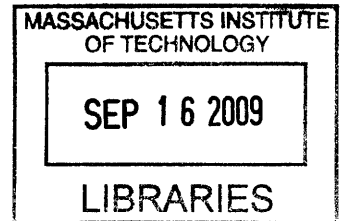


Variation of French Horn Timbre over the Frequency and Intensity
Range of the Instrument

By

Kathryn E. Shroyer



SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL
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Submitted to the Department of Mechanical Engineering
on May 21, 2009 in Partial Fulfillment of the
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ABSTRACT

Timbre describes the perceptual difference between sounds with the same loudness and pitch generated from different sources such as different instruments. Each instrument has its own unique timbre making it distinguishable. Within each instrument however, this timbre changes slightly with respect to frequency and intensity of sound. This is perceived qualitatively by the use of words such as “bright”, “mellow”, “harsh” and many others to describe sounds of different intensity or frequency in a given instrument. However, this is only a subjective view and does not describe what changes in the acoustic properties produce these different timbres. This study quantitatively examined the change in timbre over the frequency and intensity range of the French horn. Two main acoustical properties were measured: number of frequency partials and shape of the spectral envelope, where “partials” refers to harmonics of the fundamental frequency. The parameter represented by the number of partials includes both the total number of partials as well as the number of partials with critical band overlap. The shape of the spectral envelope was characterized through its center frequency and width of the major peaks as well as the strength of the fundamental frequency. Each of these parameters was related to qualitative timbre descriptions such as “fullness” or “roughness”. The results showed a significant change in timbre over the frequency and intensity range of the French horn. The extremes of French horn span from timbre that is “thin” and “smooth” to “rich” and “rough”. Within this spectrum, low frequency notes and high intensity sounds lie at one end exhibiting “rich” and “rough” timbre. The high frequency and low intensity sounds lie at the other extreme exhibiting “thin” and “smooth” timbre. As frequency increases and intensity decreases the number of partials decreases and the spectral contour shifts from wide and flat to a strong narrow peak. This produces a timbre shift from sounds that seem “rough” and “rich” to those that seem “smooth” and “thin”.

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1 Introduction

What is it that allows us to recognize the wide variety of different sounds in our environment? The sound of a French horn, for example, is immediately recognizable from that of a piano, or even a similar instrument such as a trumpet, but what is it that makes this possible? It is well understood that we perceive acoustical characteristics such as frequency and intensity as pitch and loudness, respectively, but there are many other characteristics as well that influence how we perceive a sound. Timbre, also commonly known as tone color, is the perceptual quality used to describe the difference heard in sounds played at the same pitch and loudness.

Each instrument has a specific timbre that allows its sound to be recognized as unique and distinguishable from other instruments. This will be referred to as large scale timbre as it is a characteristic that remains invariant over the frequency and intensity range of the instrument. For example, whether a French horn is playing soft low notes or loud high notes, the sound is still recognizable as coming from a French horn. There is however a subtle difference in character between these notes. On the French horn, notes played in the lower register are often characterized as “muddy” and “dark” while the middle register usually sounds “mellow” and the higher register “bright”. Similar words are used to note the timbre change between soft and loud notes as well. These qualitative descriptions of small scale timbre suggest that the timbre is somehow changing over the frequency and intensity range of the instrument. However, they do not give much quantitative information about how or why this is happening.

In this study, the change in small scale timbre over frequency and intensity was examined for the French horn. The timbre change was quantitatively measured by recording sets of long tones of different frequency and intensity. Timbre was then linked to characteristics of the spectra of these notes. Two main acoustical properties of the sound spectra were observed; number of partials and shape of the spectral envelope. The change in these characteristics was then related to two qualitative timbre ranges; “rough” to “smooth” and “full” to “thin”. By describing the timbre shift over varying frequency and intensity, the physical mechanism for creating these timbres can be discovered. This can aid in instrument modification or construction to achieve specific timbres.

The ability to understand the acoustic characteristics that result in timbre changes can provide a means to make instrument design more scientific. While it is clear that people desire certain timbres it is not always clear how to achieve them. For example, Stradivarius violins are highly valued for their beautiful sound, but it is not well understood why this craftsmanship created such a desirable timbre. Many studies have been performed to understand what acoustical elements produced such a distinctive sound so that it could be reproduced. However, most musical instrument construction today depends heavily on tradition rather than exact science. As more is known about instrumental acoustics a more systematic approach to producing a desired timbre can be implemented.

2 Relevant Acoustics and Psychoacoustics

There are three main topics that are essential in understanding the results of this experiment; complex waves and frequency spectra, sound perception, and instrumental acoustics. The sound produced from instruments is a complex periodic wave. Different acoustical characteristics can be measured by examination of this waveform as well as its frequency spectrum. These characteristics are used to measure and track the quantitative changes in the notes played on the horn.

Sound perception is extremely important in understanding how we perceive changes in timbre because our perception does not directly relate to the physical characteristics that can be measured from the sound wave. For example loudness changes with respect to frequency if intensity is kept the same. Finally, instrumental acoustics are important in determining how some of the characteristics of large scale timbre are created. For example the method of creating sound has a great effect on the resulting acoustical characteristics of that sound, explaining the large difference in timbre between a piano, in which a string is struck by a hammer, and a violin, in which the string is pulled with a bow.

2.1 Complex Waves and Frequency Spectra

Due to the periodic nature of sound it is often useful to examine its frequency spectrum. According to the Fourier series, complex waveforms can be described by a sum of sinusoids for all frequencies each containing a specific amplitude and phase. The sound can therefore be decomposed into these parts and the amplitude and phase of each frequency component can be determined. This is known as the sound's frequency spectra. Fourier determined that a waveform could be completely defined by amplitudes and phases of a harmonic series. Later Ohm's acoustical law stated that the ear was phase deaf. Ohm presumed that if two sounds were presented to the ear with the exact same amplitudes but different phase components for each frequency component the ear would not be able to tell the difference.¹ Later research demonstrated that the ear is not actually phase deaf and that the changing phase relationship between the harmonics can alter the timbre. The contribution of phase however is typically so weak that it is inaudible and is made even more so by any reverberance in the room.² Therefore, it is appropriate to only consider the amplitude when examining the Fourier spectrum.

The frequency spectrum of a sound depends greatly on how the sound is produced. Tonal instruments have very specific and recognizable spectra often referred to as the harmonic series because they rely on simple harmonic oscillators such as strings and vibrating air columns. The harmonic series is a frequency spectrum that contains only whole number multiples of the fundamental frequency. This is well demonstrated by a string fixed at both ends. When the center of the string is displaced a standing wave occurs with a wavelength that is twice the length of the string. The boundary conditions of the string are still met when nodes appear in the

¹ Diana Deutsch, ed. *The Psychology of Music*. 2nd ed. (San Diego: Academic Press, 1999) 114.

² Deutsch, 115.

middle of the string. This allows the string to vibrate not only at the fundamental, but also whole number multiple of it. Figure 1 shows the harmonic series for vibrations in a string fixed at both ends.

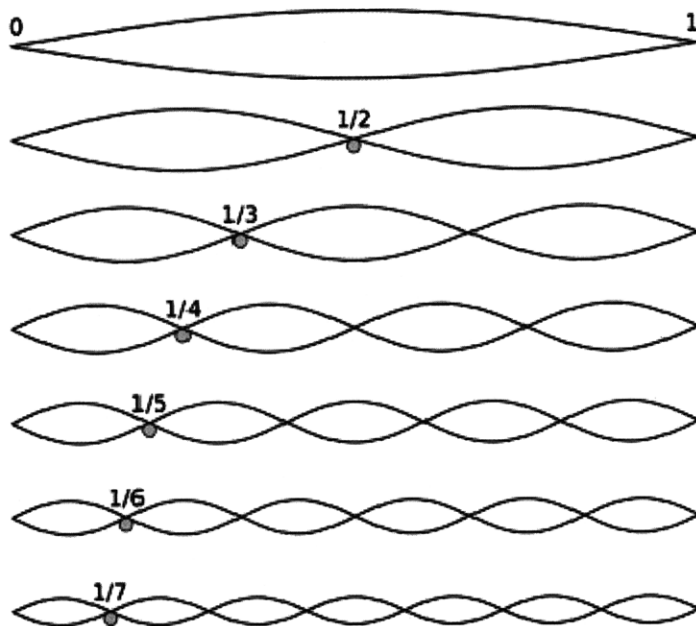


Figure 1: Standing waves in a string fixed at both ends. Each harmonic is a whole number multiple of the first harmonic (fundamental frequency).³

Standing waves can also appear in columns of air as well. Here the waves are longitudinal rather than transverse but the results are similar. Wind and brass instruments employ a tube that is open at the bottom but closed at the top where the reed or mouthpiece is attached. The boundary conditions dictate that at the open end the air pressure is atmospheric but at the closed end there is a pressure maximum. Like in the string, these boundary conditions allow for standing waves with different numbers of nodes to occur. Figure 2 shows the pressure waves in a tube opened at one end and closed at the other.

³“Fiddle Physics” <<http://www.physicscentral.com/explore/action/images/string.gif>>

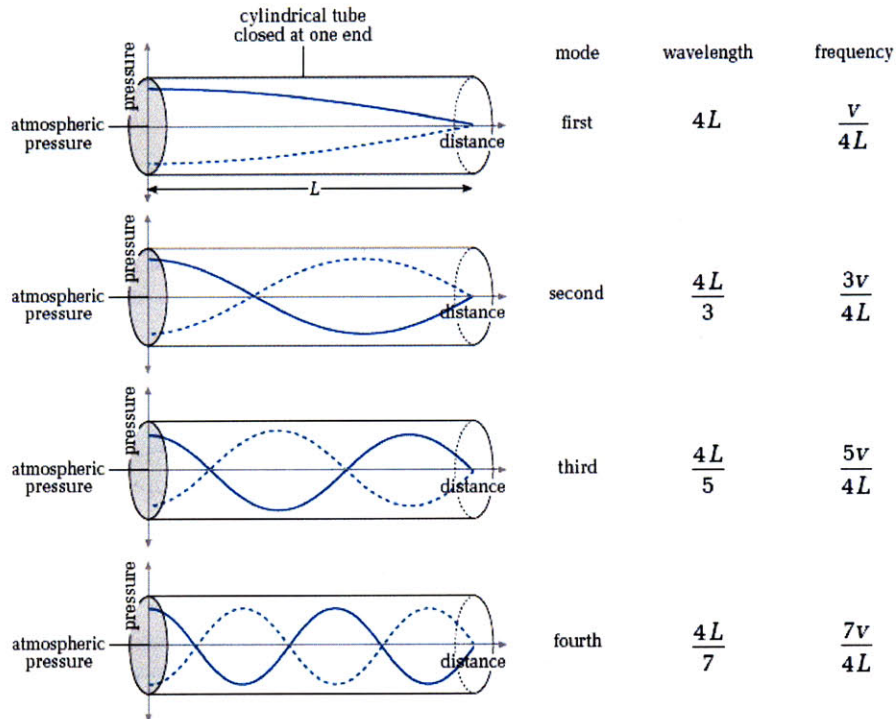


Figure 2: Standing waves in a tube open at one end and closed at the other.⁴

Different disciplines use varying terminology to refer to the frequency components of a sound spectrum. **Partial** is the most general term, referring to any of the sine waves that describe the complex waveform.⁵ A **harmonic** is a partial that is a whole number multiple of the fundamental frequency.⁶ Anharmonicity measures how far a partial is from the nearest harmonic.⁷ Tonal pitched instruments that operate based on strings or air columns are designed to produce partials with very little anharmonicity. It is therefore common to hear the partials for tonal pitched instruments all described as harmonics even if they contain some anharmonicity. Percussion instruments such as the marimba or timpani contain non-harmonic partials. Non-pitched instruments such as the cymbal or gongs produce sounds with many anharmonic partials. The French horn contains predominantly harmonic partials because it employs a vibrating column of air. It is therefore appropriate to use either the term partial or harmonic to refer to the frequency components. One other term to be aware of is **overtone**. Overtone refers to any partial except the lowest.⁸ In harmonic instruments such as the French horn, overtones and harmonics refer to the same frequencies, but the numbering system is different. The fundamental frequency is referred to as the first harmonic or the first partial. However, the first overtone is the second partial (or second harmonic) so careful attention must be paid to which terminology is

⁴ "Primary Vibrators" Learning Space, <<http://openlearn.open.ac.uk/mod/resource/view.php?id=289491>>

⁵ Harry Olson, *Music, Physics, and Engineering* 2nd ed. (New York: Dover Publications, 1967) 36.

⁶ Olson 36.

⁷ Donald E. Hall, *Musical Acoustics* 3rd ed. (Pacific Grove: Brooks/Cole, 2002) 8.

⁸ Olson 36.

being used. For the remainder of this document, partial will be used to refer to the harmonics of the fundamental frequency, where the latter is also referred to as the “first partial”.

Two important characteristics of the frequency spectrum were measured and related to qualitative timbre; number of partials and shape of the spectral envelope. Number of partials refers to how many different frequency components contribute to the sound. The spectral envelope refers to the relative strength of the partials. The envelope is therefore a contour of the discrete frequency spectrum that shows how the strength of different frequencies varies. The frequency spectra for F3 played at an intermediate intensity is shown in figure 3.

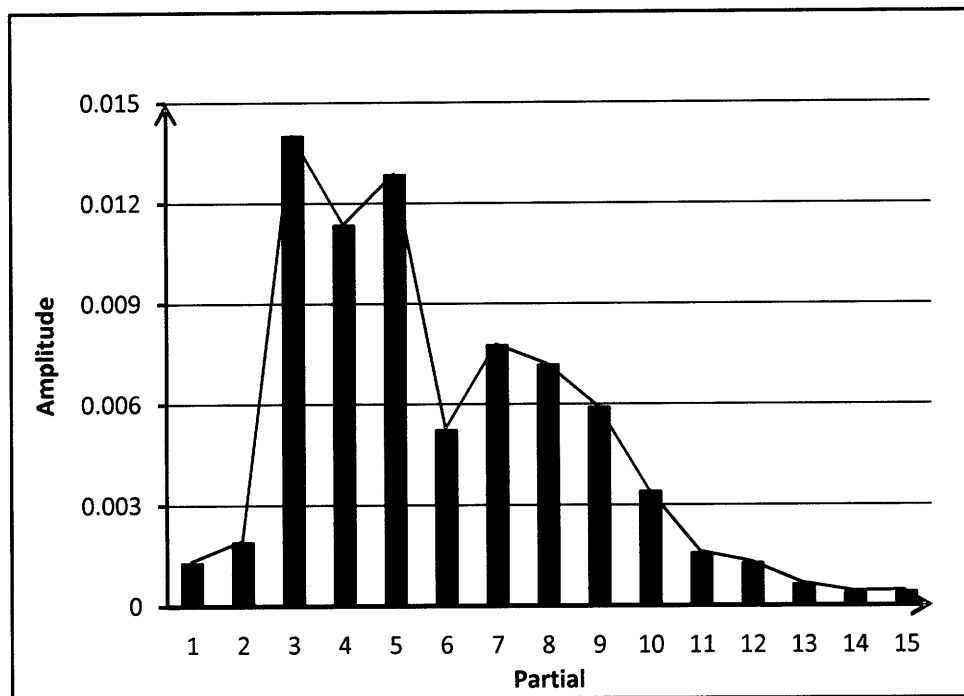


Figure 3: Frequency spectrum for the F3, the lowest note recorded. The spectral envelope is indicated by the thin black line connecting the frequency components.

When measuring the number of partials attention must be paid to which partials have amplitudes that are significant. As seen in figure 3, the thirteenth, fourteenth, and fifteenth partials are significantly less intense than the lower order partials. For this study, only partials with amplitudes of two percent or greater of the amplitude of the largest partial were included.

Measuring the spectral envelope is more complicated. The envelope was broken up into three main features that could be related back to qualitative timbre; the center of the spectral peak, the width of the peak, and the strength of the fundamental frequency peak. Figure 3 shows one of the most complicated frequency spectra obtained in the course of this research. It exhibits two spectral peaks centered at the fourth and eighth partial that overlap at the sixth partial. The position of these peaks was recorded as an acoustic factor contributing to timbre. The location of the partial with the largest amplitude was also recorded and monitored over changing frequency and intensity.

The envelope width was defined from the number of partials falling within fifty percent and twenty-five percent of the maximum amplitude. Finally, the third parameter defined from the spectral envelope is the strength of the fundamental frequency. In figure 3, it is evident that for this low note the fundamental and second partial are very weak. The strength of the fundamental was defined as a percentage of its amplitude to that of the strongest partial.

2.2 Sound Perception

There are three main aspects typically used to describe instrumental sound; pitch, loudness, and timbre. These are all psychoacoustic properties that are perceptions based on physical characteristics of sound. The perception of pitch, for example, is fairly well correlated to the physical frequency of a note. While related, pitch and frequency are not exactly the same. Pitch is a relative measure while frequency is absolute. The pitch A is typically tuned somewhere between 440 and 443 Hz in different groups. Pitch is also a function of how the ear perceived frequency. For example, tone bursts shorter than 2 to 4 cycles long will be heard as clicks rather than tones with pitch.⁹ Loudness in a similar way strongly correlates to the intensity of a sound. Again however they are not the same thing. For example, as a pitch is varies over the frequency spectrum of hearing, the intensity must be changed for the ear to perceive constant loudness.¹⁰ Timbre similarly is a perceptual quality that can be linked to physical acoustic characteristics of a tone. Unlike loudness and pitch, timbre it is far less understood and has a complicated dependence on both frequency content and loudness.

Classically it was thought that timbre depended only on the frequency spectra of a note.¹¹ It was also presumed that this spectrum remained constant over the duration of the note. Years of experimentation and study have made it clear that other physical characteristics contribute to the perception of timbre as well. These other characteristics have to do with elements that change over the duration of the note and will therefore be referred to as dynamic timbre. The present study focused on the constant spectral timbre of the instrument because the note samples were long tones where the bulk of the note was constant in pitch and loudness. Dynamic timbre, while important, is a stronger determining factor of large scale timbre between instruments than the small scale timbre changes within an instrument that were the focus of the present work.

2.2.1 Constant Spectral Timbre

Spectral timbre focuses on sound that is constant in intensity and frequency. Often the sustained portion of a note does not contain significant intensity or frequency changes and can thus be approximated as invariant with time. This means that spectral timbre accounts for small scale timbre changes for a given instrument where the sound mechanism does not change. As mentioned before, the two main acoustical properties of the sound's spectra that were observed

⁹ Deutsch 13.

¹⁰ John M. Eargle, *Music, Sound Technology* 2nd ed. (Boston: VanNostrand Reinhold, 1995) 38.

¹¹ Deutsch 113.

were the number of partials and the shape of the spectral envelope. Each of these characteristics can be related to the qualitative timbre descriptions of “fullness”, ranging from “thin” to “thick” and “roughness”, ranging from “smooth” to “rough”.

Recall that the partials present on the French horn are all harmonic partials and therefore whole number multiples of the fundamental frequency. The fundamental is the frequency that determines what pitch is heard. The additional partials give the note a different texture or color. In the harmonic series, the lower partials correspond to consonant intervals while the higher partials become smaller and more dissonant intervals. For example the second harmonic makes the interval of an octave with the fundamental. The third harmonic makes the interval of a fifth with the second harmonic. As new partials are added the interval between them becomes smaller and more dissonant. This principle is the primary means of relating physical acoustic characteristics to perceptive qualities such as “thickness” or “roughness”.

Number of Partial

The total number of partials in a spectrum contributes greatly to the perceived “fullness” of the sound. In addition, a phenomenon called ***critical band overlap*** that occurs for higher partials and contributes to the perceived “roughness” of the note.

Pure tones contain only one frequency component. As a result they lack texture and depth. Complex tones are given thickness by the number of partials in their frequency spectrum. A single partial can in a way be compared to a single note. Adding other partials adds other frequencies and is in effect similar to producing a chord by adding more notes. The more partials that are added, the more frequencies are combined in the note. This gives the note a fuller sound. The strength of the partials is extremely important in determining which are most prominently heard, but the overall number gives a good idea of how full the note will be. Notes with a small number of partials will therefore sound “thin” while notes with a greater number of partials will sound “thick” and “full”.

As partials become higher, their frequency spacing with respect to each other becomes smaller. This produces an effect called critical band overlap. Inside the cochlea of the human ear is a thin sheet of fibers called the basilar membrane.¹² These fibers are set into motion by pressure signals that enter the ear. There is a spatial dependence on frequency in the membrane such that different frequency components of sound activate different areas of the membrane. Each frequency component strongly activates a particular fiber, but also weakly activates adjacent fibers. If the frequencies are spaced far apart they activate different regions of the membrane. If the frequencies are sufficiently close together, however, they activate the same fibers. The area of overlap for these close frequencies is called the critical band.¹³

¹² Hall 92.

¹³ Hall 391.

For low frequencies the critical bandwidth is around 100 Hz. For higher frequencies it becomes twenty percent of the center frequency.¹⁴ If multiple frequency peaks are spaced closer than one critical bandwidth apart the human ear cannot discriminate them as distinct separate pitches. Instead beating can occur and the notes are perceived as being rough or harsh instead of having distinct pitches. For most pitches on the French horn overlap of critical bandwidth begins to occur around and above the sixth partial. As a result, as the number of partials above the sixth increases, notes become more “rough” or “harsh” sounding.¹⁵ *Spectral Envelope*

The spectral envelope of a sound can be broken down into three measurable acoustic characteristics; the center of the spectral peak, the width of the peak, and the strength of the fundamental frequency. Each of these can be related to the perceived “roughness” and “fullness” of the sound.

The location of the spectral peak is a good way of observing whether the most prominent partials are consonant or dissonant. Since, as described above, higher partials correspond to more dissonant frequencies, if the peak is centered on a high partial then the note will be more dissonant and therefore have more “roughness”. The width of the peak determines how many partials make strong contributions to the sound. A wider peak will have more partials and therefore create a timbre that sounds “fuller”, albeit “rougher”.

If the spectral center is on a high partial, it is likely that the fundamental frequency is very weak. Even if the fundamental is weak or not present, the fundamental is perceived by the auditory system. This is called the missing fundamental or suppressed fundamental. If the ear is presented with a harmonic series without the fundamental it can still perceive the pitch of the fundamental because it is sensitive to the frequency spacing of the partials, which will be equal to the fundamental frequency even in its absence.¹⁶ This means that in spectra where the fundamental is very weak, the pitch will still be perceived as corresponding to the frequency of the fundamental. The strength of the fundamental therefore only changes the timbre and not the perceived pitch of the note.

2.2.2 Dynamic Timbre

The frequency spectrum of the steady state portion of a note is extremely important in determining timbre, but it is certainly not the only factor. For example, under heavy distortion, such as poor recording quality, the frequency spectrum of a note changes. Despite this change, it is still possible to identify the instrument.¹⁷ This means some other factors must be affecting instrument timbre besides the static frequency spectrum. Observations like this lead to studies that brought to light other acoustical characteristics that affect large scale timbre. These characteristics all deal with the change in certain aspects of the tone over time. The resulting

¹⁴ Max Mathews. “Introduction to Timbre.” *Music, Cognition, and Computerized Sound*. Ed. Perry R. Cook. (Boston: MIT Press, 2001) 84.

¹⁵ Mathews 84.

¹⁶ Hall 385.

¹⁷ Deutsch 117.

timbre with therefore be referred to as dynamic timbre. Three types of dynamic timbre are intensity, frequency, and spectral.

Intensity timbre considers changes in intensity over the duration of a sound and how this affects the resulting timbre. For instrumental sounds this deals with the attack, sustained, and decay portions of a note. Figure 4 shows examples of different dynamic intensity characteristics for various types of musical instruments. Drums, for example (diagram G), demonstrate a sharp attack and immediate decay with almost no sustained portion. This is due to the high damping of the instrument and the nature of the sound coming from an impulse of force. Lip-reed instruments, brasses and woodwinds (diagram E), in contrast have an attack that is not quite as sharp, contain a long sustained region, and exhibit a short decay.

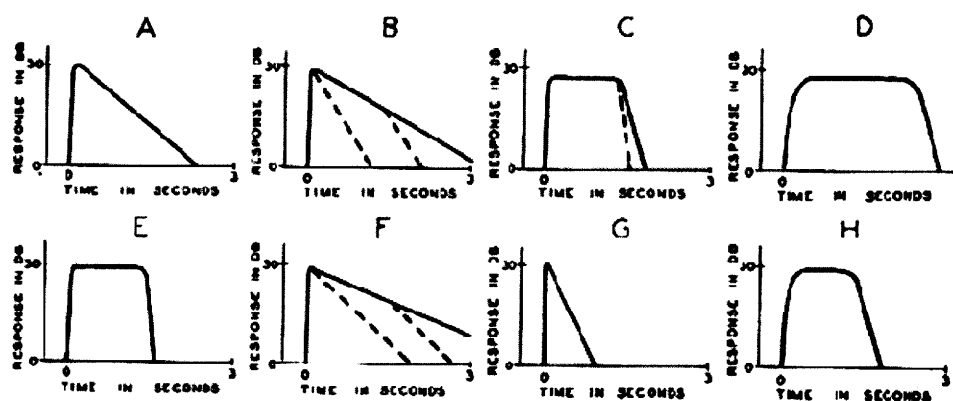


FIG. 6.45. Growth, steady-state, and decay characteristics of various musical instruments. *A.* Plucked-string instruments. *B.* Struck-string instruments. *C.* Bowed-string instruments. *D.* Flue organ pipe. *E.* Air-, mechanical-, and lip-reed instruments. *F.* Percussion instruments of definite pitch. *G.* Drums. *H.* Voice vowel sounds.

*Figure 4: Attack, sustain, and decay characteristics of different instruments.*¹⁸

Studies on the identification of instruments when the attack and decay portions of the notes have been removed have found that such removal impairs the ability of the listener to recognize the instruments producing the sound.¹⁹ Another study looked at the influence of the overall contour by time-reversing recorded samples of notes played on a piano. Piano notes have a distinct contour because of the way the strings are struck with a felt hammer. When the sound is time-reversed, it takes on a very different timbre, uncharacteristic of the piano even though the note's frequency spectrum is the same. These studies demonstrate that the time behavior of a note is critical in identification of the instrument. Another dynamic timbre having to do with intensity is tremolo, an effect that uses periodic vibrations in the amplitude of the note to create a distinctive and different timbre from a sustained note.

Changing pitch or frequency within a note has been studied less as a timbre quality. This timbre deals with the perceived tone quality that comes from fluctuating pitch over the duration

¹⁸ Hall 238.

¹⁹ Deutsch 117.

of the note. Common examples of this are effects such as vibrato or pitch bends. While the pitch change is somewhat perceived in these effect, overall this is heard as a coloration or texture rather than a different pitch, and therefore can be considered a timbre.

The third dynamic timbre deals with changes in the frequency spectrum over the duration of the note. The spectrum is often not constant for the entire duration of the note. While the sustained portion of the note often contains a constant spectrum, there are some transients and variations that occur in the attack and decay portion of the note. For example, experiments have shown that in trumpet tones the higher frequency overtones enter later than some of the lower ones.²⁰ Pitched percussive instruments such as the piano exhibit significant changes in frequency spectrum between the attack and decay portions of the note.

Dynamic timbre appears to be most important to large scale timbre changes. The studies that have looked at these factors deal with the identification of instruments. Within an instrument the contour and dynamic timbre are assumed to be fairly similar for different pitches and volumes because the mechanism for producing the sound remains the same. Therefore, the present study, which focuses on small scale timbre changes within the French horn, will not consider dynamic timbre, but will focus on the constant spectral timbre as a function of pitch and loudness throughout the instrument range.

2.3 Instrumental Acoustics

In order to understand how different timbres are created, it is important to understand how different instruments produce sound. Every instrument contains a power source, means of coupling the source to the instrument, oscillating element, and means of converting this oscillation into acoustical power.²¹ Most traditional instruments can be categorized into four basic groups based on how they produce sound. These four groups are chordophones, aerophones, membranophones, and idiophones.²²

A chordophone is an instrument which produces sound by some means of displacing and releasing a string that is constrained at both ends. This includes instruments in the piano, violin, and guitar families. The power comes from displacement of the string. The string is then released creating an impulse that allows the string to execute simple harmonic motion vibrating at its resonant frequency. This means that the string produces the harmonic series. This string is coupled to a resonating body in order to increase the acoustical output. The resonant characteristics of the attached body act as a filter and help determine which of the string's frequencies will be damped or reinforced. These characteristics combine to create a specific spectral timbre for each instrument. The string can be set into vibration many different ways. For example, it can be plucked, as with a guitar or harpsichord, bowed, as with the violin family, or struck, as on a piano. These different power sources determine the attack characteristic and there for dynamic timbre of the produced sound.

²⁰ Deutsch 119.

²¹ Eargle 68.

²² Eargle 67.

An aerophone is an instrument which produces sound by means of a vibrating column of air. This includes instruments such as brass and woodwinds. The power source for these systems is the forcing of air through a mouth piece or reed. These instruments are constructed of some form of hollow tubing which allows a column of air to vibrate and execute simple harmonic motion. This, like the string, creates a harmonic series that depends on the boundary conditions of the tube as well as the length and characteristics of the air. The air column instruments are driven harmonic oscillators and can be made to resonate at the fundamental as well as different harmonics by varying the air speed. The body of the instrument again acts as a filter for the produced harmonic series. These characteristics combined determine the striking features of the frequency spectrum that effect spectral timbre. The attack characteristics of these instruments are determined by the transients present in the source, for example, by the initial forcing of air through the instrument. The attack characteristics that determine the dynamic timbre are largely dependent on the device that couples the instrumentalist's air to the vibrating column, which can be classified as a single reeds, double reeds, air reeds, or lip reeds. The latter category includes the French horn.

Membranophones are instruments that produce sound by means of a struck membrane stretched over a frame, such as a drum. As with chordophones, the power source is an impulse created by striking the membrane and sending it into vibration. While strings and air columns execute simple harmonic motion, the motion of a stretched surface becomes a three dimensional vibration with more complicated modes of vibration than the simple harmonic series. Again the struck nature of the instrument produces a strong attack and sharp roll off that influences the dynamic timbre.

The final category is idiophones. These instruments are self resonant structures usually represented by the percussion section, such as vibraphones and xylophones. . The driving mechanism here is usually an impulse created by a striking with a mallet. The instrument is then allowed to resonate. Here the spectra are determined by the geometric and material properties of the object.

The complex waveforms for several aerophones: the flute, clarinet, and harmonica, are displayed on the left in figure 5. This demonstrates how each signal is complex and periodic but it does not really give good physical acoustical parameters to look at. The frequency spectra of each instrument, seen on the right, give a more quantifiable measure of the differences between the three instruments. The flute for example is missing the fourth harmonic and the clarinet is missing the sixth and seventh harmonics. The harmonica in contrast to the other two instruments has its peak frequency at the third harmonic rather than the first.

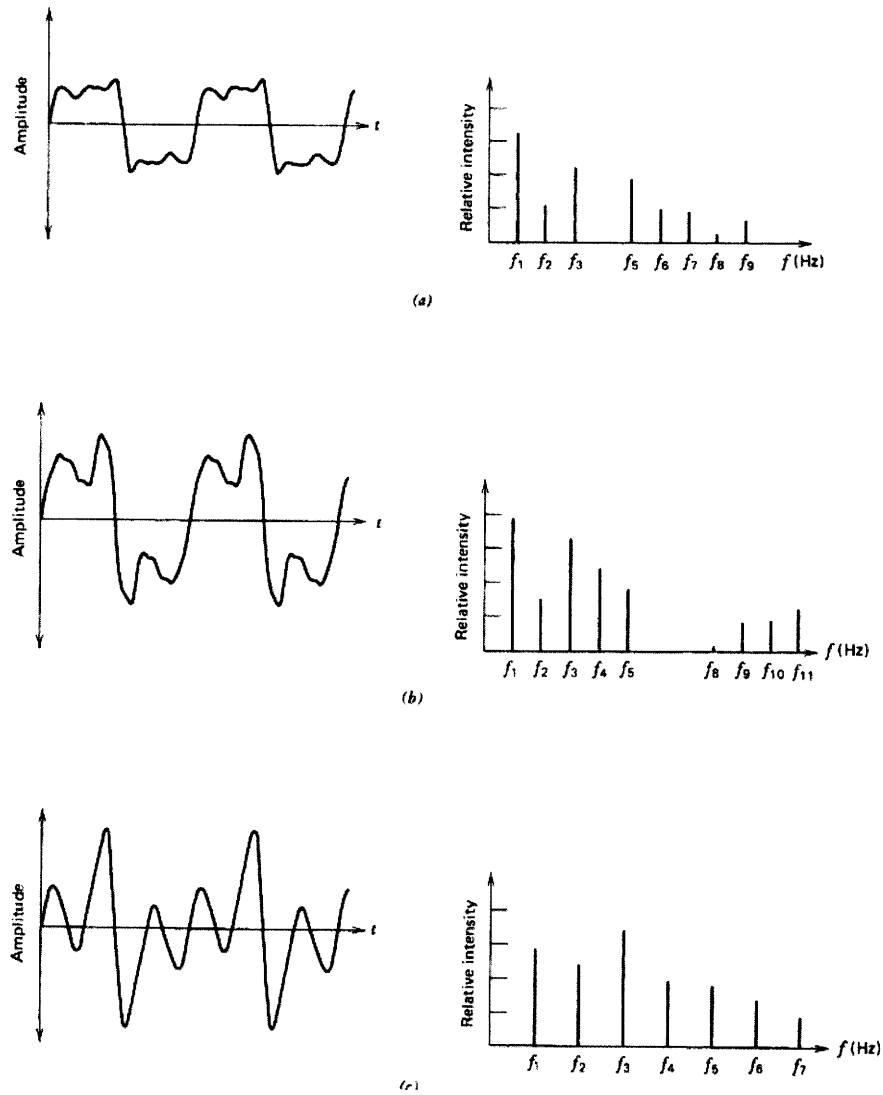


Figure 5: complex waveform (left) and frequency spectrum (right) for flute, clarinet, and harmonica (top to bottom)²³

The French horn is a lip reed aerophone made of a long length of brass tubing that flares out at the end. Brass instruments can be divided into two categories based on their geometry; cylindrical tubing with a flared bell (trumpet, trombone, and French horn) and conical tubing with a less flared bell (flugelhorn, tuba, and baritone).²⁴ The tubing geometry is in large part responsible for the harmonic series and thus the timbre of the instrument.

²³ John S. Rigden, *Physics and the Sound of Music* 2nd ed. (New York: John Wiley and Sons, 1985) 97.

²⁴ Earle L. Kent, *Musical Acoustics: Piano and Wind Instruments*. (Stroudsburg: Dowden, Hutchinson & Ross, Inc., 1977) 123.

From the acoustics of a tube it might be presumed that the French horn, and other brass instruments, can only play a harmonic series. In early horns this was true, meaning they could not play all 12 notes in the western scale. To compensate for this, early horns had crooks, or different length sections that could be changed in order to play music in different keys.²⁵ Modern horns have valves to make it possible to play all 12 tones in the diatonic scale. Valves open up extra lengths of tubing to change the effective length of the horn therefore allowing for a new harmonic series that includes the necessary note.

The modern French horn contains two sides each in a different key: the F side and the Bb side. The F side is used for lower notes because it has a longer length of tubing, about 3.77 meters.²⁶ The Bb side is activated by a valve and gives access to a shorter length of tubing, about 2.8 meters in length.²⁷ This makes it easier to play high notes because the fundamental frequency of the tube is higher.²⁸

In this experiment only the open notes of the F side of the horn were used. This only allows for a modest amount of the range to be used but it keeps many things consistent to reduce the number of confounding variables when looking at the change in timbre as frequency changes. Examination of the effect of opening valves on timbre will be deferred for future work, since when valves are opened, introducing a new section of tubing, the impedance of the horn changes.

²⁵ Eargle 127.

²⁶ Eargle 130.

²⁷ Eargle 131.

²⁸ Eargle 130.

3 Audio Acquisition and Analysis methods

In order to qualitatively analyze French horn timbre, sound samples of long tones played on the instrument were recorded and analyzed. Two different sets of samples were generated: one which varied in frequency, the other which varied in intensity.

3.1 Sound Production and Recording Equipment

The equipment and procedure used to acquire timbre samples in this experiment can be loosely broken up into two main systems; sound production and sound recording. For the sound production portion, a metronome, head phones, musician, and French horn were used. The instrument used was a Holton H275 Merker-Matic double French horn in the keys of Bb and F. The instrument has a 12.25" large-throated, had-hammered, detachable bell. The instrument is made of solid nickel-silver and contains a dual 0.468"/0.460" bore.²⁹ The mouth piece used was a Holton Farkas MC. Figure 6 shows a photo of the horn and mouthpiece used in this study.



Figure 6: Photo of the Holton H275 Merker-Matic double French horn used in this study

For the sound recording portion, a microphone, preamplifier, XLR cable, USB cable, and computer with recording capability were used. The microphone was a Sennheiser e609 silver dynamic guitar microphone. This microphone is meant to pick up high sound pressure levels

²⁹ Musicians Friend <<http://band-orchestra.musiciansfriend.com/product/Holton-H275-Professional-MerkerMatic-French-Horn-?sku=460388>>

without distortion therefore it was ideal for measuring the high level output of a brass instrument. The frequency range of the microphone is from 40 Hz to 18 kHz. The Mbox 2 Mini by Digidesign was used as a preamplifier. The Mbox supports an intensity resolution of ± 0.1 dB, a dynamic range of 103 dB, and a sampling rate of 48 kHz. The preamp is necessary to adjust the level of the microphone input to levels suitable for the computer to record. A laptop with Digidesign ProTools software was used to record the sound files to be analyzed.

3.2 Sound Recording Network

A block diagram of the sound recording network is illustrated in figure 7. The network is divided into two subsystems: sound production and sound recording. In the sound production portion, the metronome was used to regulate the duration of each note using a 75 beats per minute pulse. The metronome output was sent directly to the musician using headphones so as not to interfere with the sound being recorded. The musician produced sound on the instrument by forcing air through the mouthpiece. This air created acoustical output from the bell of the horn that was then recorded by the sound recording portion of the network.

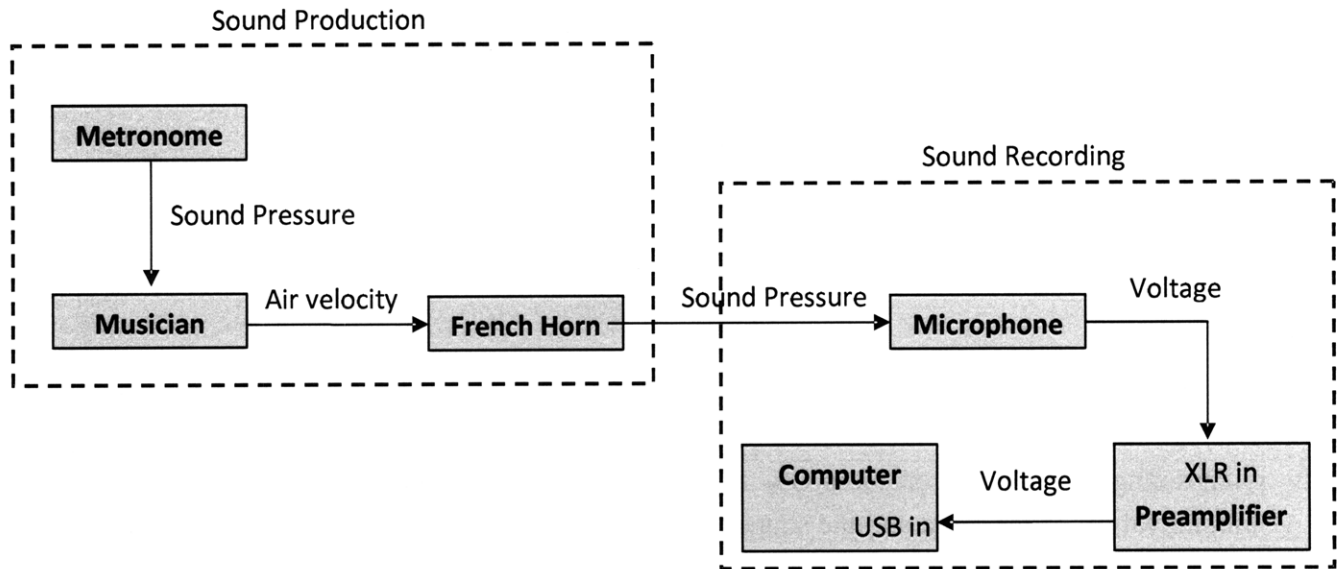


Figure 7: Block diagram of sound recording network. The musician, listening to the metronome, produced long tones on the French horn. The sound pressure from these notes was picked up by the microphone, fed through the preamplifier and recorded with 48 kHz sample rate and 16 bit resolution.

In the sound recording portion, the microphone was positioned directly behind the French horn bell about 2 feet away and connected to the preamp using an XLR cable. The preamp was adjusted so that no clipping was present, even for the loudest amplitude sounds, and the output was sent to the computer via a USB cable, where it was recorded in ProTools software at a sampling rate of 48 kHz and saved as a .wav file with no compression.

3.3 Recording Procedure

In order to observe the change in timbre with frequency and intensity, two sets of data were acquired. In one case frequency was varied across the data set at constant amplitude and in the other intensity was varied at constant frequency. In both cases it was necessary to produce single sustained notes. The metronome was used to produce recordings of equal duration. Using a pulse of 75 beats per minute, the notes were held for 8 beats giving each note duration of about 6.4 seconds. A sample sound file is given in Fig. 8, where the increments on the time axis, 0.8 seconds, correspond to metronome beats. Due some delay in response time as well as the decay of the sound after the musician stopped playing, the note duration is slightly longer than 8 beats.

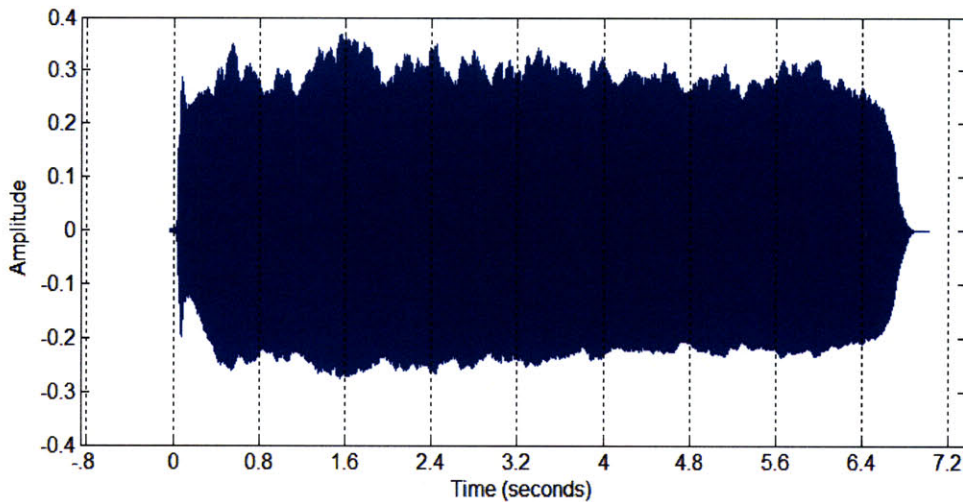


Figure 8: Sample of recorded waveform for pitch F4. The increments marked on the time axis correspond to metronome beats.

To observe the variation in timbre over different frequencies a data set was generated over part of the frequency range of the French horn. This data set included eight different pitches ranging from concert F3 to G5. All of these pitches were played on the F side of the horn with no valves compressed and the sound volume was kept as constant as possible. Using only open notes insured that physical characteristics of the instrument that could affect sound production were kept constant, but limited the highest note that could be recorded. The typical playing range of the horn extends up at least another fifth to D6, but this note could not be accessed without employing valves and therefore was not used. For each frequency, four notes were played. The attack and decay portion of these notes was removed, leaving the steady state constant portion in the middle. They were normalized for volume and the FFT of these segments was taken. The amplitudes in the frequency domain of the four samples were then averaged to factor out some of the inherent variation introduced by a human player.

A summary of the notes played, their fundamental frequencies, and harmonic relation to the fundamental note of the French horn is given in table 1. The fundamental of the French horn is around 87 Hz, and varies slightly for different instruments.³⁰ The notes that are part of the frequency data set include the harmonics 2 through 9 for the natural frequency of this particular French horn.

Concert Pitch	F3	C4	F4	A4	C5	D5	F5	G5
Partial	2	3	4	5	6	7	8	9
Average Observed Frequency [Hz]	175.8	259.1	347.9	438.4	519.7	601.3	690.5	781.5
Standard Error [Hz]	1.7	1.8	1.0	3.1	1.5	4.6	1.1	1.4

Table 1: Notes present in data set for observing change in timbre over frequency.

To observe the shift in timbre over different intensities a data set was generated over the common intensity range of the French horn. This data set included 19 samples played at different intensities but at the same frequency, F4 (348 Hz). The range was varied from the quietest sound producible for this pitch level to the loudest. Effort was originally made to play several notes at specific intensity levels so that they could be averaged. It was difficult to reproduce a certain intensity level so the 19 samples are just spread over the range of intensities playable on the horn for F4.

3.4 Recording Concerns

It is important to bear in mind that for this experiment the tones were played by a human source. Particular attention was paid to keeping certain elements constant; however there are inherent inconsistencies involved. These include human factors, room acoustics, and microphone placement.

Human Factors

Because the input into the French horn is produced by a human rather than machine, it is subject to variation. In many studies a machine has been used to create well controlled vibrational input. This gives a good sense of how the instrument responds to a particular frequency input, but does not necessarily give a good indication of what the final sound will be when the horn is played by a person. By using a musician, the input characteristics are not well known and are subject to variation, but the resulting conditions are much closer to those encountered in the actual use of the instrument.

³⁰ Eargle 130.

As described above, care was taken in the experimental design to keep repeated notes invariant in factors other than the variable being observed, frequency or amplitude. For sustained notes it is exceedingly difficult to keep pitch and amplitude constant, leading to some fluctuations in output sound. To compensate for this, averaging of several samples was used in the analysis.

Room Acoustics

Architectural structures such as rooms and performance spaces have acoustic properties strongly related to their geometry and materials, leading to natural resonant frequencies that affect the sounds produced within a particular space. The room acts as a filter, reinforcing pitches that have a strong resonant characteristic and damping those that do not. Because of this, the sound heard by the audience, as well as recorded by a microphone, will depend on the acoustic characteristics of the room. To get the “true” unfiltered sound from the instrument an anechoic chamber should be used. Logistical difficulties precluded the use of an anechoic chamber for the present study, and therefore a well damped room was used instead.

Microphone Placement

Microphone placement is also an important variable in instrumental recording. For the present study, the microphone was placed directly behind the bell about two feet away. The French horn is unique among orchestral instruments in that in a concert environment the sound emitted from the bell is never directly heard by the listener. The horn bell curves backward such that it points 30 degrees back from the side of the player.³¹ For the sound to radiate into the audience it must first reflect off of the walls behind the player. This makes the final sound highly dependent on the acoustic environment. Hard structures are often placed behind the horn section to help reflect more sound into the audience. By placing the microphone behind the horn a direct sound signal was captured. This is not what is heard in a concert environment but it will allow us to determine the sound emitted from the instrument. An important extension to the present work would be to study the acoustic effects of the environment on French horn timbre.

³¹ Eargle 130.

4 Results and Discussion

Two main acoustical properties of the French horn sound were measured as a function of frequency and intensity. The first of these was the number of partials in each note’s frequency spectrum. This included both the total number of partials and the number of partials with critical band overlap. The second characteristic was the shape of the spectral envelope. This included observing the center of the spectral peak, the width of the peak, and the strength of the fundamental. These measured characteristics showed strong trends both over the frequency range and intensity range measured. These trends were able to be related to qualitative timbre parameters such as “fullness” and “roughness”.

4.1 Frequency Range

For the eight open notes tested in the frequency range, it is clear that as frequency increases timbre shows a qualitative shift from “rough” and “full” notes to “smooth” and “thin” notes. The frequency spectra for the lowest and highest notes, F3 and G5, are given in figure 9. These spectra are averages of the four samples for each note. Just by observing the extremes, it is clear that the number of partials and spectral contour change as a function of frequency. The details of this change are described below in terms of the measured number of partials and the shape of the spectral contour for the all eight notes. The data has been presented in terms of the partials of the particular fundamental rather than frequency in order to more easily show the difference in the spectrum of partials for each note.

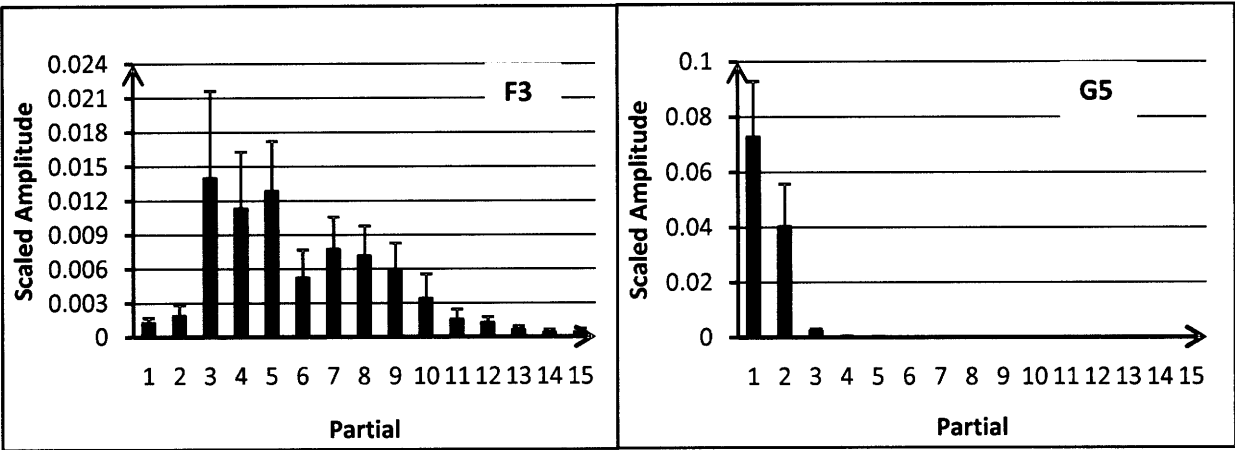


Figure 9: Frequency spectra for the lowest (F3) and highest (G5) notes tested. These spectra are averages in the frequency domain of the four trials measured for each note

The error bars in figure 9 indicate the standard error from the averaging of four samples for each note. The error is generally larger for the higher amplitude partials. There is a significant amount of variation, but the main features observed in the spectral envelope will be largely unaffected.

4.1.1 Number of Partial

As discussed in Sect. 2.2.1, the number of partials contributes to both the “fullness and “roughness” of the sound. The total number of partials determines “fullness” while the number with critical band overlap contributes to “roughness”.

Figure 10 shows the total number of partials present in each note. As pitch increases the number of partials present in the note decreases. While the lowest note, F3 contains 15 partials, the highest note, G5, only contains three. This marks a sizable dependence of the number of partials on pitch. This supports the perception of low notes as “thick” and “full” in timbre. As pitch increases the notes become more “thin” and “pure tone” in timbre.

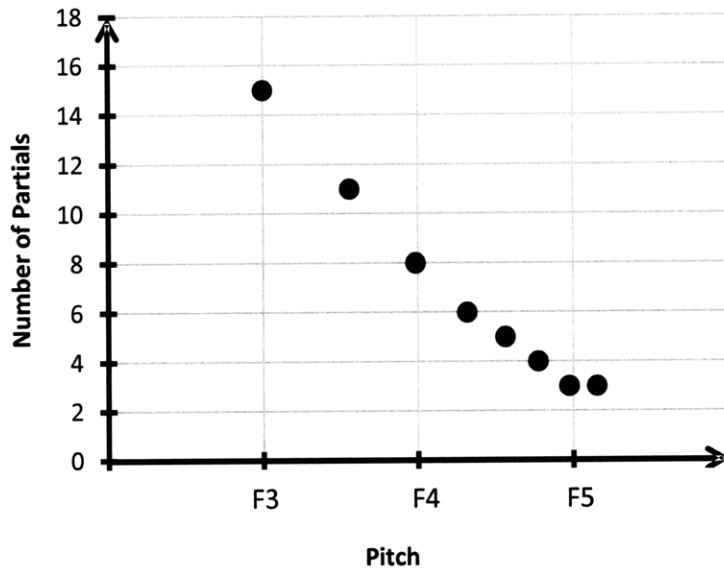


Figure 10: Plot of the total number of partials present in each of the eight notes tested in the french horn frequency range.

The number of partials with critical band overlap is plotted for each note in figure 11. Since the number of partials present in the note decreases as pitch increases, the lowest note, F3, contains 10 partials with overlap while the highest four notes do not contain any at all. Like the total number of partials, this marks a sizable dependence of the number of partials with overlap on pitch. This supports the perception of low notes as “rough” and “buzzy” in timbre. As pitch increases the notes become more “smooth”. The highest four pitches appear to have no roughness at all.

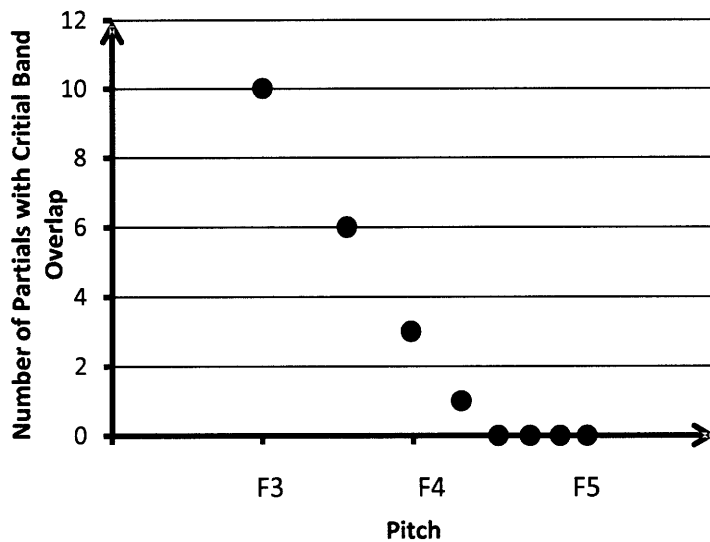


Figure 11: Plot of the total number of partials with critical band overlap (partials 6 and above) in each of the eight notes tested in the french horn frequency range.

4.1.2 Shape of Spectral Envelope

The relative intensity of partials in the French horn sound can be observed by looking at the note's spectral envelope. The spectrum for the lowest frequency note in the data, F3, is illustrated in figure 12. The spectra envelope is pictured here as a dark line connecting the amplitudes of the discrete peaks.

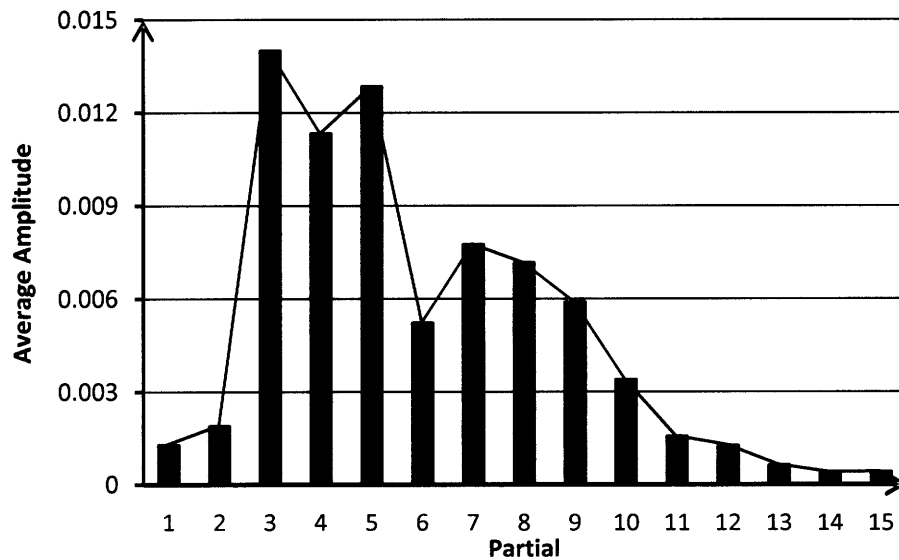


Figure 12: Frequency Spectrum for the lowest note (F3)

Recall that timbre relates to three main features in the spectra; position of the spectral peak, the strength of the fundamental, and the width of the peak. Figure 13 shows the spectral envelope for the notes F and C. These spectral envelopes show visually how these three features change with respect to pitch.

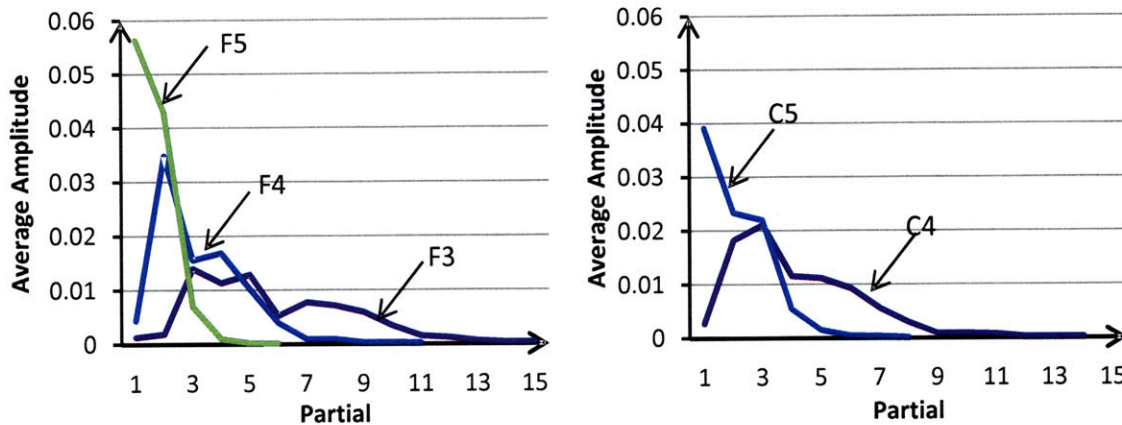


Figure 13: Spectral envelope for the notes F and C. F (left) contains three notes each evenly spaced in pitch one octave apart. C (right) contains two notes spaced an octave apart.

It is evident from Fig. 13 that the spectral peaks not only change in location but also in number. As pitch increases the number of peaks decrease and the center moves to lower partials. For example, in the lowest note, F3, there are two peaks, one centered about the fourth partial and one centered about the eighth partial. An octave higher, F4, the two peaks are now centered on the second and fourth partials. This means they have moved to lower partials and decreased their spacing from four partials to two. One more octave up, F5, the peaks have merged and the center of the peak has shifted even lower to the fundamental frequency. The same thing can be observed with C4 and C5.

Defining the “center” of the spectral peak is difficult because the peaks are not evenly spread on either side of the maximum amplitude. Instead, examining the location of the maximum amplitude partial was used as a metric. Figure 14 shows the partial number for maximum amplitude for each note. As the pitch increases the highest amplitude partial decreases from the third to the fundamental. This means that as the pitch increases the note will become more consonant and therefore “smoother” sounding.

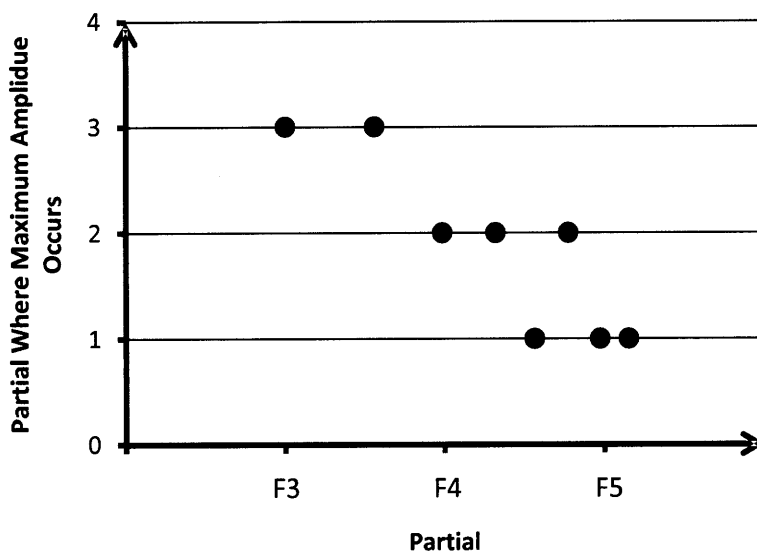


Figure 14: Plot of the partial with the maximum amplitude as a function of pitch

As pitch increases the width of the spectral peak decreases spreading the energy of the note over fewer partials. This can be observed in figure 13. For example, the energy in F3 is distributed over many partials. An octave higher, F4, the envelope has compressed and the total energy of the note is concentrated in fewer partials. Finally, another octave higher, F5, nearly all of the energy is concentrated into the first two partials. In general there is a compression of the spread of the energy as the pitch increases. A similar trend is seen with C4 and C5.

This trend can be more quantitatively measured by looking at how many partials fall within a certain percentage of the peak amplitude. Figure 15 shows the number of partials with amplitudes within fifty and twenty-five percent of the maximum amplitude. As pitch increases the number of partials within a certain percentage of the peak decreases. This occurs approximately linearly for both fifty percent and twenty-five percent. This trend dictates that for low notes, where the energy is spread out over more partials, the timbre will be “thick” and “rich”. As the pitch increases the timbre will become more “thin”.

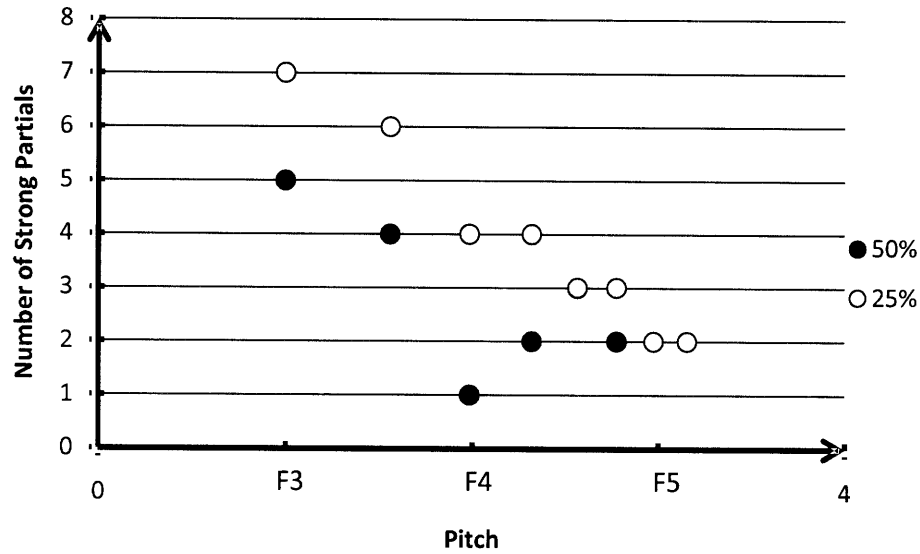


Figure 15: Plot of the number of partials within a certain percentage of the maximum amplitude as a function of pitch

Finally, the spectral envelope shows a change in the strength of the fundamental frequency. For F1 in figure 13, the first two fundamentals are hardly present. An octave higher the fundamental is still weak but the second partial is stronger. Another octave higher the fundamental is the strongest partial. This trend can be more clearly exemplified by the plot of fundamental strength in figure 16. As pitch increases, the strength of the fundamental frequency increases as well. The dependency of the fundamental strength is almost discrete in the sense that it seems to be very strong or very weak and not between these extremes for very many notes. This trend dictates that for low notes there will be a stronger sense of texture than pitch. As the pitch increases the sense of pitch with strengthen.

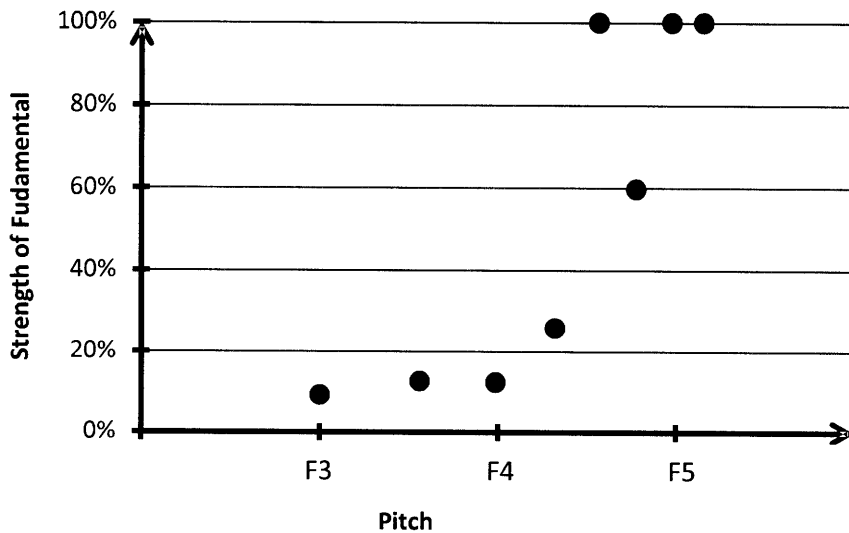


Figure 16: Plot of the strength of the fundamental (expressed as a percent of the maximum amplitude) as a function of pitch

Both the number of overtones and the spectral envelope considerations support a change from “rough” to “smooth” and “full” to “thin” as pitch increases. This means that low notes should sound “rough” and “full” with a strong texture but less definite sense of pitch. High notes on the other hand should sound “smooth” and “thin” with a very definite sense of pitch. This seems to coincide well with the perception of French horn notes and the idea that the low notes are “dark” while the higher notes are “bright”.

4.2 Intensity Range

The intensity range tested varied from the softest to the loudest playable intensity on the note F4. It was found that as intensity increased timbre showed a qualitative change from “smooth” and “thin” to “rough” and “full”. The frequency spectra for the lowest and highest intensity notes are shown in figure 17. By observing the extremes, it is clear that the number of partials and spectral contour change as a function of intensity. The details of this change are described below through the measured number of partials and shape of the spectral contour for all nineteen recordings in the data set.

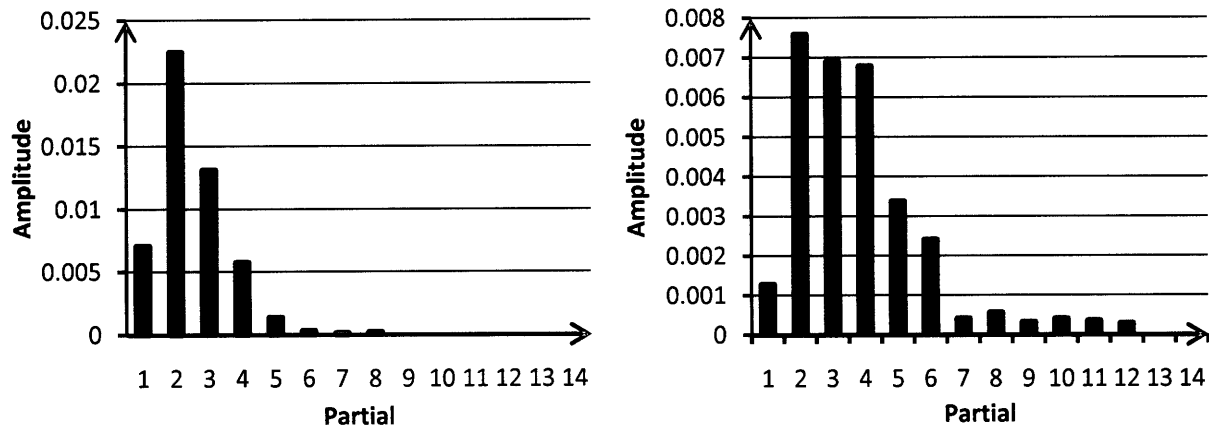


Figure 17: Frequency spectra for the softest (left) and loudest (right) notes tested.

4.2.1 Number of Partial

As demonstrated in figure 17, the number of partials increases as intensity increases. This can be more easily observed for all the data in figure 18. This figure shows the number of partials present in each note as a function of intensity. While the quietest note only has five partials present, the loudest note has 18. This plot also shows a linear dependence of the number of partials on the intensity of the note. This trend dictates that as the intensity increases from the softest to loudest note the timbre changes in “fullness” from “thin” to “thick”.

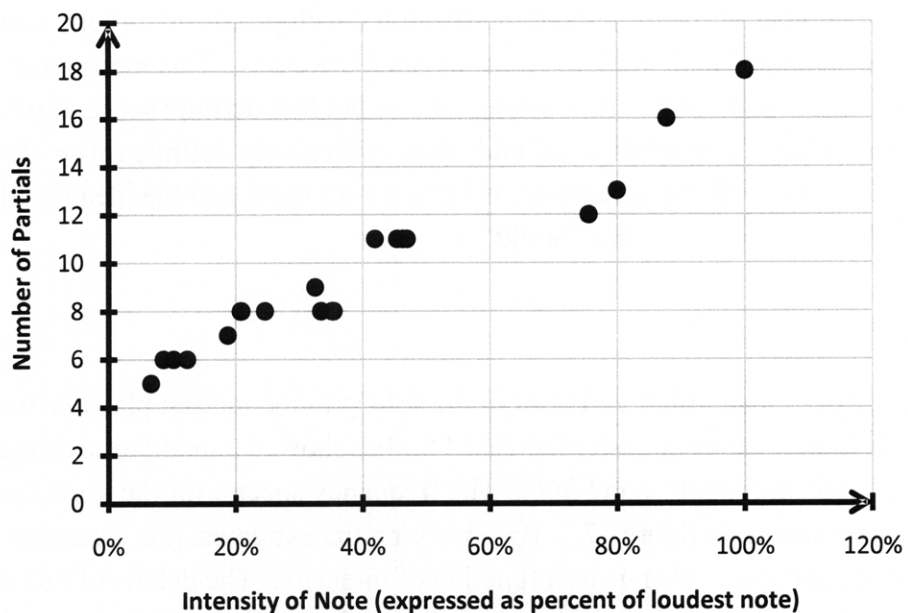


Figure 18: Total number of partials present as a function of Intensity

The amount to partials with critical band overlap is plotted in figure 19. As intensity increases, so does the number of partials with critical band overlap. This suggests that as intensity increases from the softest to loudest note the timbre changes in “roughness” from “smooth” to “rough”.

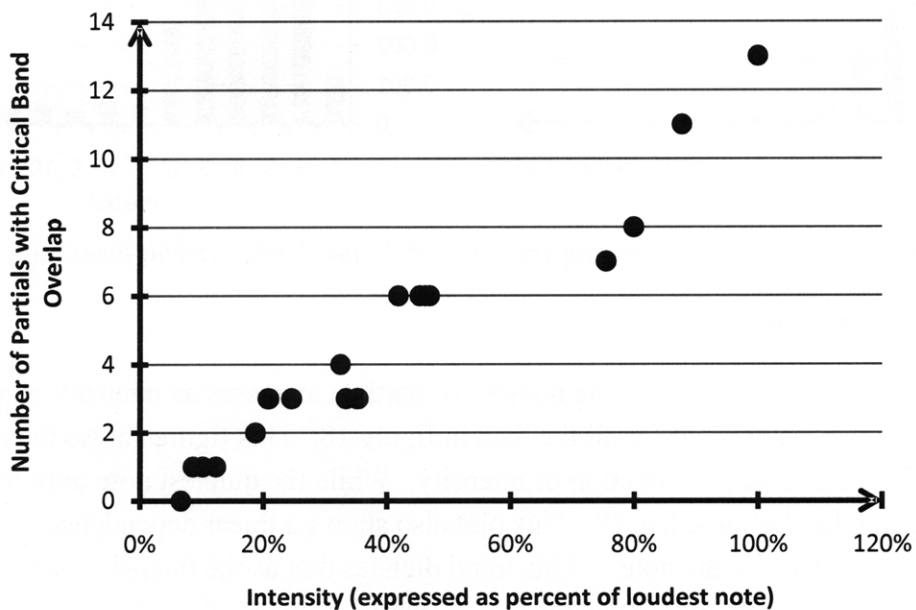


Figure 19: Total number of partials with critical band overlap present as a function of Intensity

4.2.2 Shape of the Spectral Envelope

As before, the relative intensity of overtones in the French horn can be more easily observed by looking at the spectral envelope. The spectra envelope seems to be heavily dependent on pitch; however, it does change some with intensity as well. Figure 20 shows a plot of the spectral envelope for several intensities of the note F4. The scaled amplitude is the amplitude of each partial divided by the total amplitude of the note.

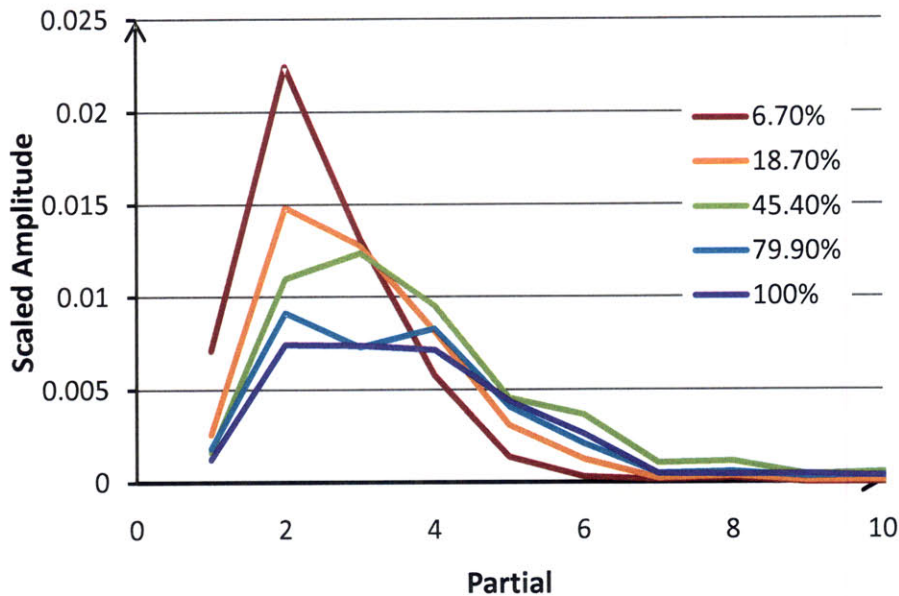


Figure 20: Spectral envelopes for five different intensity of the same pitch

Recall that timbre relates to three main features in the spectra; position of the spectral peak, the strength of the fundamental, and the width of the peak. In the case of intensity for this particular note there is only one spectral peak. The position of the center of this peak moves toward higher partials as the intensity increases. In order to facilitate comparison of all 19 samples, the maximum amplitude is shown for each sample in figure 21.

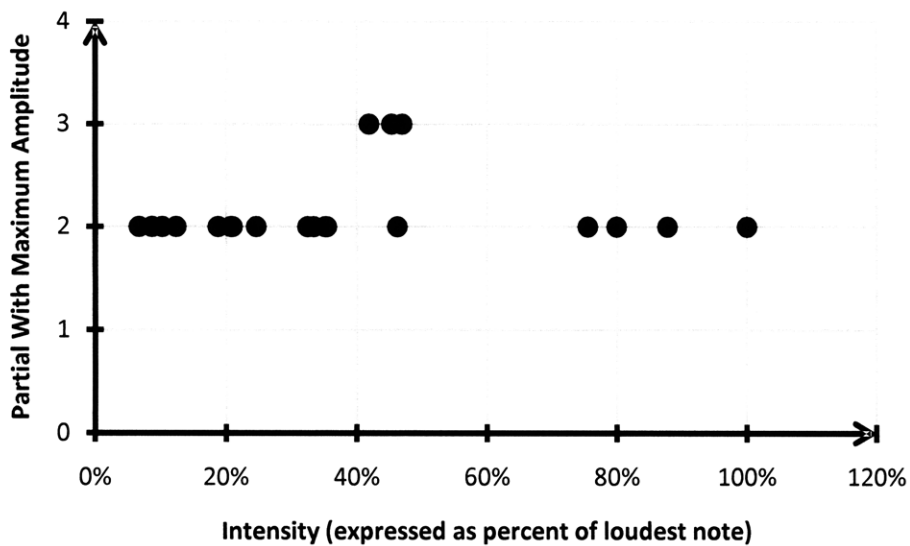


Figure 21: Partial where the maximum amplitude occurs as a function of intensity.

From this plot it is apparent that the peak occurs at the second partial for high and low intensities and at the third partial for intermediate ones. This seems to contradict the trend seen in figure 20. The five notes with intensities above 40% of the max have the peak of the spectrum on the second partial. However, if the data is observed each of these notes have very similar values for the second, third, and fourth partials. This makes a flat peak with the center at the third partial. If the center of the spectral peak is observed, it moves to higher partials as intensity increases. This is a slightly smaller change than was seen with frequency, where the center of the peak moved two partials from the third to the fundamental. When intensity, rather than pitch is varied, the peak only moves one partial. As the intensity increases the center of the peak shifts toward higher frequencies and the note becomes less consonant and therefore “rougher” in timbre.

Another key characteristic of the spectral envelope is the width of the peak. Looking back to figure 20, it can be seen that as intensity increases the width of the spectral peak increases and the energy is more evenly distributed over a larger number of partials. This can be further examined by plotting the number of partials that fall within 50% or 25% of the amplitude of the peak partial as seen in figure 22.

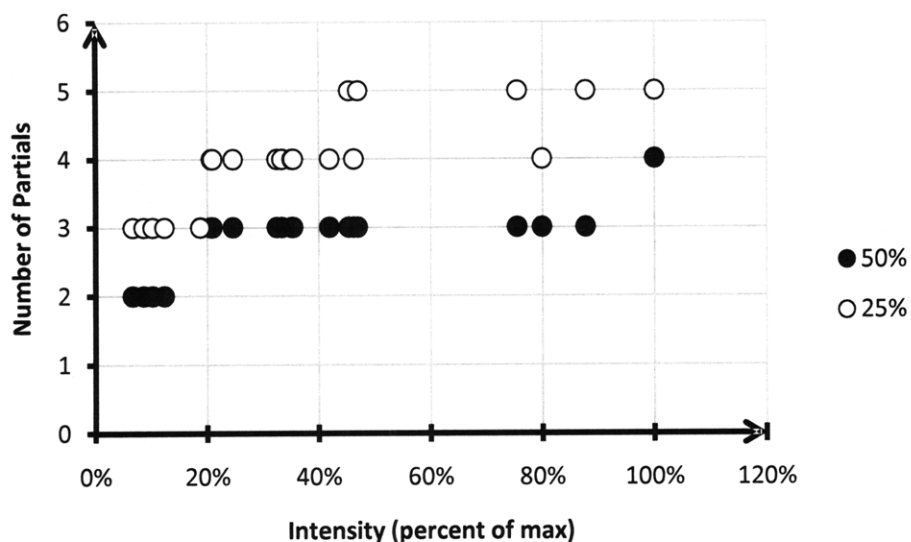


Figure 22: Number of Partial within a certain percent of the maximum amplitude as a function of note intensity.

Figure 22 shows an increase in width as the intensity increases for both the 50% and 25% of maximum intensity plots. This proves that as the intensity increases the notes total energy becomes spread more evenly over more partials. This trend suggests that as intensity increase from the softest to the loudest note, the timbre changes in “fullness” from “thin” to “thick”.

The final characteristic to observe is the strength of the fundamental. It is hard to tell from figure 20 exactly how the strength varies over intensity. Figure 23 plots the strength of the fundamental as a percentage of the maximum partial amplitude for each note. There seems to be a lot of variance, but in general the strength of the fundamental is stronger for lower intensity notes. As the intensity increases the fundamental becomes weaker. The means that as intensity increases the sense of pitch will become weak and texture will dominate the perceived sound.

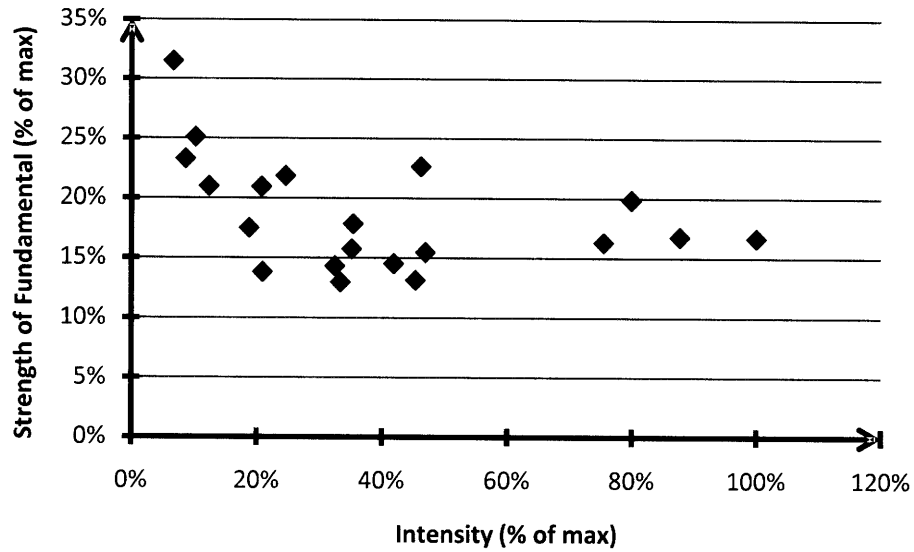


Figure 23: Strength of the fundamental (as a percentage of the maximum amplitude) as a function of note intensity.

The results of the number of partials and spectral envelope analysis presented above both support the conclusion that low intensity notes are “thin” and “smooth” with a strong clear sense of pitch. As the intensity increases the notes become “thicker” and “rougher” with a strong sense of texture but a less clear sense of pitch.

5 Conclusions

It is clear from this study that the frequency spectra of French horn tones changes in measureable ways as a function of frequency as well as intensity. In looking at the number of partials and the spectral envelope it is clear that low frequency notes and loud notes lie together on one end of the timbre spectrum while high frequency and soft notes lie on the other end. The low or loud notes are comparatively “rougher” and “fuller” sounding than their high or soft counterparts that sound comparatively “smooth” and “thin”.

These timbre changes are supported by the two acoustical properties measured in this experiment: number of partials and shape of the spectral envelope. The number of partials present in the frequency spectrum increases for both decreasing frequency and increasing intensity. This applies to both the total number of partials and the number of partials with critical band overlap. The increase in the total number of partials changes the timbre from “thin” to “full” as different frequency components, both consonant and dissonant, are added to the note. The increase in the number of partials with critical band overlap changes the timbre from “smooth” to “rough”. This occurs due to beating in the higher partials because of how close they are in frequency.

The shape of the spectral envelope supports these timbre changes as well. As the center of the spectral peak moves from higher to lower harmonics, the timbre changes from dissonant and “rough” to consonant and “smooth”. As pitch decreases and intensity increases, the center of the spectral peak moves toward lower harmonics. As the width of the spectral peak increases, the timbre of the note changes from “thin” to “full” as more partials contribute significantly to the note. For increases in intensity and decreases in pitch, the width of the spectral peak increases. Finally the strength of the overtone controls whether the note will sound stronger in pitch or texture. Strong fundamentals give a very strong sense of pitch to the note. As frequency increases and intensity decreases the strength of the fundamental increases.

The results of this study give a clear and quantitative measure of how static spectral timbre for the French horn varies with frequency and intensity. This study shows how intensity and frequency affect spectral timbre, but the specific mechanisms that cause this change have not been explored. The next step in extending this experiment would be to systematically link these changes to the physical characteristics of the instrument so that the timbre can be easily predicted given the instrument geometry and material proportion as well as the environmental properties. Further analysis could also be explored in the area of dynamic timbre especially attack and decay characteristics. This would be particularly useful when looking at different articulations. There is also an interest in the effect of mutes or the positioning of the hand in the bell and how this changes the timbre characteristics of the notes. Finally, the effect of room acoustics is extremely important in the horn because of how the bell is positioned while performing and would be worth studying. Only once many aspects of timbre are quantitatively explored can a mathematical model for predicting timbre be developed and readily used in instrument design.

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