TRUMPET TIMBRE: A COMPARATIVE INVESTIGATION
OF THE TONE QUALITY OF TWO PROFESSIONAL C TRUMPETS

DOCUMENT

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By

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* * * * *

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Quartet in Two Movements

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   Fanfare
   Hornpipe
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   By the Lake
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   Vif
   Nocturne
   Final

Concerto
   Introduction and Dance
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   March

Music for Five Trumpets
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   Finale

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CHAPTER I
INTRODUCTION

Musicians frequently discuss the virtues of one particular instrument versus another, or compare the results obtained from modified or unmodified versions of the same instruments. The flautist who invests in a gold or platinum headjoint, or the violinist who procures a fine old instrument at great expense, illustrates the importance that a quality instrument holds for the performer. Manufacturers of musical instruments are vitally concerned with designing and building instruments that will produce the results most desired by musicians.

Of the many components which contribute to excellence in instrumental music performance (tone quality, intonation, technique, etc.), tone quality is the one most dependent upon the instrument itself. An enormous amount of an instrumentalist’s time is devoted to obtaining a "good" tone, and it is tone quality more than any other single factor that the professional player evaluates when selecting an instrument.

The current study reports the author's own investigation of the tone quality of two currently available professional quality trumpets. This effort was prompted by the small amount of research related to the topic, and by a desire to contribute a source of descriptive
information on trumpet tone quality for musicians and instrument makers. The present investigation includes an examination of the related literature and previous research concerning trumpet tone quality, a comparison of the physical properties of tones produced by the professional instruments, and a presentation of subjective evaluations by selected artist performers.

In one of the more comprehensive sources of information relating to musical timbre, researcher John Grey relates:

The state of knowledge concerning the perception of sounds which have the complexity found in musical instrument tones is much less advanced on a scientific level than on the practical and intuitive basis obtained by experienced musicians. (Grey, 1975, p. 1)

It is with this thought that the present study was undertaken.

Evaluating tone quality of musical sounds is a subjective task. Magnitude estimation procedures or other means of subjective ratings may be used with listeners of varying sophistication. Anecdotal information by performers and listeners may also be assembled. Because such evaluations are subjective, relying on a value judgement by the listener, the perceptions of what is considered a "preferred" tone quality will vary due to personal tastes, training, or a host of other factors. This may or may not impugn the validity of such evaluations, depending on one's perspective. Often, the more empirically-minded members of the scientific community will dismiss the results of this sort of investigation, while those doing research in psychoacoustics will freely accept such subjectivity. It is often this subjective information that is the most highly valued by the musician.
Identifying and comparing measurable characteristics of musical sounds is less subjective, and may be accomplished by comparing tonal spectra of musical tones. A spectral analysis provides a visual display of the relative amplitudes of the component frequencies, and the varying relative strengths of partials during a given tone. By using such spectral analyses, one is able to compare the physical composition of tones from different instruments. The particular *musical* value of such investigations is sometimes questioned. It is true that timbre is a humanly perceived quality, and that even the most sophisticated test instruments are merely devices to simulate the human ear.

**Background**

The trumpet most frequently used by orchestral players in this country for the last few decades has been the Bach Stradivarius. This instrument, originally manufactured by the Vincent Bach Corporation, and now by the Selmer Company of Elkhart, Indiana, is used extensively by college music faculty, and has been widely recommended by brass teachers to instrumental music students. In recent years the Bach trumpet was the instrument of choice of most of the principal trumpet players in major symphony orchestras in this country. Since that time, some notable players have begun to adopt instruments designed and built by the D. G. Monette Co. of Chicago, Illinois, a relative newcomer to the instrument manufacturing business. Among these performers are Adolph Herseth, principal trumpet of the Chicago Symphony Orchestra; Charles Schleuter, principal trumpet in the Boston Symphony; and Thomas Stevens, principal trumpet in the Los Angeles Philharmonic. Instruments by these two manufacturers, Bach and
Monette, were selected for the present investigation because they are being used extensively by such prominent and respected performers. Similarly, these performers, each of whom are familiar with both of the instruments in the present study, have contributed subjective information concerning their impressions of characteristics of the two trumpets.

**Purpose and Significance**

The purpose of this study was to investigate the differences in tone quality between the Bach and Monette C trumpets by examination and comparison of the physical differences found in spectral analyses of tones produced by the two instruments, and through subjective evaluations of the tone quality by several recognized artist/performers. An important aspect of this study is a critical examination of the related research and literature concerning trumpet tone quality.

The selection of the Bach and Monette instruments in the present study was made because of their use by prominent and respected professional players in major American orchestras. The information presented here should be relevant to performers of the trumpet and other brass instruments, and is intended primarily for musicians. In the trumpet-playing community, and other musical circles as well, many claims and unsubstantiated opinions are exchanged concerning the relative merits or differences in the sound of one instrument versus another. This has been true recently in the case of the Bach and Monette trumpets. The present study was undertaken in part to provide evidence of some basis for these claims.
While research is available concerning the timbre of musical instrument tones in a general sense and some investigations specific to trumpet tone quality have been done, detailed information concerning similarities and differences between like instruments is not plentiful. Musicians of course do not accept that all violins, pianos, or trumpets produce the same tone quality by virtue of their familial similarities; yet the experimental literature concerning timbre is lacking in information about tonal characteristics of like instruments from different manufacturers, or of different models, etc. The subtle differences in the timbre produced by particular instruments are significant to musicians, and contribute to a large degree in the selection process. The current study is intended to provide an initial source of detailed information comparing two professional quality C trumpets from different manufacturers.

It is of some importance to be able to identify the characteristics of trumpet tone quality, or timbre, that are considered superior by recognized artist-performers. This information is significant to manufacturers wishing to pursue instrument designs that maximize the physical attributes of sounds preferred by artists who perform on these instruments. Information derived in the present study may also add to the growing body of knowledge concerning the physical characteristics of trumpet tones.

Some research has been done using visual feedback, such as spectrographic or oscillographic displays, as teaching aids for the development of tone quality in instrumental or vocal performance (Small, 1969; Stancil, 1977; Wilson, 1979). Investigators in this area may
find the information in the present study helpful in establishing appropriate spectral models for such applications requiring trumpet tones.

Assumptions and Limitations

This study, because it involves aspects from the dissimilar disciplines of music and acoustics, presents some interesting considerations. For the purposes of this investigation, it is important that the information provided be of interest and value to musicians, and particularly trumpeters. Unfortunately, much of the research available on musical instrument timbre involves such a severe reduction of information due to test design that the results are of questionable musical value. Several such studies will be discussed in Chapters II and III.

Although the use of verbal descriptors for tone quality has not been successful in providing a large amount of empirical information about the perceptual process of timbre discrimination, it is perhaps the most valid measure of aesthetic responses to sounds -- musical or otherwise. Because this study was being undertaken in large part for musicians and seeks to describe similarities, differences, and preferences in perceived tone quality in addition to relative physical differences, it was concerned in part with subjective verbal descriptions of sound characteristics. For this reason, subjective musical terms such as resonant, edgy, bright, thick, brilliant, as well as others will be considered musically and aesthetically valid. No effort to reconcile specific terms to physical data were made. A
discussion of previous studies concerning verbal descriptions of timbre is a topic in Chapter II.

Characteristics of the instruments in the present study may be discussed and differences noted, but specifications and manufacturing methods are not factors of this investigation. Readers will find this information available from the companies themselves. Though the focus of this study is the tone quality of the two trumpets being analyzed, subjective comments often refer to impressions of the way an instrument "feels" or responds to a performer. These impressions are included in the information presented in Chapter VI.
CHAPTER II

RELATED LITERATURE - MUSICAL TIMBRE

In order to establish an understanding of the subject of musical timbre as it is used in the context of this study, this chapter will examine some of the major points related to the topic that have been clarified by previous research. Several studies dealing more specifically with trumpet timbre will be discussed in Chapter III. Readers interested in a comprehensive review of the literature related to musical timbre are encouraged to consult An Exploration of Musical Timbre (1975) by John Grey.

Problems in Defining Musical Timbre

An often cited definition for timbre is the one approved by the American Standards Association in its publication, American Standard Acoustical Terminology (1960):

Timbre is that attribute of auditory sensation in terms of which a listener can judge that two sounds similarly presented and having the same loudness and pitch are dissimilar....Timbre depends primarily upon the spectrum of the stimulus, but it also depends upon the waveform, the sound pressure, the frequency location of the spectrum, and the temporal characteristics of the stimulus (American Standards Association, 1960).
From this definition one can see that differences in timbre may be attributed to any features of a sound except for loudness and pitch. These may include the attack and decay portions of a sound or any other features that may change throughout the duration of a tone, as well as possible influences of particular listening environments.

Recent literature in psychoacoustics and music perception shows that timbre is even more complex than the preceding definition suggests. Timbre is an attribute of sound which enables differentiation between sounds of differing loudness and/or pitch also. In the realm of acoustic wind instruments, timbre is often dependent on either loudness or pitch, or both. Experimental literature on timbre has only recently begun to unanimously assert that it is a multidimensional quality of sound — that is, dependent on a number or interrelated features. It is interesting that the term itself is from the realm of music, and has been applied to the acoustical phenomenon which enables listeners to discriminate between two different sounds of equal pitch and loudness.

Early definitions of timbre were concerned with only the steady-state portion of complex sounds, without regard to the various temporal features. The concept that musical sounds are made up of a number of harmonically related simple tones of varying strengths was presented in 1843 by George Ohm. Jean Baptiste Fourier showed that periodic waveforms consist of a set of harmonically related sine waves, and that every periodic waveform results from the sum of one or more sine waves. Building on these works, Helmholtz deduced that the timbre of a complex tone is dependent on the number and relative strength and
distribution of its harmonics (Helmholz, 1877, pp. 126-127). This important study was restricted to steady-state sounds, and is therefore limited in application since musical tones and naturally occurring sounds are characterized not only by such spectral characteristics, but also by time-dependent features. More thorough investigations have recently taken into account additional factors which can contribute to perceivable changes in timbre.

One feature of sound which causes tones to be perceived as having similar timbre, and which is related to the tone's spectral composition, is its formant structure. In terms of the human voice and acoustic instruments, the instrument itself encourages a particular vibration system which provides the individual timbral signature for the source by emphasising spectral peaks in absolute frequency regions, known as formants, which are related to the size, shape, and material of the resonating body (Dodge and Jerse, 1985, p. 54).

Importance of Transient Features of Musical Sounds

Research has shown that the timbre of musical sounds is dependent not only on the number, relative strength, and distribution of the various partials present in a steady-state sound, but also on the transients, or features that change, during the attack and decay portions of the sound. We know that one of the most important cues for the identification of musical instruments comes from the attack portion of a tone, and also that instrument recognition for steady state tones -- even those without attack and decay information present -- is better for tones with vibrato than for those without (Saldanha and Corso, 1964). The changes in a musical sound during the attack and
decay consist of more than simply an overall change in amplitude of all harmonics. The spectral analysis for the decay portion of the Bach trumpet's E natural (figure 1) illustrates how the relationship between harmonics changes as the tone dies away.

![Power Spectrum: D_E5_DECAY](image)

Figure 1. Monette trumpet E5, decay portion.

Even an instrument tone of short duration -- approximately one-quarter of a second -- contains a great deal of variation in the harmonic content, amplitude, and frequency, as may be seen in many of the spectral analyses in the Appendix of the present study.

The differences in rise-time and amplitudes for the various harmonics of brass instrument tones have been investigated. It is known that the onset of a particular harmonic is related to its frequency, with the higher frequency components beginning later,
rising more slowly, and achieving a smaller amplitude than lower frequencies (Risset, 1966; Luce and Clarke, 1967; Beauchamp, 1975). One method of synthesizing cornet tones has made specific use of these interharmonic characteristics of acoustic sounds (Beauchamp, 1975).

Recent interest in synthesizing acoustic instrument tones has provided much of the available information concerning musical timbre. A computer study by Risset (1966) determined that the most important characteristics of trumpet tones included the attack time, which was shorter for low frequency harmonics than for high; the minute fluctuations in the frequency of the tone as it is sustained; and the spectral content of the tone, which is richer in high frequency components as the intensity increases. Subsequent measurements have been done to determine the relative importance of the spectral envelope, or steady-state portion, and the temporal envelope which includes onset and decay components. It has been found that the importance of these two characteristics varies from instrument to instrument, and that for the trumpet, they are of approximately equal value (Strong and Clarke, 1967, p. 284). Risset claims he was able to generate synthesized tones "indistinguishable from the real tones by skilled musicians" making use of these characteristics (Risset, 1965, p. 1). It has further been found that synthesized trumpet tones sounded "unrealistic" and "uncharacteristic of a musician blowing into a horn" when the frequency variations during the attack portion of the sound were not included (Freedman, 1967, p. 803).
The importance of the attack transients is generally accepted in the literature, and the initial findings of Saldhana and Corso have been reinforced by other studies since their original publication more than twenty years ago. It should be noted however, that the original research, as well as that of Risset, Freedman, and others was carried out using only single, isolated tones -- independent of any musical setting. Further, these studies used only synthesized tones for testing. A 1984 study used digitally recorded and edited musical phrases rather than only single tones to test listener instrument identification responses, both with and without attack transients. Findings indicated that although transients were sufficient for musical instrument identification of single tones, they were not sufficient or necessary in whole-phrase contexts (Kendall, 1984). This suggests that in other than single-note occurrences, attack transients may not be as important to timbre perception as previously thought. Obviously, one must be careful not to assume that research findings will apply to situations differing from those in which they are derived. It may also be true, as many musicians suspect, that investigations done in a musical context may arrive at different conclusions than those conducted in psychacoustic research settings.

A recent study by Charbonneau (1981) investigating the effects of data reduction on the perception of timbre has reinforced the findings of Risset and Freedman, showing that the spectral envelope and variations of component frequencies are important and necessary for timbre recognition. In fact he underlines the importance of the temporal properties of musical timbre by stating that "the analysis of
one instrumental note is rarely sufficient for synthesizing a note of differ ing pitch, intensity, or duration." (Charbonneau, 1981, p. 19). His finding that the amplitude of the component frequencies of complex tones is the most critical feature to timbre recognition is in agreement with the theories of Helmholz and the findings of Beauchamp and Risset.

The Influence of Pitch and Intensity on Timbre

The dependence of pitch upon timbre is obvious to musicians. The differences heard between the lower and upper ranges of an instrument are striking. Examination of the spectral analyses in the Appendix of the present study will show the changes that occur in the harmonic content of trumpet tones in the different ranges of the instrument. These analyses also show clearly the differing rise times of the various harmonics of the sound mentioned in the previous discussion of attack transients.

Another characteristic of musical tone which may influence timbre is loudness. It has been shown that the spectrum of trumpet tones varies greatly with changes in dynamics (Benade, 1976, p. 424). This assertion is reinforced throughout the literature, and is evident in the spectral analyses in the present study. An investigation of timbre variations due to changes in loudness discovered that waveforms for acoustic instruments tend to vary in more than just amplitude. It was found that the shape of the spectral envelope changes continuously during a tone (Luce, 1975, p. 568). This same study noted that the harmonic content of trumpet tones showed a strong increase in high frequency components relative to low when played at fortissimo levels.
An investigation which seems to contradict this body of information used instrument tones recorded at different dynamic levels which were then altered electronically to be played back to listeners at the same loudness. Listeners were unable to guess the dynamic at which the recorded tone was originally played. This information was used to imply that loudness may not be a factor in timbre judgements (Clark and Milner, 1964).

Not only may the perception of timbre be influenced by pitch and intensity, but in a previous investigation by the author, changes in the timbre of recorded trumpet tones were incorrectly interpreted by listeners to be changes in pitch, when in fact only the amplitude of particular frequency bands had been changed. A similar effect has been demonstrated for changes in clarinet tones (Wapnick and Freeman, 1980). The reverse is also true. Grey (1975) indicates that he has found slight mistunings of notes with identical timbre have been judged to be of different timbres (p. 26). This interrelationship of timbre and other features of sound is largely responsible for the limited understanding of the topic due to the difficulty of isolating variables for study.

While responsible to a large degree for the identification of instrumental timbre and timbral perception generally, the previously discussed studies of temporal features are limited to single tones. Grey makes the following point concerning musical tones in a melodic context:

Another possible component of the timbral signature of an instrument comes into play with the existence of more than one note, as in a melodic phrase, and has been referred to
as the tracing of the *resonance structure* of an instrument by the sampling of several differently pitched spectra played upon that instrument. Of course, the existence of invariant temporal features in a set of differently pitched notes played upon the same instrument would also comprise an important cue for identification (Grey, 1975, p. 10).

The sort of investigation suggested by Grey would be of value because it would incorporate a setting more similar to that normally occurring in a musical context. Until recently, very little had been done in this area, perhaps due to the complexity of dealing with the number of variables inherent in a melodic series of musical tones. In addition to the investigation by Kendall (1984) cited earlier, another very recent study on this topic, an analysis of the tones of orchestral instruments performing different ascending and descending intervals in both slurred and articulated manners, revealed a number of interesting features. Both slurred and articulated notes were found to be *connected* in performance, characterized only by a drop in amplitude between them. The difference between slurred and articulated (tongued) transitions was found to be simply a greater drop in amplitude for tongued intervals. The transitional material was found to influence the sound of the notes, with a greater effect on the decay portion of the first pitch than on the attack of the second. The transition between both tongued and slurred notes was found to be very quick -- generally only a few cycles of the waveform, and the connections by skilled players was found to be very consistent (Strawn, 1986, p. 879). Some, though not all, of these findings are confirmed in the current investigation.
Subjective Descriptions of Timbre

For a musician, timbre may describe the characteristics of a tone which enable the listener to tell the difference between a trombone and a clarinet or, more generally, between a brass instrument and one from the woodwind or string family. The term is also used to describe the more subtle differences between the sounds of like instruments, for example, "dark" or "bright" trumpet tones. Such verbal descriptions are common in music, and must be accepted as accurate judgements of dissimilarity by the listener. These are also judgements upon which musical and aesthetic preferences may be based.

For the experimental psychologist investigating the perception of specific acoustical events, there are several problems with verbal descriptions of timbre. It is possible that listeners may use different terms to describe the same perceived differences, or conversely, the same term may describe different timbral qualities to various listeners. Psychological studies of timbre perception have offered verbal labels such as "roughness," "brightness," "fullness," sweetness," and "pleasantness," for differences in complex tones (Helmholtz, 1954; Lichte, 1941). These responses provide little information on timbre perception, but are significant to musical studies.

One study attempted to investigate verbal descriptors of clarinet tones in terms of frequency of use, consistency of selection, and to determine whether or not the same terms were used by both musicians and non-musicians. Beginning with a list of more than one hundred adjectives, it was found that while it may be possible to identify a number of terms which were not appropriate descriptors of clarinet
timbre, it was not possible to identify a small group of terms useful to describe specific aspects of timbre. It was discovered that musically trained listeners did tend to be consistent in applying verbal descriptors to particular clarinet timbres, while the same was not true for listeners with no formal musical training (Abeles, 1979, p. 6).

Although it may be argued that verbal descriptors have limitations when applied to tone quality, the fact remains that musicians commonly use words for pedagogical purposes as well as to differentiate between musically relevant timbral features. The uniformity of the use of these terms by musicians is striking.

Studies by Pratt and Doak (1976) and von Bismarck (1974) have had success in developing semantic scales for the timbre of musical sounds. These scales were found to be applied consistently by musicians to sounds with varying harmonic content, and less consistently by non-musicians. Unfortunately, the stimulus tones used in both of these investigations were somewhat non-musical in that they were synthesized and generated electronically. Interestingly, the "dull-bright" scale of Pratt and Doak, and the "dull-sharp" scale of von Bismarck (which seem to correspond), were found to be the most reliable in each study. The similarity between these two scales and the "dark" to "bright" scale traditionally employed by trumpeters may be more than coincidental.
CHAPTER III

RECENT INVESTIGATIONS INTO THE TIMBRE OF TRUMPET TONES

While Chapter II reviewed a portion of the experimental literature concerning musical timbre in general, with some specific mention of information relating to trumpet timbre, the present chapter will examine four investigations into the timbre of trumpet tones which are closely related to the present study.

Figgs

An investigation of trumpet tone quality was undertaken in 1978 by Linda Drake Figgs. Her study evaluated tones from nine different Bb trumpets. The nine instruments were divided into three groups according to price range, and tones were evaluated in order to determine: 1) if musicians were able to discriminate between the tone qualities of the instruments, 2) if the more expensive instruments were preferred by listeners, and 3) whether the more expensive instruments produced more elaborate waveforms. The answers to these questions were sought in order that music educators, armed with this information, might be able to recommend instruments with the best tone quality/price relationship to students.

The instruments tested were randomly selected from those available in four northeastern Kansas music stores. Seven isolated tones and two contrasting excerpts were performed by a professional
jazz/commercial trumpet player using his own customized "lead" trumpet mouthpiece. The performance was recorded on magnetic tape at 7 1/2 i.p.s., and the tape used for analysis and for subjective judgements was a second-generation copy dubbed from the original at 3 3/4 i.p.s. Subjective evaluation used a magnitude estimation procedure by which university trumpet players and area band and orchestra directors (n=51) rated the tone quality of the tones and excerpts. Results were submitted to statistical analysis.

Objective evaluation of the trumpets was limited to the steady state portion of three tones on each instrument. Spectral analysis of the tones was done by computer, generated from the dubbed copy of the original analog recording. Analysis yielded the mean number of "prominent" partials, order of partials in terms of relative amplitude, and an indication of each tone's "departure from harmonicity." Graphic time/frequency/amplitude representations of the tones are presented, as well as single "slice" amplitude/frequency plots of tones from some of the trumpets.

Conclusions drawn from the study were that tone quality and waveform varied for the different trumpets, but not in a conclusive way. Price range appeared irrelevant to listener's judgements, as did the generation of more elaborate waveforms. Figgs also noted that "further study of the differences in trumpets is highly recommended."

There are several factors which must be considered when interpreting the significance of the study. Figgs points out some of them, citing the somewhat nonstandard mouthpiece, the jazz/commercial orientation of the performer, the fact that several different testing
locations were used, and various player inconsistencies and errors on the recorded tones and excerpts. Some additional questions might also be posed. Is the signal quality of a copy of a 3 3/4 i.p.s. analog dub sufficient to reveal minute timbral differences in tone quality between trumpets? Will the resolution of a spectral analysis from such a source, and limited to nine harmonics be sufficient to reveal any physical evidence of subtle timbral changes between trumpets? Is a spectral analysis limited to frequencies below 4,000 Hz. adequate for an investigation of this sort? In addition to these points, the researcher's contention that harmonicity is a desirable attribute of trumpet tone quality is an assumption unsupported by previous research. The landmark investigation of trumpet tone by Risset, which is not cited in Figgs' references, suggests that this is not the case (1966, p. 35). Even if harmonicity is, in fact, a significant feature of trumpet tone, an analysis of no more than seven spectral peaks may not be sufficient to establish degrees of harmonicity.

The study does present a large body of statistics analyzing the subjective responses from listeners. If one accepts the evaluations of college-age trumpet players and public school band and orchestra directors as valuable, Figgs statistics are of considerable interest. Subjects were very consistent in choosing a preferred instrument for isolated tones and for excerpts, in spite of the reported performance errors and inconsistencies which were judged to be insignificant. Curiously, a different instrument was preferred for single tones than for complete excerpts. The trumpet preferred for isolated tones was one of the low priced instruments, while the trumpet preferred for the
taped excerpts was a high priced one. In nearly all cases, higher
pitches were preferred to lower ones. This is perhaps due to the the
particular mouthpiece employed by the performer.

It was not possible to establish any correlation between listener
preference and the features revealed by computer analysis. Waveforms
varied for the individual trumpets. Figgs concedes that the spectral
analysis might have been more revealing if attack transients had been
included, but limitations in the computer analysis program precluded
this.

Dunnick

A different approach was taken in 1980 by Kim Dunnick who
investigated physical differences in trumpet tone qualities. The study
is limited to measuring by spectral analysis the relative strengths of
harmonics present in the steady-state portion of five tones on four
different brands of Bb trumpets.

The tones were performed by the researcher, a professional
trumpeter, using his own mouthpiece, a Bach 1 1/2-C with a size 24
throat, and tape recorded at 7 1/2 i.p.s.. Thorough efforts were made
to insure that the recordings of all tones were done under conditions
as identical as possible. Three recordings of each of the test tones
taken from the end of a short orchestral excerpt were made on each
trumpet, and fifteen instruments representing four different brands
were selected for analysis.

After spectral analysis, the resulting amplitudes of component
harmonics were manipulated as described in the following excerpt:
The spectrum for a given pitch was then compared with the spectra for the same pitch from the other two instruments of the same make and model. The standard deviation from the mean of these tones was found for each partial. Then the average deviation for all the partials of the pitch was found. This procedure was followed for all five pitches within each group of like instruments chosen for the experiment. The five average standard deviations for the five respective pitches of each group were then averaged to give one number indicating the average standard deviation for the spectra of the given instrument group (Dunnick, 1980, p. 17).

The rationale given for averaging average standard deviations of average deviations from the mean of individual partials for five different pitches is to arrive at a number which "represents the average standard deviation for all the amplitudes within all the analyzed pitches of a given instrument... (to measure) the conformity of the spectra of the three instruments within each group" (Dunnick, p. 23).

Results of Dunnick's spectral analyses are included in a forty page appendix to his document. The conclusion that there is no significant difference in sound spectra between the different instruments investigated under the conditions of the test is fully warranted. Because the timbre of instrument tones varies throughout the range of an instrument, it is logical to assume that different notes may tend to have different characteristic spectra. It is a questionable step to average averaged means from individual harmonics of different pitches to derive a figure useful in meaningful comparison. For this reason, the value of the conclusions of the study may be questioned.
Dunnick speculates on the reasons for his unexpected conclusions. The possibility that the performer may be the largest factor in the production of a particular tone quality is mentioned, as is the possible influence caused by recording the various tones on several different days. A suggestion is made to carry out a similar study using a mechanical device to sound the instruments, thus eliminating the variability of a human performer. While this may (or may not) insure stability of that one factor in tone production, it certainly would not yield any useful information about trumpet tone quality in any realistic musical setting. In order to tell us anything about the sound of a trumpet, the trumpet must be blown by a trumpeter. This simple idea is often neglected in psychoacoustic and perceptual research, yet the results of this same research are claimed to be meaningful to the musical field. The possible role of attack and decay transients, and the influence of the particular recording conditions, and the role of the mouthpiece in timbre production are also suggested as possible reasons for the conclusions of this study.

Enough data was assembled in the course of Dunnick's study to derive useful information concerning the harmonic content of trumpet tones, though the opportunity was not seized. A more thorough review of previous experimental literature on timbre might have provided a different direction to this study, which sought to provide some interesting information about brass instrument timbre.
Risset

An early computer study of trumpet tones was undertaken by Jean Claude Risset at the Bell Telephone Laboratories in 1966. The study was undertaken to obtain detailed information concerning the physical attributes of trumpet tone in order to develop a method of synthesizing trumpet-like tones sounds by computer.

Selected tones from musical fragments (including the *Concerto in Eb* by Haydn and Gershwin’s *Rhapsody in Blue*) were recorded in an anechoic chamber on a reel to reel tape deck at 15 inches per second. Selections were performed by a professional trumpeter and included examples from various ranges, tempos, dynamic levels, and articulations, both with and without mutes.

Copies of the recorded tape were spliced or filtered to create segments of trumpet tones for use in experiments to determine importance of attack, steady state, and decay portions. The analog tape was filtered to remove information above 4000 Hz, and processed through an analog to digital converter for computer analysis. Analysis results were used to create models for simplified synthesis of short (.15-2.5 seconds) brass-like tones. Synthesis was accomplished using separate individually controlled oscillators for each harmonic.

This early computer study provided a large amount of previously unavailable information concerning the physical properties of trumpet tones. The importance of attack portions and overtone structure to instrument identification were measured. The sufficiency of limiting frequency information to below 4,000 Hz is a shortcoming of this study, and was imposed on the study by the state of computer equipment.
available and the excessively long time required for computations. It has since been shown that a great deal of the harmonic content of trumpet tones, particularly at loud dynamic levels and in the low register, exists above the 4,000 Hz limit of Risset's filters.

Despite the limits of his method, Risset was able to establish a number of general characteristic of trumpet tones. He determined that the tones are essentially harmonic in nature, and that the frequency spectrum varies for tones of different pitch. This fixed formant model (versus fixed spectrum) proved to be a workable synthesis technique. A formant region near 1500 Hz was identified, and the presence of larger numbers of high frequency components as intensity increases was noted. Tones from the low register were found to be especially rich in harmonics, while upper register tones were less so.

Asynchronous attack and decay properties were found for tones in all registers, with high frequency components entering last and decaying earliest. Risset also noted the presence of transients at onset, and a stability of the steady state waveform.

Tones synthesized using the findings of Risset's study were judged to be indistinguishable from authentic recorded trumpet tones during informal testing with musical subjects. This early use of the computer for analysis and manipulation of sounds demonstrated a potential still being realized today, and provided a large amount of detailed information concerning the physical correlates of trumpet tones which has proved to be quite accurate.
Morrill

A more recent effort by Dexter Morrill to develop a method of synthesizing trumpet tones parallels that of Risset. Morrill undertook a detailed investigation of trumpet tones for this purpose in 1977. He created an analog reel to reel tape recording at 15 i.p.s. of the thirty-one chromatic trumpet tones from F#3 to C6 as played on a Bach C trumpet by a professional commercial trumpeter. Isolated tones with a duration of approximately .5 seconds each, at a "comfortable volume, without a hard or very legato type of attack." The recording was then digitized and analysed by computer to obtain spectral information to use as a basis for data reduction synthesis.

Although Morrill's synthesis technique was limited in success at a convincing synthesis for the lowest tones on the trumpet, he was able to create a useful and versatile algorithm for manipulation and creation of a large number of sounds with trumpet-like characteristics. In doing so, a large body of information concerning the spectral evolution of trumpet tones throughout the complete range of the instrument was assembled. This information, which unfortunately was not analyzed beyond the requirements of Morrill's synthesis project, is in the form of time x frequency x amplitude plots and graphs of the relative amplitude of component harmonics (Morrill, 1976, 1977).
CHAPTER IV

METHOD FOR PHYSICAL COMPARISON

OF BACH AND MONETTE TRUMPET TONES

This chapter describes the trumpets used to obtain recorded examples, outlines the procedures used to record and analyze sounds for the present study, and describes the forms of the resulting data.

Description of the Trumpets

The instruments used to record the sounds for the comparative analyses were a Bach model C180L C trumpet with a 229 bell and a 25-S leadpipe (serial number 286174), and a Monette C trumpet (serial number 046). The Bach instrument is silver plated, and the Monette is unplated brass. In order to assure that the instruments themselves were responsible for any differences in physical spectra revealed by analysis, the same mouthpiece was used on both trumpets for all recorded tones. The mouthpiece used was a standard silverplated Bach 1-1/4C.

Procedures

All tones were performed by the author in the electronic music studio at The Ohio State University School of Music. Intonation for all of the tones was checked with a Korg AT-12 tuner calibrated to A=440 Hz. Tones were performed at a dynamic level subjectively judged by
the performer to be an orchestral *mezzo-forte*, unless otherwise indicated. To minimize potential variables in recording situation, noise levels, etc., the recording of all tones for the present study was done during a single session, and time was taken by the performer to tune and adjust to each instrument before any tones were recorded.

Recording was done using an AKG-451-E microphone into both channels of a Sony PCM 601 ES D digital audio processor and recorded in digital format on a Sony SL-HF-450 videocassette recorder using Sony L-750 ES-HG videotape. The microphone was placed slightly off-axis less than one meter from the bell of the instrument. Several recordings of each sound were made on each of the instruments, and the master digital tape was edited using the Sony PCM 601 ES D and a second Sony SL-HF-450 videocassette recorder to provide one example of each selected sound played on each of the two instruments.

The recorded digital signals were further edited to eliminate extended silences between tones or to isolate attacks and decays of selected tones, and were then transferred to individual computer files using MacMix 1.1 and Dyaxis software on an Apple Macintosh Plus computer with a Dyaxis hard disk storage system. Hard disk files were copied to floppy disk and transferred to a MicroVax II computer for spectral analysis.

The spectral analysis program is capable of providing information in several formats, including graphic output in the form of a three dimensional "landscape" plot of frequency, time, and relative amplitude (Figure 2). The frequency scale may be specified for each plot, and has been selected to provide the most easily readable display.
Figure 2. Frequency x Time x Amplitude plot. (The tone is E5 on the Bach trumpet)

Figure 3. Single sample plot of frequency and amplitude (The tone is A5 on the Monette trumpet)
The amplitude display in every case is relative, with the strongest harmonic component present in each sample plotted at full scale. It is possible to isolate attack or decay portions of given soundfiles by specifying the start time relative to the beginning of the file.

It is also possible to isolate a single sample, or "slice", from a longer sound (see Figure 3, preceding page). This has been done in order to illustrate the spectral components of the steady-state portions of some of the tones. The amplitude in these single slice plots is again relative between harmonics, with the strongest frequency band represented at full scale in the plots.

Waveform representations from the Dyaxis files on the Apple Macintosh are also reproduced in the present study to illustrate spectral energy present during the slurred and tongued transitions between notes, and to show the relative amount of time required for the particular transitions to occur (see Figure 4, next page). These amplitude envelope graphs have been edited to approximately .3 seconds each to facilitate comparison. The various shadings in the waveform representation are artifacts of the display, and are not significant.

A comparison of the individual evolution, strength, and decay characteristics of the first nine harmonics of two different tones on each of the instruments is also presented. This is possible through the use of Amplitude x Time graphs of each harmonic (numbers 1-9) produced by Phase Vocorder analysis and a graphing program. The amplitude of these plots (included in the Appendix) is also normalized, and each plot illustrates 2.0 seconds of the soundfile.
Figure 4. Amplitude envelope plot of a tongued transition.

Comparisons of these various representations have been used to identify similarities and differences of the steady-state, attack, decay, and transition portions of the digitized Bach and Monette trumpet tones. The tones recorded for analysis are listed in Table 1, along with the musical notation for each soundfile, and an indication (under "analysis") showing which files have plots included in the present study.

Tones are referred to by the American Standards Association convention of numbered octave designations beginning from C. For example, the low C on the trumpet (notated "middle" C) is C4. All notes in the octave above this tone are specified with a "4", until the C one octave higher, which is C5, etc.
<table>
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<td>G5_1.25C</td>
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All spectral plots and amplitude envelope representations are found in the Appendix to the current study. Whenever possible, the two spectral analyses representing the same tone(s) on both instruments are presented on the same page to facilitate comparison. The first graph is a representation of a sound on the Bach trumpet, and the second graph a representation of the same sound on the Monette trumpet. Each graph is referenced by figure number when cited in the discussion of results in the next chapter.
CHAPTER V

RESULTS OF PHYSICAL ANALYSES

The results of the information yielded by the computer analysis of recorded trumpet tones will be presented in four ways. First, a comparison of spectral energy present in the steady state portions of sounds on the two instruments will be examined. Second, attack and decay portions of selected tones will be compared. Third is a comparison of slurred and tongued transitions between two different pairs of notes. Last is a comparison of the amplitude envelopes of the first nine harmonics of two different notes on each trumpet. Spectral analysis plots are found in the referenced figures in the Appendix.

Analysis of Steady State Tones

Samples from the steady state portion of the recorded trumpet tones represent the relatively stable waveform established after the onset and before the decay portions of the sound. The landscape plot of the tone D5 on a Bach trumpet (Figure 5) illustrates the characteristic stability of a trumpet tone over .25 second sample of the steady state portion. This is representative of each of the tones that were examined for the present study. A comparison of randomly selected single samples from steady state portions of tones recorded for the present investigation showed little or no variation in relative strengths of harmonics.
Figure 5. Bach trumpet, D5. Steady-state portion.

The plots for the note F#3 (figures 7 and 8) on the two instruments illustrate features consistent with many of the other analyses of steady state sounds presented in the current study. The Monette trumpet spectral display shows a larger number of bands of energy, with 23 spectral peaks apparent between 100 and 5500 Hz compared to 17 peaks for the Bach trumpet. The seventh harmonic is the strongest for both instruments, but the order of decreasing relative strength of harmonics is strikingly dissimilar for the two trumpets (Bach: 7, 5, 2, 4, 6, 3, 8, 1, 9, 11; Monette: 7, 6, 5, 8, 2, 3, 10, 4, 9, 11). A feature illustrated in these plots that is consistent throughout the current study is a concentration of energy in the frequency region from 1000-1400 Hz. This is the location of the strong
seventh harmonic for the note F#3 seen in the plots of both instruments, although the Bach trumpet plot displays two other relatively strong peaks at lower frequencies outside the region from 1000–1400 Hz. It can be seen that for this tone, the Bach trumpet tends to distribute spectral energy in several strong harmonics over a wider frequency range, while the Monette tends to focus energy into a narrower frequency region. The formant region from 1000–1400 Hz is typical of the trumpet, and has been noted in other more general studies of trumpet tones (Figgs, 1978; Morrill, 1977; Grey and Moorer, 1977; Risset, 1966).

The amplitude of the individual peaks in the spectral analyses are plotted so that the strongest peak is represented at full vertical scale, with a numerical value of the relative scale indicated. From this information, it is apparent that the strength of the individual harmonics on the two instruments is different. As can be seen in the plots for F#3, the dominant seventh harmonic of the Monette trumpet is stronger than the same harmonic for the Bach, while the fundamental of the Bach trumpet is stronger than the fundamental of the Monette. By comparison, the sixth harmonic (the second strongest peak) of the Monette trumpet displays nearly the same amplitude as the dominant seventh (strongest) harmonic of the Bach trumpet.

Analysis of graphs for the note C4 (figures 9 and 10) displays fifteen harmonics for the Monette and 13 for the Bach. Although the fifth harmonic is the strongest for both trumpets, the strength of this peak relative to the surrounding ones is different for the two instruments. Again, the Bach trumpet analysis reveals several
relatively strong harmonics surrounding the strongest peak, while the Monette shows a dominant single peak, more than twice as strong as the adjacent ones. The order of relative harmonic strengths is different for the two instruments. (Bach: 5, 4, 6, 3, 8, 7, 9; Monette: 5, 4, 6, 7, 8, 3, 9).

Similar characteristics are seen in the spectral plots for the note F4 (figures 11 and 12). The Monette has a greater number of harmonics (13, as compared to 10 for the Bach) present in the sound. The same harmonic, the fourth, is strongest for both instruments. Though the two instruments display very similar spectral composition for this tone, differences are the greater amount of high frequency energy for the Monette, and the presence of an additional strong peak for the Monette trumpet which is not present for the Bach. This is the third harmonic, which falls into the previously mentioned formant region of 1000-1400 Hz. Later in this chapter, individual plots of the first nine harmonics from this tone are presented for comparison.

At very soft dynamic levels the lower frequency components increase in strength relative to the higher frequencies. A comparison of the pianissimo A4 analyses (figures 13, 14, 15, and 16) shows six harmonics for the Bach trumpet and seven for the Monette, with the second harmonic the strongest for both. There is an obvious difference in the strength of the peaks adjacent to the second harmonic. The Monette trumpet shows a much stronger third harmonic, which also falls within the 1000-1400 Hz range, and a stronger fundamental than the same tone on the Bach. This is different from most other analyzed notes in which the Monette trumpet shows a single
peak that is notably stronger than the surrounding ones, as compared to the Bach trumpet which tends to show several relatively strong peaks. The strength of the dominant harmonic for these tones is nearly the same, making visual comparison easier than for other tones with dissimilar amplitude scales.

Comparison of the pianissimo plots of F4 with plots of the same note played fortissimo (figures 17, 18, 19, and 20) shows the characteristic increased number of harmonics for the louder tones discussed in Chapter II. Again, the Bach analysis reveals the presence of fewer harmonics than the Monette, with eleven peaks and fifteen peaks respectively. Along with a more complex waveform at the louder dynamic levels, the fundamental also decreases in strength relative to the higher harmonics. The distribution of energy is also different for the two trumpets. The Monette instrument generates a single very strong peak at approximately 1320 Hz, and the Bach shows two nearly equal but less strong peaks at approximately 880 Hz and 1320 Hz. The significant differences in the spectra of the tones at very soft and at very loud dynamic levels are quite evident. Despite the differences in detail between the Bach and Monette trumpets, the characteristics correspond generally with the previously mentioned findings of Risset and Morrill. In terms of relative strength and distribution of harmonics, the spectra of the recorded pianissimo A4 on the Monette trumpet is more similar to that of the Bach A4 at fortissimo than to the same note played pianissimo.
The center samples of staccato tones may not be from what is generally considered the steady state portion of a tone. Because staccato tones are of such short duration -- often no more than .2 seconds -- the tones are essentially all attack or decay. Inspection of the spectral analyses for the present study shows that it may take longer than this for a waveform to stabilize. This is particularly true in the lower register of the trumpet where the high frequency components enter after the initial attack. Examination of the spectral plot of single samples from a staccato D5 (figures 21 and 22) reveals fewer dissimilarities between the two trumpets than for lower frequency tones discussed above. The number of harmonics and order of strength is the same for both instruments. A difference is evident in the relative strength of the dominant second harmonic. On the Monette instrument the amplitude of the second harmonic is more than twice as great as the next strongest peak, while on the Bach the third harmonic is nearly as strong as the second. It appears that the energy is distributed into more than a single peak on the Bach, and into one primary band on the Monette. A more detailed examination of this and other staccato tones will follow in this chapter in a discussion of attack and decay characteristics of the recorded tones.

The plots of the note E5 (figures 23 and 24) on both instruments reveal similar distributions of energy, but dissimilar relative strengths. The Monette trumpet again shows more high frequency energy than the Bach, and more energy in the dominant peak which is centered at approximately 1320 Hz. The shape of the peaks of the odd numbered harmonics is unusual and different for the two trumpets. The Bach
displays flat topped peaks, and the Monette sloping peaks. A similar characteristic was also evident in the the plots for the note A4.

The plots for A5 (figures 25 and 26) show a difference in the location of the strongest spectral peak, and for the relative distributions of energy. The strongest harmonic for the Bach trumpet is the fundamental at approximately 880Hz. It is nearly matched in amplitude by the second harmonic. The Monette trumpet's dominant harmonic is the second, followed by the fundamental which is nearly as strong. Neither the first or second harmonics for A5 fall into the formant region of 1000-1400 Hz. Again, the Monette displays more energy in the higher frequency bands, and also more energy in the dominant harmonics, as can be seen from the difference in amplitude scale for the two plots.

Distribution of energy is similar for both instruments for the note C6 (figures 27 and 28). On both trumpets the fundamental (at approximately 1046 Hz) is dominant, with the strength of the overtones descending in ascending order. The Monette trumpet shows traces of one additional harmonic (the fifth) not found on the Bach. Although the strength of the second harmonic is nearly the same for both instruments, there is a significant difference in the strength of the fundamental which is considerably stronger on the Monette.

The smaller number of harmonics found in the upper register notes on both instruments is not unexpected. This characteristic, found in other studies (Risset, 1966; Morrill, 1977) has been explained by Benade in terms of the resonance properties or "regimes of oscillation" for the trumpet (Benade, 1973, p.32).
Characteristics of Attack Portions of Tones

Manipulation of the spectral analysis program enabled examination of selected portions of individual soundfiles by selecting start times relative to the beginning of the files. Attack (or "onset") and decay portions of selected tones were chosen for examination in this section. In addition, isolated staccato notes were recorded for the purpose of examining spectral evolution and decay. The staccato tones often proved to be short enough that a steady state was never achieved. These staccato notes are, essentially, all attack and decay.

The three dimensional "landscape" plot of the note D4 on the Monette trumpet (fig. 6) illustrates the gradual rise in amplitude of the component harmonics and the sequential entrances of the higher

Figure 6. Attack portion of a fortissimo D4 on the Monette trumpet.
harmonics as the sound evolves. The frequency scale is from left to right along the bottom axis, and is logarithmic in 1000 Hz increments. The vertical scale is relative amplitude. Time is indicated by samples ("slices") moving from front to back. Note that the frequency scale is not the same for all plots in this study. The frequency scale was chosen for each individual plot in order to present the maximum amount of information as clearly as possible.

The plots for F#3 (figures 29 and 30) and C4 (figures 31 and 32) show the evolution of the harmonics as they approach the steady state configurations previously described. Though difficult to read because of the large number of harmonics present, the plots illustrate the development of the single strong peak for the Monette, and the cluster of relatively strong peaks for the Bach. Although differences are very difficult to identify, the Bach trumpet plot for C4 shows more energy in the 3000 Hz area immediately after onset of the tone than the Monette.

The spectral analyses given for the note F4 (figures 33 and 34) show more clearly some differences in the onset characteristics of the two instruments. Both trumpets show energy up to 2000 Hz almost immediately after the attack, and up to 3000 Hz after only a few samples. The Monette continues to add energy in the 3000-5000 Hz range within the first fifteen samples plotted, while the display for the Bach shows a small amount of spectral energy above 3000 Hz and none above 4000.
The staccato G4 representations (figures 35 and 36) show a much quicker and nearly identical rise in amplitude for all harmonics present on both instruments. The differences evident for this pitch and for the note E5 (figures 37 and 38) are those noted in the earlier discussion of steady state tones concerning the distribution and strength of component harmonics, rather than any notable difference in immediacy of spectral evolution. The Bach trumpet displays less energy in the 3000-5000 Hz range than the Monette. The flat-topped and slope-topped peaks in plots for the note E5 were also noted in the steady state analyses, and are present in this study primarily on plots of fifth harmonic tones.

The two instruments show more dissimilarities for the upper register notes. The plots for A5 (figures 39 and 40) illustrate again some differences which have been previously noted; i.e. the Bach instrument produces two strong peaks of nearly equal strength while the Monette shows a single dominant peak, and the Monette displays more energy than the Bach in the frequency range above 4000 Hz. For this note, the fourth and fifth harmonic traces on the Bach trumpet appear several samples later in the tone than for the Monette. The plots for the tone C6 (figures 41 and 42) show essentially the same spectral components for both instruments, but different relative strengths. While the second harmonic is approximately the same strength on both instruments, the fundamental is nearly three times as strong on the Monette and considerably less on the Bach. This is in addition to the difference in scale represented on the plot (vertical axis). One additional feature not seen previously is a single sample
"spike" in the fundamental of the Bach trumpet immediately after the onset.

**Characteristics of Decay Portions of Tones**

The analyses for the decay portions of selected tones were obtained by editing the digital recordings into smaller attack-only soundfiles, or by specifying start times for spectral analysis relative to the beginning of a longer soundfile. It was found that the latter strategy was more successful due to the fact that data was occasionally damaged in the edited soundfiles, presumably as an artifact from the end-of-file markers of the editing software.

Examination of the plots for the decay of the tone E5 on both instruments (figures 43 and 44) reveals the sequential high to low frequency rolloff and dropout of harmonics characteristic of all the analyses for the present study. In all cases, the fundamental is the last remaining band of energy — a feature which is found regardless of the harmonic components of individual pitches. It may be generalized that the spectral energy of a trumpets tone nearing its decay is very similar to that of a very soft, sustained tone of the same pitch. As was observed in the steady state analyses, the fundamental is relatively stronger than other harmonics for softly played tones than for tones played at louder dynamic levels.

Although not a clear representation of a decay, the complexity of the harmonic content and the high to low frequency sequential dropout of overtones for the pitch F4 on the Monette trumpet (figure 45) is evident.
Plots of staccato tones provide an opportunity to examine and compare decay portions. The staccato G4 plots (figures 46 and 47) illustrate the extremely rapid appearance and rise in amplitude of the component harmonics for both the Bach and Monette instruments. The two strong harmonics of the Bach trumpet and the single strong peak of the Monette which were observed in steady state analysis are quite evident even in tones of very short duration. The length of time required for the decay of these tones is longer than for the attack. This was found to be true for every staccato tone examined. Each of these characteristics are further illustrated in the plots for the staccato tone D5 (figures 48 and 49).

As was the case in comparison of attack portions of tones, more differences between the two instruments are evident for notes higher in the trumpet's range. Plots for staccato F5 (figures 50 and 51) illustrate clearly the rapid entrance of harmonics in the attack and their slower sequential disappearance during the decay on both instruments, and the greater number of harmonics present on the Monette trumpet.

A characteristic which was consistent for most of the staccato tones examined in the present study was the shorter length of a staccato sound on the Bach trumpet. In nearly all cases the staccato notes lasted fewer samples from onset to disappearance of energy on the Bach trumpet, even though the tones were subjectively judged to be the same length by the performer.
Comparison of Performed Transitions

Melodic tones are generally performed in a sequence one after another and connected by some means or other in performance. On wind instruments, including the trumpet, connections are made by articulating with the tongue or by slurring from one pitch to another without use of the tongue. The present study compares the region between two different pairs of notes performed in both a tongued and a slurred manner. Analysis for comparison is provided by landscape plots and by graphic representations of waveforms showing energy over time for the transition portions of two note soundfiles.

It was found that both articulated and slurred transitions were very consistent in the recorded samples. Both amplitude envelopes and transition times were nearly identical for the various recordings. This is consistent with another recent investigation of performed transition by John Strawn (1986), who found that trained performers could easily replicate given transitions.

Comparison of the analyses for the tongued transition from G4 to Bb4 (figures 52 and 53) shows a very similar transition time for the two instruments. The distribution of energy is quite different, as might be expected after previous examination of both the steady state and attack/decay analyses, but the actual transition time is nearly identical. The tongued transition displays a clear separation of the two tones. The amplitude drops to zero after the decay of the G4 and before the onset of the Bb4.
A plot of the slurred transition between the same two notes is provided for the Bach trumpet only (figure 54) due to data transfer problems with the Monette soundfile. The plot displays a period of lower amplitude for the harmonics present, but no separation between the notes.

Examination of the energy/time (amplitude envelope) plots for the same intervals (figures 55–58) confirms the difference in transition time between slurred and tongued transitions generally, and displays additional characteristics as well. Although both instruments were played at what was subjectively judged to be the same dynamic level by the performer, there is an obvious difference in the total energy present. The Monette instrument analyses display a greater amplitude for both notes of the pair.

The slurred transition on the Monette trumpet takes slightly longer than that for the Bach, while the separation of the tongued tones is virtually the same. The second tone (Bb4) on the Bach trumpet displays a period of fluctuation before stabilizing. This is found to a lesser degree on the Monette. The decay of the first tone (G4) for both instruments takes place very suddenly -- in reality, almost no decay is present. The tone simply changes frequency. This is not unexpected for an ascending interval where it is unnecessary for the performer to reduce breath pressure to obtain the second tone.

The articulated transition amplitude envelope graphs (figures 55 and 56) display more of a decay at the end of the first note, as would be expected due to the interruption of the airflow by the tongue. Nonetheless, transition is very fast -- on the order of .07 seconds.
Landscape plots of the descending interval from F5 to C5 (figures 59, 60 and 61) display more clearly the differences between the tongued and slurred transitions. The definite space between the tongued tones is easily seen, as is the relocation of the harmonics for the second tone. The tongued notes on the Bach trumpet are slightly farther apart than on the Monette. This separation can be more easily seen in the energy/time graphs for the same tones (figures 62 and 63). These have been edited to approximately .3 seconds and show the separation to be a bit less than .10 seconds for the Bach and approximately .07 seconds for the Monette. A second feature which appears to be different on the two trumpets is the duration of the decay portion of the first tone (F5). The decay is longer for the Bach trumpet, a characteristic of the instrument which was consistent throughout the present study.

The slurred F5 to C5 landscape plot for the Monette trumpet (figure 61) shows a connection between the notes, a drop in amplitude at the moment of transition, and a relocation of component harmonics from the first to the second tone. Examination of the energy/time graphs for the same tones (figures 64 and 65) reveals a decay of the tone preceeding the transition which was not found in the ascending G4 to Bb4 graphs. This is a characteristic of each descending interval examined for the present study. The Bach and Monette instruments display different waveforms for the onset of the second tone (C5), presumably due in part to the disturbance of the valve change between tones.
Comparisons of Individual Harmonics

In order to examine and compare the two instruments in additional detail, the first nine harmonics present in each of two tones, D4 and F4, were isolated and graphed. This is possible using Phase Vocoder software that employs a series of frequency-specific filters to isolate the spectral components of a tone. The resulting amplitude information is written to individual computer files which can be plotted separately. Graphic output is in the form of Amplitude x Time plots. Amplitude information has been normalized for all harmonics to enhance resolution, and each plot represents 2.0 seconds of sound.

Examination of phase vocoder (PV) plots amplifies some of the details revealed in the spectral plots discussed previously, and allows for more specific comparisons of amplitudes and envelope characteristics. The PV analyses of the mezzo-forte tone F4 (figures 66-74) show that the strongest harmonic for both trumpets is the fourth, followed by the third -- both within the 1000-1400 Hz formant region previously noted. On the Monette instrument these two harmonics are considerably stronger than the remaining ones, while on the Bach instrument harmonics 2, 3, 5, and 6 are all strong and relatively equal in amplitude. Also, the amplitude of the higher harmonics is greater for the Monette trumpet than for the Bach. These details confirm previous observations.

Examination of the plots for the fortissimo tone D4 (figures 75-83) reveals similar features. The Bach trumpet’s strongest harmonics, the second and third, are of equal amplitude, and located among several other relatively strong peaks (1, 4, and 5). The Monette
instrument produces a single very strong harmonic, the second, which is more than twice the amplitude of any other harmonic analyzed. This second harmonic is also more than twice the strength of any harmonic produced by the Bach trumpet. The amplitude of each of the harmonics produced by the Monette trumpet is greater than the corresponding harmonics on the Bach. From this information it appears that the Monette trumpet produces more energy than the Bach at loud dynamic levels. For harmonics above the fifth, amplitude of the Monette harmonics is generally more than double that of the Bach.

Additional differences between the two trumpets are revealed by examination of the temporal location of peak amplitude for each harmonic during the tones. For the mezzo forte F4, the time after onset for the occurrence of peak amplitudes of the first nine harmonics show that for the Bach trumpet, high frequency energy reaches its apogee very early in the tone and is followed by the tone’s strongest harmonic and and lower frequency components -- including the fundamental. The reverse seems to be true for the Monette trumpet where low frequency components (harmonics 1, 2, and 3) occur first, followed by the strongest harmonic, and the high frequency energy. The time between the earliest and latest occurring amplitude peaks during these tones is different for the two instruments: approximately .475 seconds for the Bach trumpet, versus .18 seconds for the Monette. This variance occurs during tones with a total duration of approximately 1.5 seconds.
The Monette trumpet maintains the same relationship of early and late occurring peak amplitudes for the fortissimo D4, while the Bach trumpet reverses the tendency displayed in PV plots for the mezzo forte F4. For the louder tone, peak amplitude of the Bach instrument’s lower frequency components (harmonics 1 and 2) occurs before the higher harmonics which follow very quickly. Nevertheless, amplitude peaks for each of the harmonics of the Bach tone occur later in the tone than for the Monette trumpet. Additionally, the Bach trumpet harmonics display considerably more fluctuations in amplitude, especially during the attack portion of the tone, and a lower overall amplitude for each harmonic.

The rise-time for each of the harmonics to reach peak amplitude during the tones is shorter for the Monette trumpet than the Bach. These peaks not only occur more rapidly on the Monette, but they also occur nearly simultaneously -- within approximately .15 seconds or less for the tones examined. On the Bach instrument more than .5 seconds separates the occurrence of peak amplitude between the earliest and latest developing harmonics for the tone F4, and approximately .3 seconds for the fortissimo D4. These characteristics are summarized in the information presented in Table 2 on the next page.
Table 2. Comparison of approximate time after onset and relative strength of the peak amplitudes for harmonics 1 - 9 for the fortissimo tone D4 on the Bach and Monette trumpets. Amplitude is relative. Time after onset was derived from the Phase Vocoder graphs presented in the Appendix (Figures 75-83).

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<th>Time (seconds)</th>
<th>Monette Peak amplitude</th>
<th>Time (seconds)</th>
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<tr>
<td>9</td>
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Summary

A detailed comparison of the physical characteristics of tones from the two instruments selected for this study was done using spectral analysis plots and amplitude envelope graphs generated by computer from digitally recorded tones. Graphical representations of selected steady-state, attack, decay, and two-note transitions were examined, and individual harmonics (1-9) of two tones were plotted. Characteristics of the displays for tones from both instruments essentially conformed to expectations for trumpet tones as described in related studies by Risset (1966) and Morrill (1977).

The analyses in the present study did not reveal the sudden "spike" at the onset of tones found in many of the sounds analyzed by Morrill. This may possibly be attributed to a different manner of
articulation used by a player with an orchestral and chamber music background, as in the present study; as opposed to that of the "commercial" player used in the study by Morrill (1977).

While it might be argued that the use of the single Bach 1-1/4C mouthpiece on both the Bach and Monette trumpets is inappropriate, giving an advantage to the instrument by the same maker, it is the only way to insure that the trumpets themselves are responsible for differences in tonal spectra. In actual practice, it is common to find performers using mouthpieces and trumpets of dissimilar brands. The additional variable of different mouthpieces and their effect on tone quality is entirely outside the scope of the present investigation, though an interesting topic for further research.

It was not possible to develop empirical methods to analyze and compare the different plots resulting from computer analysis. However, physical differences between the Bach and Monette trumpet tones are evident. Examination and comparison of the computer analysis plots yielded the following results.

The Monette trumpet produces a greater number of harmonics for a given note than does the Bach. This is true for tones in both the high and low registers of the instrument, but the difference in total number of harmonics is greater for lower pitches which are characteristically richer in spectral energy. The additional harmonics present in the Monette tones are located in the higher frequency regions. As many as 23 harmonics are visible in the spectral plots for F#3, as well as in very loud notes played an octave higher on the
Monette trumpet. Analyses of the Bach trumpet tones revealed up to 17 harmonics.

The Monette trumpet generally shows one spectral peak which is considerably stronger than others for each tone. The Bach trumpet spectra generally includes several relatively strong peaks. The amplitude of the prominent single peak of the Monette is most often greater than the strongest peaks represented in Bach trumpet tones of the same frequency.

The strongest frequency bands for a given note tend to fall in to the frequency range from 1000-1400 Hz for both instruments. This is true for tones in all registers. Therefore, the numerical relationship of the strongest overtones to the fundamental varies with frequency. This formant region of 1000-1400 Hz is slightly lower than 1500 Hz region noted by Risset (1966). Departure from adherence to this formant region is noted more often for the Bach trumpet than for the Monette.

The duration of the attack portion of tones are very similar for both instruments, although the resultant spectral distribution of energy is generally different. Analyses of attacks did not reveal the momentary disturbance or amplitude spike shown in many of the analyses of Morrill. The spectral evolution of component harmonics progresses from the low to higher frequencies until the steady state is achieved. Traces of high frequency components occur more quickly after onset of a given tone on the Monette trumpet.
Staccato tones are generally shorter on the Bach trumpet than on the Monette, although they were performed at what was subjectively judged to be the same length. Analysis of the short tones on the Bach trumpet revealed a smaller number of harmonics than for the Monette.

Articulated pairs of tones are separated. This is in contrast to the findings of Strawn (1986) who identified only a period of reduced amplitude between articulated tones on the trumpet and other instruments. Both spectral landscape plots and amplitude envelope graphs show a break between articulated pairs of ascending and descending notes.

Slurred notes in performance are connected, and display the characteristic drop in amplitude described in the study by Strawn (1986). The decay of the first note is affected more by the transition than the attack of the second. Slurred transitions are slightly quicker on the Bach trumpet than on the Monette. Amplitude of pairs of tones fluctuates less in slurred transitions than in tongued.

Amplitude for Monette tones is generally greater than for Bach tones. This was evident even though tones were played on both instruments at what was judged to be the same dynamic level.

Spectral components of the Bach trumpet tones displayed more fluctuation in amplitude throughout the duration of tones than for the Monette. Amplitude envelopes for individual harmonics of the Monette instrument tended to be similar in shape. The Bach trumpet plots displayed larger temporal interharmonic variation than the Monette.
CHAPTER VI
SUBJECTIVE IMPRESSIONS OF PROFESSIONAL PLAYERS

Subjective impressions of the Bach and Monette C trumpet from selected performers are presented in this chapter as an ancillary topic to the present study. Players contacted were chosen for their prominent and respected positions in major American orchestras, and for their familiarity with both instruments. It is the intent of this chapter to present opinions concerning the sound of the two instruments as expressed by the following performers: Thomas Stevens, principal trumpet of the Los Angeles Philharmonic Orchestra; Adolph Herseth, principal trumpet of the Chicago Symphony Orchestra; and Charles Schlueter, principal trumpet of the Boston Symphony Orchestra. Each has performed, or is performing, on both the Bach and Monette trumpets during their orchestral careers. Information was obtained from Mr. Herseth and Mr. Schlueter by interview, and from Mr. Stevens by letter (see References).

As a result of being asked to describe differences between the two trumpets, the responses tended to attribute "more" of a particular characteristic to one instrument or the other, with the performer's preferred instrument possessing the characteristic to a greater degree.
Herseth

A primary consideration to Mr. Herseth's comments about the Bach and Monette trumpets is his strong belief that a performer's impression of the tone quality of an instrument cannot be separated from that performers sense of "feel", or response, of the instrument while playing. To speak only of the sound of an instrument without concern for its playing characteristic is to ignore the subjective and intrinsic factors which color the players perception of that sound.

Although tone quality is often described in psychoacoustic research in terms of a semantic rating scale for various attributes, Mr. Herseth does not subscribe to such a system. His descriptors are purely subjective, and he believes that terminology for timbre is a learned response based on experience, and is always changing. With these caveats, the following observations were offered.

- Both the Bach and Monette C trumpets are "marvelous" instruments, but very different.

- In terms of attack, the Bach has more "transients" at the moment of articulation than the Monette, or, conversely, the articulations on the Monette trumpet are less noticeable. This is an advantage on the Monette because it permits the performer the ability to produce more gradations of articulation.

- It is possible to play louder with the Monette trumpet before the tone becomes "edgy", or breaks up.
- The quality of the sound of the Monette trumpet is "thicker" than the Bach, and more similar to that of the German rotary valve instruments.

- The Monette instrument is "more stable" in terms of pitch and quality, and more "homogeneous" in terms of tone. This is due to the fact that it is a heavier instrument. A heavier horn is generally a better orchestral instrument, though not necessarily the best solo instrument.

**Stevens**

Of particular interest to Mr. Stevens are the potential benefits of instrument designer/builders dealing with top performers in the workplace, and the importance of makers continuing to develop and improve existing designs. It is this factor in itself to which Mr. Stevens attributes the Monette trumpet's acceptance by "many of the world's top performers, many of whom were Bach players for decades."

The difficulty of discussing non-scientific elements of performance such as the response or "feel" of an instrument and of describing musical phenomenon verbally is a concern which Mr. Stevens addressed before his discussion of the instruments. His subjective observations were general in nature, and included primarily discussions of intonation and timbre.

- Because intonation is a constantly changing variable in performance, an instrument must afford the performer the ability to adjust. The Monette trumpet does this "...without
the destabilizing effects on the embouchure that is (sic) the case with other instruments."

- The stability of the Monette instrument when adjusting for various intonation requirements results in increased endurance for the performer, a characteristic which is superior to instruments by other manufacturers.

- A flexibility in terms of timbral changes is possible to a greater extent on the Monette trumpet than on others. This characteristic, which allows the performer the ability to extract a variety of tonal "colors" from one instrument, is an improvement over other available instruments.

Schlueter

The particular instrument used in performance has long been a concern for Mr. Schleuter, leading him to experiment with various modifications and adjustments to trumpets and mouthpieces throughout much of his career. He is quite outspoken about his feelings concerning desirable playing characteristics and sound concepts for the trumpet. Mr. Schlueter feels strongly that the mouthpiece and trumpet combine to create a unified system, and that selecting a mouthpiece which is "correctly balanced" for a particular instrument is of primary importance. His subjective comments were quite specific concerning aspects of tone quality and instrument response.
- It is possible for the performer to exercise a greater control of timbral changes with the Monette trumpets than on the Bach. The Monette tone quality remains consistent throughout the range of the instrument, in contrast to the Bach trumpet which tends to have different timbres for some notes unless compensated for by the performer.

- The Monette trumpet provides more brilliance, resonance, and concentration of tone quality than the Bach instruments.

- At very loud dynamics, the Bach instrument "breaks up" and projects a distorted "white noise" type of sound. It is possible to play much louder on the Monette trumpet and retain an undistorted tone quality. This is a particular asset in an orchestral setting.

- The mouthpiece may be even more important than the instrument itself, in terms of playing characteristics, response or "feel", and even tone quality.

- The Monette trumpets "speaks" more easily and consistently than the Bach. This is a particular advantage to starting notes with breath only.

Summary

The validity of any performer's subjective response to a particular instrument or tone quality cannot be disputed. It is a personal opinion based on experience, training, taste, and individual biases. In the opinion of this researcher, the thoughts of the three
professional trumpeters included in this brief chapter provide an interesting and provocative addition to the objective comparisons of spectral analyses already presented. The decision to provide anecdotal information in this manner was based on this author's doubts concerning the musical value of survey-type responses from larger numbers of arguably less-qualified respondents, and respect for the opinions of the experienced and highly regarded performers who were willing to share their insights.

The fact that all three performers have elected to perform primarily on the Bach or Monette trumpets during recent years in their prestigious positions is a strong endorsement for both of the instruments. Each of the performers indicated a belief that the two brands, Bach and Monette, represented the best choices available in this country for orchestral musicians during recent years. Several characteristics of the trumpets were mentioned by more than one of the performers. These include: articulation response, quality of sound at loud dynamics, and "stability" of the instrument in terms of both pitch and timbre.

Terms used to describe the timbre of the Monette trumpet included "thick," "homogeneous," and "resonant" to greater degrees than for the Bach trumpet. There was an agreement from each performer that at very loud dynamics the Bach trumpet sound tended to "break up" or become "edgy" in quality with a diminishing ability to project or "carry." All three players said that it is possible to play louder with a satisfactory tone quality on the Monette trumpet.
A difference in the attack was noted. The Bach trumpet was felt to have a more audible "pop" at the beginning of articulated tones. This characteristic was not as evident with the Monette trumpet. A "stability" of intonation was noted to a greater degree with the Monette trumpet. This characteristic was credited with contributing to an ability to perform with increased endurance by one player.

Stability and consistency of timbre throughout the range of the instrument were mentioned as attributes found in the Monette trumpet to a greater degree than with other instruments. A tendency for notes with different fingerings to also have a different timbre was noted as a characteristic of the Bach trumpet. Despite recognizing a greater "stability" of timbre with the Monette trumpet, the same performers also felt that the instrument offered greater timbral "flexibility".

A discussion of the subjective impressions summarized above and their possible relationship to the physical spectra of tones in the present study is presented in Chapter VII.
CHAPTER VII
SUMMARY, DISCUSSION AND RECOMMENDATIONS

The growing sophistication of digital signal processing has enabled detailed examination of complex sounds, such as those produced by musical instruments. Spectral analysis by computer has yielded much information about musical instrument tones and other complex sounds. This has enabled researchers to experiment with various synthesis techniques to produce sounds for research in perception, and for use in electronic music composition.

Summary

The body of research on timbre has established that it is a multidimensional feature of sound, and that temporal features of musical sounds contribute to their unique qualities. This has resulted in a move from steady-state tones to musical tones in timbre research. Only the most recent studies have begun to investigate musical tones within melodic phrases -- an exercise which would be the ultimate test of timbre perception. Although examination of individual tones may be sufficient to evaluate some aspects of musical sounds, the application of results derived from such research to musical settings may not be valid. This has become a familiar disclaimer for experiments in timbre perception.
The intent of the current investigation was to identify and describe similarities and differences in the tone quality of two trumpets, and to provide an additional source of information on trumpet tone quality for musicians. Several previous studies have provided information about trumpet timbre in a general sense. These have contributed information relating to the temporal features and spectral content of trumpet tones (as distinct from tones of other instruments) and have served frequently as a basis for synthesis of trumpet-like tones for experimental and compositional purposes. The present study is one of the first to offer a detailed comparison of the physical attributes of tones from like instruments.

In the current study, individual tones and two-note transitions were performed on two different C trumpets by a professional trumpet player and digitally recorded. Digital information from selected tones was transferred to computer files and analyzed with a spectral analysis program at the Sound Synthesis Studio of The Ohio State University. Results from analysis provided graphical output which was used to compare the physical properties of the tones on the two instruments.

Graphical representations resulting from analysis included perspective plots of Amplitude x Frequency x Time ("three dimensional" or "landscape" plots) which reveal temporal relationships and relative strengths between harmonics, amplitude envelope plots, and "single slice" samples of tones which illustrate the relative amplitudes of the harmonics of particular tones.
In addition to the physical analysis and comparison of trumpet tones, subjective comments concerning characteristics and differences in the tone quality of the two brands of instruments were solicited from principal trumpet players in three major American orchestras, each of whom is familiar with trumpets by both of the manufacturers included in the current investigation. Their impressions were summarized and presented as anecdotal information relating to the physical comparisons of tones.

Results

There are a number of characteristics of musical instrument tones that contribute to the multidimensional quality of their various timbres. Among them are changes in relative strength of the fundamental, the increasing number of harmonics present in tones played at louder dynamic levels, and the changes of distribution of energy among the various harmonics throughout the duration of even a very short tone. Examination of tones of the Bach and Monette trumpets show that while these and other expected changes occur, they do not take place in entirely similar ways, even on like instruments.

There is objective physical evidence to support the commonly held opinion that the Bach and Monette trumpets produce sounds with different tone qualities -- a finding which is probably not surprising to most trumpeters. Results show that tones from the Bach and Monette C trumpets display different physical characteristics under the conditions of the current investigation. Differences between the instruments tended to be consistent, and pertain primarily to relative strengths and distributions of spectral energy. The following
generalizations seem warranted from comparisons of spectral plots for
the single tones and two-note transitions transitions examined:

1. Both the Bach and Monette instruments displayed spectra
   consistent with the characteristics for trumpet tones
   found in experimental literature.

2. There are generally more harmonics present in tones on
   the Monette trumpet than for the same tones with the
   Bach trumpet.

3. The Monette trumpet tends to be richer in high frequency
   energy than the Bach.

4. There is a formant region between 1000-1400 Hz for both
   instruments.

5. The spectrum of the Bach trumpet displays prominent
   energy bands outside the identified formant region more
   frequently than the Monette trumpet.

6. Differences in spectral content of tones for the two
   trumpets is greater in the low register than in the high
   register.

7. For a given tone, the Bach trumpet tends to have several
   strong and relatively equal harmonics which dominate its
   spectrum, while the Monette generally has a single
   harmonic considerably stronger than others.

8. The single dominant harmonic of a Monette trumpet tone
   is generally stronger than any harmonic present in the
   same tone of the Bach trumpet.
9. The order of relative strength of harmonics for the two trumpets is generally dissimilar, except in the upper register.

10. There is more interharmonic variation during a given tone on the Bach trumpet than on the Monette.

11. At differing dynamic levels, the temporal characteristics of the Monette trumpet spectra are more consistent than those of the Bach trumpet, which exhibits very different characteristics at different dynamic levels.

12. The duration of the attack portions of tones is very much the same for both the Bach and Monette trumpets.

13. Staccato tones tended to be of shorter duration for the Bach trumpet than for the Monette.

14. Slurred transitions are connected in performance, with a very short period of low amplitude between the notes.

15. Transitions articulated with a single tongue are separated by a period of zero amplitude between the decay of the first tone and the onset of the second.

16. Differences in amplitude are evident between the first and second notes in both slurred and articulated transitions.

Discussion

The present study reinforces many of the findings from previous research concerning general features of trumpet timbre, and the spectral characteristics of the two instruments examined here conform to the expected norms for trumpet tones. Yet this first detailed comparison of two specific makes of trumpets does yield some
consistent differences between them. Obviously these spectral differences are subtle to the ear, and not so striking as to cause either of the instruments to be aurally perceived as anything other than trumpets. This familial similarity is a result of the formant structure of the trumpet.

The particular latitude of spectral characteristics that must be exceeded before similar tones are perceived as dissimilar is a topic of study for research in timbre perception. The fact that Risset (1966) was able to analyze trumpet tones from analog recordings, filter out spectral information above 4000 Hz, and use a data reduction process to generate synthesized tones judged "indistinguishable" from the originals suggests that the latitude is quite wide. This is apparent from the successes of other synthesis techniques which have proved useful in generating artificial musical instrument tones.

The existence of many different brands of professional instruments at widely disparate prices argues for the reality of noticeable differences between them. The subjective impressions from the professional performers cited in the present study leave no doubt that they clearly perceive differences between the two trumpets examined.

It is possible to suggest relationships between particular spectral characteristics of the instruments revealed by comparison of the computer analyses and the subjective impressions from performers. Such speculations may serve to focus on specific areas for further research.
No particular differences were evident from examination of spectral plots for attack portions of tones on the two instruments. The "transients" during onset of a tone are either not present to any significant degree, or if present, were not revealed by the particular analysis techniques used. The importance of the attack to instrument identification may refer primarily to the specific evolution of spectral components and their changing relationships as a tone grows toward a steady state, rather than inharmonicity during the attack.

In actual practice, it may be that a "good" attack is one in which the tone begins most immediately without the presence of transients or inharmonic components. The tones analyzed in the present study display a gradual rise of component harmonics without a significant initial onset "disturbance" like those found in analyses by Morrill (1977). It may be that the player or another factor is a stronger variable contributing to "spikes" or transients in the initial attack than the instrument itself.

The two-note transitions included in the present study showed that slurred transitions are connected in performance with only a drop in amplitude between the tones, while single tongued transitions are separated by a brief period of zero amplitude at the moment of articulation. These findings were consistent on both ascending and descending intervals for both trumpets. This is in contrast to the findings of Strawn (1986), who found both slurred and articulated transitions on a trumpet to be connected in performance, with no separation between tones. It is possible that this significant difference was caused by room resonance at the recording site.
Both the present investigation and that by Strawn found that transitions are very quick, and easily replicable by the performer. Despite the performer's effort to play both notes at the same loudness, it was found that the amplitudes of the two notes tended to differ. The Monette trumpet generated a greater amplitude for both notes of transition pairs, although all tones were performed at a mezzo forte dynamic level, as judged by the player at the time of recording. There appears to be some consistency of amplitude variation for ascending versus descending intervals, however additional samples will need to be analyzed to determine this.

Difference between the Bach and Monette trumpets in the ability to perform at loud dynamic levels was mentioned by each of the professionals in Chapter VI. The fact that the Monette instrument displayed greater amplitude in the transitions when performance was subjectively determined to be at the same dynamic level may imply that a similar relationship exists at louder dynamic levels. This feature was not a topic of the present investigation, but might prove a worthwhile topic for future studies. It is clear that the amplitude of the spectral components of Monette trumpet tones tends to be greater than for the same tones performed on the Bach trumpet. This is true at each of the dynamic levels tested in the current study.

A particular feature revealed in the current study which may have an influence on the perceived loudness of tones is the distribution of spectral energy among the component harmonics of the two instruments. As noted earlier, the Monette trumpet characteristically displays one very strong harmonic (relative to the
others present for the tone), generally located in the frequency region between 1000-1400 Hz. This particular formant region corresponds to a frequency range in which the ear is particularly sensitive, and partly explains why trumpets are considered "loud" instruments.

By contrast, the Bach trumpet plots most often display several relatively equal but less strong harmonics for tones. These peaks are lower in amplitude than the formant peak of the Monette trumpet for the same tone. Further, relatively strong harmonics at times occur outside the formant region identified between 1000-1400 Hz. This dispersion of spectral energy between more than a single harmonic and over a wider frequency range may correlate with the subjective impression that the Bach trumpet cannot produce as loud a sound as the Monette. It may be that this same dispersion of energy contributes to the sense expressed in the subjective comments that its sound "breaks up" (to use the words of Mr. Herseth and Mr. Schlueter) or distorts at very loud dynamic levels. This difference in distribution of spectral energy may also contribute to differences in perceived consistency or homogeneity of sound noted in the subjective comments of the performers.

These same differences in formant structure may contribute to perceived differences in "stability" and/or "flexibility" of timbre, if in reality a single formant peak (as opposed to more than one) is the factor responsible for those attributes. It seems logical that a single very strong formant might be an indication of favorable resonance properties of an instrument, and would be consistent with Benade's explanation of "regimes of oscillation" (1973, p.31-32). The possibility
that, in an optimal vibrating system (instrument), the partials in a tone reinforce one particular formant peak may explain differences in sound illustrated by the single versus multiple peaks found in the Monette and Bach trumpets respectively, and may also contribute to a "stability" of sound or consistency of timbre -- particularly if combined with a concentration of spectral energy in a well-defined formant region.

A second feature which may account for the increased ability to perform at louder dynamic levels on the Monette instrument is the additional high frequency energy present in its spectra. For most tones analyzed in the present study, the Monette trumpet plots displayed a greater number of harmonics located at the higher frequencies. Benade has shown that the trumpet bell radiates higher frequencies more efficiently than lower (1973, p. 32). It follows that the instrument with the greater amount of high frequency energy in its spectra will transmit a greater amount of energy into the air, resulting in greater amplitude.

Dodge and Jerse have noted that "the qualitative description 'brilliant' or 'bright' characterizes spectra that have a great deal of energy at high frequencies. The spectra produced by most brasses exhibit this trait." (1985, p. 52). Whether or not the Bach or Monette trumpet tones could be classified as "bright" is a moot point. Using words to categorizes timbral characteristics is inexact at best, though a number of studies have been undertaken to establish semantic scales of timbre descriptors. Musicians, teachers, and conductors by necessity use words to describe tone quality. It has been this author's
experience that these efforts often result in confusion, with different people using identical words to describe differing timbral characteristics, or to describe identical timbral characteristics with different terms.

The terms "bright" and "dark" are frequently used to describe trumpet tone quality, but whether they correspond to particular spectral characteristics is as yet undetermined. In the experimental literature, "bright" is the term most often applied to tones with greater amounts of high frequency energy than tones considered to be "dark" (Abeles, Elliot & Bowsher, Pratt & Doak, Wapnick & Freeman).

David Monette has developed a taxonomy of tone quality descriptors in four categories which he uses in his work with trumpeters, and Vincent Bach used various descriptors of tone quality characteristics for his products in published materials. It would be most helpful in timbre research to have a standardized vocabulary to describe tone quality, and its value to musicians -- particularly for teaching purposes -- would be considerable.

**Recommendations**

In addition to providing a large amount of detailed information on trumpet timbre, the results of the present investigation suggest some directions for further study.

Efforts toward developing a common set of accepted verbal descriptors for timbre is one area which could be of value to many, including performers, conductors, and sound engineers. Attempts at correlating adjectives with timbral characteristics are found throughout the experimental literature. In the world of performing musicians, it
would be most helpful to have a semantic "common ground" with which to communicate ideas about tone quality; however the multidimensional nature of timbre makes this a formidable task. Whether investigations in this area should focus attention on identifying and categorizing terms presently in use by various populations, or rather on developing terminology and hoping to establish its widespread use is a question to consider.

The results of examinations of two-note transitions in the present study produced results which seem to differ with an earlier study by Strawn. Further detailed investigations of the spectral activity in musical instrument tone at the moment of transitions is needed. This information is neccessary for the development of synthesis techniques that will need to take into account the effect of transitions of various types (articulated, slurred, ascending, descending, etc.) on attack and decay characteristics of the tones involved. Additional work in this area must be done before meaningful analysis of timbre in musical contexts can occur. There is presently no satisfactory method for analysis of timbre applicable to musical phrases.

The problem of applying results of existing timbre research, which has primarily dealt with isolated tones, to more musical contexts is also discussed by Grey:

The great difficulty met by many musically-trained listeners in attempting to identify the instruments which produce isolated tones testifies to the rather limited nature of current research. It is certain that other dimensions of timbre perception come into play when listening to a contextual passage of music. Not only do specific idiomatic traits of instruments occur, but more global data bases for perception are presented. One such data base which is opened to the listener is the pattern of resonances traced
as the instrument is played through a register. This sort of information must be significant in normal listening situations (Grey, p. 126).

Areas for additional study more specifically related to the present study of trumpet timbre could investigate additional or different variables. The single mouthpiece employed for all tones in the present study enabled a comparison of two trumpets without any additional variables. A casual comparison of spectral analyses of tones performed on the same two trumpets but with other mouthpieces revealed some differences. Replication of the present study with a different mouthpiece may produce somewhat different results. The contention by Schleuter that the mouthpiece may be a more significant factor than the instrument should not be dismissed. Additional study may prove or disprove his intuitive impression.

An obvious area for further study is the influence of the performer on timbre. In order to compare instruments, it was necessary in the current investigation to eliminate the player as a variable. This was done by using a single performer (and mouthpiece) for all tones on both trumpets. Similar studies with different players may provide information on the role of the player in producing particular timbral characteristics.

Observations have been made concerning attack characteristics in this and other studies of trumpet timbre. It has been speculated that inharmonic transients and amplitude spikes during the onset of a tone are player-related. This is an important topic in need of further investigation.
A replication of the current study using different instruments would add considerably to the present knowledge of trumpet timbre. As mentioned previously, the amount of detailed information concerning the subtle timbral differences of like instruments is not large, and further investigations of this kind would be useful. From studies of this kind, it may be possible to generalize about timbral characteristics of instruments by different makers, or with specific design features. It would seem that this information could be quite valuable to instrument designers.

A particular strategy for analysis which proved most valuable in the present study was the comparison use of phase vocoder plots of specific harmonics. These representations yielded a large amount of detailed information about the evolution and strength of spectral energy during specific tones, and made examination of temporal interharmonic relationships possible. The present study was limited to phase vocoder analyses of only the first nine harmonics. Additional studies examining a greater number of harmonics, and additional tones from all registers and dynamic ranges are suggested.
LIST OF REFERENCES


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Figure 7. Bach trumpet, F#3. Steady-state sample.

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Figure 9. Bach trumpet, C4. Steady-state sample.

Figure 10. Monette trumpet, C4. Steady-state sample.
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