 9.
Figure K.22: Sound spectra and spectral envelopes for all playings of the excerpt by Player 10.
Figure K.23: Sound spectra and spectral envelopes for all playings of the excerpt by Player 11.
Normal 3rd playing

Magnitude vs Frequency (Hz)
Figure K.24: Sound spectra and spectral envelopes for all playings of the excerpt by Player 12.
Appendix L

Intonation of intervals
Figure L.1: Intonation of intervals in scale and excerpt across feedback conditions for Player 1.
Figure L.2: Intonation of intervals in scale and excerpt across feedback conditions for Player 2.
Figure L.3: Intonation of intervals in scale and excerpt across feedback conditions for Player 3.
Figure L.4: Intonation of intervals in scale and excerpt across feedback conditions for Player 4.
Figure L.5: Intonation of intervals in scale and excerpt across feedback conditions for Player 5.
Figure L.6: Intonation of intervals in scale and excerpt across feedback conditions for Player 6.
Figure L.7: Intonation of intervals in scale and excerpt across feedback conditions for Player 7.
Figure L.8: Intonation of intervals in scale and excerpt across feedback conditions for Player 8.
Figure L.9: Intonation of intervals in scale and excerpt across feedback conditions for Player 9.
Figure L.10: Intonation of intervals in scale and excerpt across feedback conditions for Player 10.
Figure L.11: Intonation of intervals in scale and excerpt across feedback conditions for Player 11.
Figure L.12: Intonation of intervals in scale and excerpt across feedback conditions for Player 12.
Appendix M

Conference paper
The effect of hand and mute on the impedance spectra of the horn

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ABSTRACT

The effects of different horn players’ hand shapes and positions, and the effects of different mutes were quantified by the input impedance spectrum \( Z \) and related to players’ and listeners’ perceptions. \( Z \) was measured using a three microphone, two calibration technique for combinations of a horn with three different hands, four different practice mutes and representative fingerings, complete for some sets. The hands were casts of real players’ hands which could be reinserted with a typical reproducibility in the magnitude and frequency of peaks in \( Z \) of 0.1 dB and 0.4 Hz rms variation in independent measurements. Different hand configurations showed reproducible, measurable changes in \( Z \), with an rms difference in the amplitude and frequency of the impedance peaks 1 to 20 of up to 0.8 dB and 0.6 Hz, respectively. The relative magnitudes and the harmonicity of the peaks were measurably different for practice mutes compared to that for an average hand. Frequency differences in the \( Z \) spectrum correlated well with player’s perceptions of the intonation of the instrument.

INTRODUCTION

An important part of playing the horn is the placement of the player’s right hand in the bell of the instrument. Players note that different hand positions and shapes affect the pitch, loudness and timbre of notes played—and use the effects musically. Hand positions and shapes are also expected to affect transfer functions, including the input impedance spectrum \( Z \). Backus (1976), Benade (1976) and Widholm (1988) have shown that without the hand in the bell, impedance peaks above 450 Hz are greatly diminished in magnitude and disappear entirely above 750 Hz. The frequencies of peaks in \( Z \) strongly influence playing pitches (1), and the magnitudes of the peaks, as well as the harmonicity of sets of peaks, have some correlation with ease of playing particular notes. Although horn players do not generally play notes above 700 Hz (sounding F5), they are often asked to play notes between 450 and 550 Hz (A4 to D5). Further, impedance peaks falling near higher harmonics of the notes played are involved in the playing regime. These observations all suggest that the measured changes in \( Z \) due to hand shape and position could be related to players’ assessments of playability and other properties of the instrument-hand combination.

An important accessory for a horn player is a practice mute: a mute designed not for performance, but to make practice less disturbing for neighbours and cohabitants. Practice mutes range from elaborate models incorporating a feedback system to the player via headphones, to improvised arrangements. As players often spend many hours with such mutes, ideally the performance of a horn with such a mute should approximate that of the horn played normally with a hand. Of course, an object whose purpose is to diminish radiation from the bell will usually affect reflection back into the bore, so effects on the impedance spectrum are expected.

The relation between impedance peaks and playing frequency for a lip-reed instrument has previously been investigated using simplified models (e.g. Fletcher, 1993). For acoustic loads having a sharp resonance with large acoustic impedance, the operating frequency is close to the impedance peak. But what is the acoustic load? Benade (1985) made a simple model of the load on an autonomous valve using continuity of volume flow and assuming that the acoustic pressures on the up- and down-stream sides of the valve acted on equal area. He showed that the impedance loading the reed (\( Z_{\text{valve}} \)) is

\[
Z_{\text{valve}} = \frac{Z_{\text{valve}} + Z_{\text{load}}}{2} \| Z_{\text{load}}. \tag{1}
\]

Further approximations are also commonly made: firstly, that the impedance of the reed (\( Z_{\text{valve}} \)) is very much larger than that of the vocal tract (\( Z_{\text{tract}} \)) and the bore (\( Z_{\text{bore}} \)), giving the effective load as approximately the series impedance \( Z_{\text{tract}} + Z_{\text{load}} \); secondly, that \( Z_{\text{valve}} \) is very much smaller than \( Z_{\text{tract}} \), giving the simplest model, in which the effective load is simply \( Z_{\text{tract}} \). The playing frequency, based on a simple model for autonomous oscillators (Fletcher, 1993), depends on the impedance of the acoustic load, the valve’s geometry and natural frequency, and the applied pressure. Few experiments have investigated the acoustic load for lip reeds. Chen, Smith & Wolfe (2009) measured the three components independently and showed that clarinet-player-reed systems operate very close to the peak in (1) under some conditions. So far, published measurements of the impedance of players’ vocal tracts for lip-reed instruments during performance appear to be confined to the didjeridu (Tarnopolsky et al., 2005, 2006).
However, model studies and some unpublished results using trombones show a small but musically important effect due to the impedance of the vocal tract (Wolfe et al., 2003).

In the present study, the impedances of the reed and vocal tract were not measured, but it is expected that they vary considerably over the range of the instrument. It is also quite likely that players adjust them, either consciously or subconsciously, to control tuning and perhaps timbre, although these were not investigated. For comparisons among hands and mutes however, we expect that neglecting such variations will, at worst, result in the differences measured being under-estimates of the effects that might be measured in the absence of the auditory feedback which is inevitably used by musicians.

To date, in the literature, there are no studies investigating the impedance spectra of the horn with different hands or practice mutes in the bell (although Chick et al. (2004) measured the accuracy of replacing the same hand in the bell). This study aims to begin to address this gap and also correlate findings with players’ subjective responses of playing with different hands and practice mutes.

MATERIALS AND METHODS

The horn used was a professional model Yamaha 668 double horn and the mouthpiece was a Marcinkiewicz Model No. 7. The practice mutes measured were Yamaha Silent Brass (practice mute 1), Denis Wick practice mute (practice mute 2), Humes & Berg Silenced Sh! Sh! Practice mute (practice mute 3), and Trumcor Stealth #5 (practice mute 4).

Replica Hands

Replicas of the right hands of three horn players were cast in Perma-Gel, a commercially available synthetic ballistics gelatin. The replica hands were designed to imitate the exact shape and playing position of an individual player’s hand (Figure 1) and to approximate the acoustic properties of a human hand. These were positioned in the bell using a system of stays mounted to the bell in marked positions (Figure 2). Replica hands were used, rather than actual players’ hands, to control for shape and position, and to allow for many Z measurements to be made with no geometrical changes.

Impedance Measurements

Acoustic impedance measurements were made using the three microphone, two calibration technique (Dickens, Smith & Wolfe, 2007). Measurements were made with representative fingerings (complete for some sets) on both sides of the horn (F and Bb) with various practice mutes or replica hands in the bell (Figure 2).
Figure 4. Impedance spectra for the open F horn with and without hand in bell, illustrating the effect of the hand on the cutoff frequency of the bell.

Figure 5. Impedance spectra for the open Bb horn with and without hand in bell.

When the same setup (horn, mouthpiece, and replica hand) was measured in independent trials, the rms difference in the amplitude and frequency of the impedance peaks 1 to 20 was 0.1 dB and 0.4 Hz, respectively. The different replica hands (with the same horn and mouthpiece) showed reproducible, measurable changes in $Z$, with an rms difference in the amplitude and frequency of the impedance peaks 1 to 20 of up to 0.6 dB and 1.3 Hz, respectively. Differences in amplitudes of resonance peaks for the open Bb horn and the three different hands (Figure 6) are apparent above the third resonance (175 Hz) and are greater above the eighth resonance (460 Hz).

Figure 6. Amplitudes of resonance peaks for an open Bb horn with three different hands in the bell. (Error bars typically within size of symbol).

Thus the effects of different hand shapes and playing position on the amplitudes and frequencies of the impedance spectra of the horn correlate well with intonation.
Practice Mutes

As mentioned above, an ideal practice mute would simply reduce radiation from the bell of the horn without changing playing properties. This would require a low transmission coefficient with a reflection coefficient that was unchanged across all frequencies. As Figure 9 shows, the shape of the impedance spectrum changes when the hand is replaced with a practice mute. The amplitudes of low frequency resonances are lowered and the amplitudes of high frequency resonances are raised. There is also a measurable frequency shift which decreases the harmonicity of the resonance peaks.

Figure 9. Impedance spectra for valve 1, F horn with hand in bell and practice mute in bell.

The relative amplitudes of the resonance peaks for the practice mutes were measurably different to those for a hand (Figure 10) and also differed markedly among practice mutes.

The frequencies of resonance peaks also differed between the hand and practice mutes (Figure 11). Although the first resonance has a very large variation, this is of little musical significance as it is not used, except for exotic effects. Figure 11 shows that practice mute 1 is closest to the hand in its harmonicity and practice mute 2 is the least harmonic, with resonances 2 and 3 sharper than for the other mutes and resonances 6 to 17 flatter than for the other mutes. This correlates well with players’ judgements of intonation for each of the mutes, as four out of the five players (who answered this question) rated practice mute 1 as ‘in tune’ whilst practice mute 2 was considered flat by three players and sharp by the other two players.

Figure 10. Amplitude of resonance peaks for valve 1, Bb horn with hand in bell and four different practice mutes in bell. (Error bars typically within size of symbol).

Results from Z measurements quantify the change in response of the horn when a practice mute is substituted for a hand. Further, each different practice mute measured affected the amplitudes and frequencies of the resonance peaks to a greater or lesser extent. For horn players who use practice mutes often, this could potentially impact the way they play because of the intonation changes, and because of the way they change the response in the high range.

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