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WHITE, JOAN LYNN

A SPECTRAL ANALYSIS OF THE TONES OF FIVE FLUTES CONSTRUCTED OF DIFFERENT MATERIALS

The University of North Carolina at Greensboro ED.D. 1980

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A SPECTRAL ANALYSIS OF THE TONES OF FIVE FLUTES CONSTRUCTED OF DIFFERENT MATERIALS

by

Joan Lynn White

A Thesis Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Education

Greensboro
1980

Approved by

Walter L. Wehner
Dissertation Advisor

WHITE, JOAN LYNN. A Spectral Analysis of the Tones of Five Flutes Constructed of Different Materials. (1980)
Directed by: Dr. Walter T. Wehner. Pp. 127

The purpose of this investigation was to systematically analyze the tonal spectra of five modern Boehm-system flutes constructed of different materials, i.e., white gold, 14 karat gold, palladium, and sterling silver (2), and produced with the same specifications by a single manufacturer. The questions of concern in the study involved the influence of wall material, intensity level, frequency level, and the performer on the harmonic structure of tones produced on each flute used in the investigation.

Two professional flutists played a sustained tone using no vibrato on three frequencies representing three registers of the flute range, i.e., 392 Hz, 784 Hz, and 1568 Hz. Each frequency investigated was played on each flute at two intensity levels corresponding to the *forte* and *piano* dynamic levels. Three trials were conducted for each frequency at a single intensity by each performer.

All performance tasks were conducted within the anechoic chamber at The Center for Acoustical Studies of N.C. State University, Raleigh, North Carolina. Housed inside the anechoic chamber were two *Brüel and Kjaer* model 4134 condensor microphones, a mounted *Quest Electronics* 215 sound level meter, a *Korg* model WT-10A tuner, and the five flutes used in the study. The adjacent laboratory housed a

Spectral Dynamics real-time analyzer, model SD 330A, a *Brüel and Kjaer* type 2603 microphone amplifier, a *Brüel and Kjaer* type 2607 measuring amplifier, an *MFE Plotomatic* 715M x-y plotter, and a *Nagra*, Type IV-S tape recorder.

The tonal spectra for each tone investigated were plotted. The information derived from the plots was quantified, and the individual and mean strengths of the partials for each tone, derived from three trials under the same conditions, were calculated and presented quantitatively and graphically for purposes of visual examination.

A four-way multivariate analysis of variance was utilized. The general linear models procedure was employed to test the significance of main effects and interactions. The Statistical Analysis Systems package program was used, and the .05 level of probability was chosen for significance testing.

Results of a 2 x 3 x 2 x 5 factorial design, used to determine differences between the tonal spectra of all five flutes, showed that:

1. A significant difference exists between the main effects of the five flutes for partials number one, two, and four; however, the interaction of performer and flute is significant for partials number one and three.

2. Although a significant difference is found between intensity levels for all partials, the interaction of performer and intensity is significant for partial number one.

3. A significant difference exists between the main effects of frequency for all partials; however, the interaction of performer and frequency is significant for only partials number two and three.

4. A significant difference is evident between performers for the partials number one, three, and four.

Results of the 2 x 3 x 2 x 2 factorial design, used to determine differences between the spectra of the two sterling silver flutes, revealed that:

1. No significant difference is found between the two sterling silver flutes; however, the interaction of performer and flute is significant for partial number three.

2. Although the main effects of frequency and intensity are significant for all partials, the interaction of performer and frequency is significant for all partials, while the interaction of performer and intensity is significant for only partial number one.

3. Variation between performers is evidenced by the amount of interaction when comparing changes in significance from main effects to crossed effects.

4. The second partial seems to be least affected by the main effect and the interaction of performer.

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of the Graduate School at the University of North Carolina at Greensboro.

Dissertation Advisor Walter L. Wehner

Committee Members James W. Sherbon
Raymond J. Gariglio
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October 30 1980
Date of Acceptance by Committee

October 30 1980
Date of Final Oral Examination

ACKNOWLEDGMENTS

The cooperation and assistance of many individuals contributed to the successful completion of this study. To those people I am most grateful. The members of the doctoral committee who supervised the preparation of this manuscript have given freely of their time and effort. I wish to thank Professors Walter L. Wehner and James Sherbon for the scholarly advice and insight they provided throughout the course of this investigation, and Professors Lois V. Edinger, J. Gary Hoover, and Raymond J. Gariglio for serving on my dissertation committee.

I am indebted to Dr. Frank D. Hart, Director of The Center for Acoustical Studies of North Carolina State University, for permission to use the facilities of the Center, and to Mr. Robert Ciskowsky, research assistant. Special thanks are due to Mr. Andrew Cooke, research assistant at the Center, who gave so generously of his time, expertise, and assistance in the successful planning, execution, and completion of this acoustical experiment.

I am sincerely grateful to my friend and colleague, Mr. Ervin Monroe, principal flutist with the Detroit Symphony Orchestra, who found time from his busy schedule to serve as a performer, and to Custom Music Company and Muramatsu Flutes, Incorporated, who provided the flutes

used in the study. Professor Robert C. Nicklin, Department of Physics, Appalachian State University, extended a personal interest and helpful advice concerning instrumentation and procedure for which I am truly appreciative. A debt of gratitude is due to Dinah Lanning for her assistance in the typing of this project.

To my dear parents, John and Mary Botsco, who unselfishly provided for my early musical training, I am deeply indebted. Sincere appreciation is extended to music educator William Omeis, under whose tutelage I was inspired to pursue a career in music.

Finally, to my husband, Elmer, and three sons, Russell, Allan, and Marc, I am especially grateful. Without their loving patience, understanding, and encouragement, I could never have undertaken the work which culminated in this report.

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Chapter I

INTRODUCTION

The relationship between wall material and the tone quality of a musical wind instrument has long been a source of disagreement among musicians, instrument makers, and physicists. Much that has been written on the subject is based primarily on theory and conjecture. The pedagogical literature contains numerous claims by musicians that the material from which a musical instrument is constructed influences the timbre. Physicists and acousticians tend to disagree with this contention.

Recent studies of the wall material of flutes have involved either flutes which do not resemble the modern-day flute or only a single flute which is investigated via the use of an oscilloscope or a wave analyzer. The present study was conducted to examine the harmonic structure of the tones of five modern Boehm-system flutes constructed of different materials.

Need for the Study

As early as 1752, references to the tone quality of the flute were made by Quantz (1752/1966). He stated that the strength and clarity of the tone depends upon the quality of the wood, whether it is dense or compact, hard, and heavy. He believed that a thick masculine tone depends upon the interior diameter of the flute, and upon the proportionate thickness of the wood (p. 50).

Boehm (1871/1964) contended that the tone color of a flute is greatly influenced by the hardness and brittleness of the material used in the construction. His objectives regarding the timbre of the flute and characteristics of the material from which it was made were quite explicit. He stated that it is necessary that the molecules of the flute tube be set into vibration at the same time as the air column and that the material must possess this requisite vibration ability. He asserted that any variation in the hardness or brittleness of the material has a great effect upon the timbre or quality of tone (pp. 53-54). Boehm and his contemporaries constructed flutes of various materials; however, references to the tone quality of these instruments are purely subjective evaluations.

Helmholtz (1877/1954) investigated the effects of wall material on the tone quality of the flute and organ flue pipes. He stated:

> Wooden pipes do not produce such a cutting wind rush as metal pipes. Wooden sides also do not resist the agitation of the waves of sound so well as metal ones, and hence the vibrations of higher pitch seem to be destroyed by friction. For these reasons wood gives a softer, but duller, less penetrating quality of tone than metal (p. 94).

Other early studies of the effect of wall material on the timbre of organ pipes and the flute were conducted by Miller (1909). He constructed organ pipes of various materials and concluded that the quality of a wind instrument may be affected by the material of its body to the limited extent claimed by the player (p. 169).

Many of the world's leading concert artists advocate the presumed advantages of the metal used in the construction of their personal flutes. Cazzeloni plays a 14-karat gold flute and has stated that he does not like platinum (Poor, 1972, p. 18). Rampal (1971) contended that the sound of a gold flute is darker and richer, and that when he tried a platinum flute he did not like it (p. 7).

Other respected flutists have different preferences. Moyse plays a nickel silver flute, while Baker, principal flutist with the New York Philharmonic Orchestra, performs on a sterling silver flute. Kincaid preferred platinum to any other metal used in the construction of flutes, as did Barrere. Schaffer (1962) performed on a 14-karat gold flute and found that she liked neither platinum nor silver (p. 64).

In pedagogical texts pertaining to aspects of performance on the flute and other musical wind instruments, diverse opinions prevail concerning the role that wall material plays in determining the characteristic timbre of such instruments. Timm (1964/1971) states that experiments have indicated that the material from which a musical instrument is constructed does affect the quality of the tone, in spite of what some physicists claim (p. 45). Bate (1969) and Baines (1957) refer to the adaptability of particular embouchure formations to specific materials used in the construction of flutes. Bate has stated that the genius of the metal flute is of a lighter and more ethereal sort, and that these instruments respond best to a relaxed embouchure (p. 231). Baines' contention is that the wooden flute naturally produces a denser, more powerful sound than one made of metal and requires more forceful blowing and attack, and a tight embouchure, while a metal flute can sound very much like a wooden flute if played with a similar embouchure formation, but naturally yields a lighter, more limpid sound responding well to a lighter attack and to a looser or more relaxed embouchure (pp. 55-56).

Carse (1965) has asserted that the quality of sound of a wind instrument is governed mainly by the nature of the means employed to generate vibration, and that the material of which the tube is made, provided it is sufficiently dense and rigid, has either little or no effect on tone quality (p. 10). In direct contrast to this statement, Ballantine (1971) has stated that a flute's tone quality depends greatly upon the material of which the instrument's tube is made, and that silver and gold flutes when played produce tones of exquisite delicacy (p. 69).

The pedagogical literature contains much disagreement concerning the relationship between wall material used in the construction of a flute and timbre. Scientific investigation of the subject would seem justified.

Significance of the Study

The present study consisted of an analysis of the harmonic structure of the tones of five modern Boehm-system flutes, each constructed of a different material. The researcher sought to identify factors which influence the timbre of a flute.

Miller (1909) defined sound as the sensation resulting from the action of an external stimulus on the sensitive nerve apparatus of the ear, a species reaction against this external stimulus, peculiar to the ear, excitable in no other organ of the body, and completely distinct from the sensations of any other sense (p. 161). The physical nature of sound has its origin in a vibrating body. Sounds may be periodic or nonperiodic. When a pattern of motions is repeated time and again, this vibration is referred to as periodic motion or vibration that is of significance to the physics of music. The pattern of motion which occurs during one period and that is repeated over and over again is called a cycle. The pattern for one cycle is called the waveform of the vibration.

The "normal" motion of a tuning fork represents a simple vibration. The curved bar possesses a stiffness which supplies a restoring force if the prongs, which have mass, are displaced, and the system is set into vibration. In general, the tuning fork has one vibration frequency. This might be referred to as a simple or pure musical tone. Pure musical tones, however, are seldom utilized in music. The tones produced on musical instruments are almost always complex, i.e., mixtures of simple tones of various amplitudes and frequencies.

The sensation of sound as normally experienced is caused by periodic vibration or movement of molecules in the air. The ear receives three classes of sensations from these vibrations, i.e., pitch, loudness, and quality of sound. Pitch depends upon the frequency of the vibration as well as other physical characteristics, and loudness upon the amplitude, the frequency, and acuity of hearing. The quality of sound or timbre is dependent upon the number, frequency and amplitude of simple tones which make up a musical sound.

The individual simple tones which make up a complex tone are called partials, or partial tones. The partial possessing the lowest frequency is the fundamental. The frequencies of the other partials are usually integral multiples of the fundamental frequency of the vibration. They are called harmonics and form a harmonic series such as illustrated in Figure 1, page 8, based on C_2 as a fundamental. The fundamental, i.e., the vibration with the lowest frequency, corresponds to the number one and is called the first harmonic. The partial possessing a frequency twice that of the fundamental is the second harmonic, and the higher harmonics are calculated in a similar manner, e.g., the third harmonic possesses a frequency three times that of the fundamental and the frequency of the fifth harmonic is five times that of the fundamental.

In analyzing the physical behavior of a wind instrument such as the flute, the steady state sound generation must be considered. It is necessary to analyze the resonance properties of the air column and the primary excitation mechanism. Roederer (1973) states the following experimentally verified facts concerning the above:

> (1) The primary excitation mechanism sustains a periodic oscillation that is complex, of a certain fundamental frequency, and with a series of harmonics of a given spectrum. (2) Fundamental frequency and spectrum of the primary oscillations are controlled by the resonance properties of the air column; the total amplitude of the oscillations is determined by the primary energy supply (total air stream flow, blowing pressure). (3) The spectrum of the pressure oscillations outside the instrument (generated sound wave) is related to the internal spectrum by a transformation that is governed by the detailed form and distribution of the finger holes and/or by the shape of the bell (p. 122).

Thus it is essential to investigate the primary excitation mechanism which continuously supplies energy to the vibrating air column at a given rate. Such a mechanism

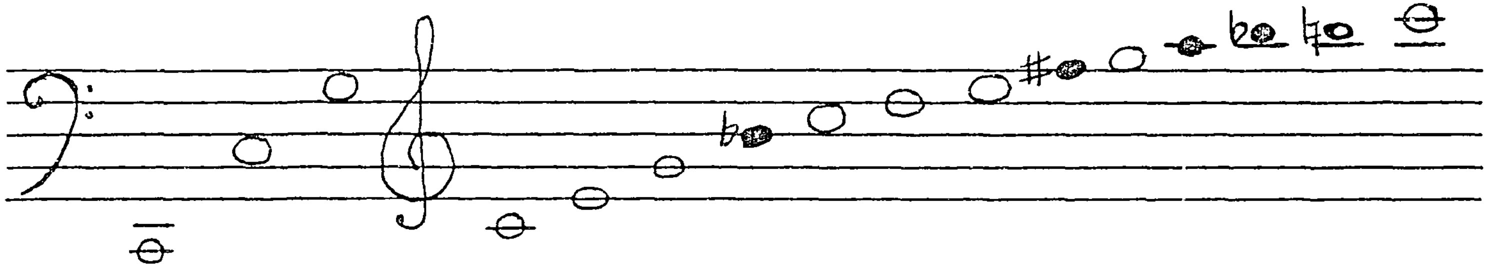

Figure 1. The Harmonic Series Based on C_2 as a Fundamental.

related to flute playing involves a high speed air stream blown against a rigid, sharp edge, located at a certain distance exactly above a slit, as in the embouchure hole. The air stream alternates back and forth between both sides of the edge, breaking into rotating puffs of air called "vortices" or "eddies," which travel upward along both sides of the edge. The air inside, possessing properties of inertia and elasticity, can be considered as a unidimensional elastic medium through which longitudinal waves can propogate.

The method by which the ear analyzes tone quality is well defined by Roederer (1973). He states that when a complex sound wave impinges on the eardrum, the eardrum will move in and out periodically with a vibration pattern dictated by the complex, nonsinusoidal vibration pattern of the wave. This motion is then transmitted mechanically by the chain of ossicles to the oval window membrane, which reproduces nearly the same complex vibration pattern. Roederer elaborated on this process:

> The complex vibration of the oval window membrane triggers traveling waves in the cochlear fluid. This is the stage at which the separation into different frequency components takes place (p. 134).

Miller (1909) discussed the method by which the ear proceeds in its analysis of tone quality with reference to Ohm's law of acoustics which states that:

> All musical tones are periodic; the human ear perceives pendular vibrations alone as simple tones; all varieties of tone quality are due to particular combinations of a larger or smaller number of simple tones; every motion of the air which corresponds to a complex musical tone or to a composite mass of musical tones is capable of being analyzed into a sum of simple pendular vibrations, and to each simple vibration corresponds a simple tone which the ear may hear (p. 62).

A quantitative investigation of the timbre of musical instruments involves the examination of the harmonic components of a complex motion. The process of determining the number and intensity of the harmonics present in a given complex tone is referred to as Fourier analysis, named after a nineteenth-century French mathematician. The representation of the analysis of a tone into its constituent parts or harmonics is called its spectrum. Tone spectra can be represented graphically. Each harmonic frequency is usually plotted on a horizontal axis and the intensity or amplitude of that harmonic component is plotted on the vertical axis.

Roederer (1973) alluded to this process when he stated that from a psychophysical point of view, a conventional harmonic representation (Fourier) of a tone spectrum makes no real sense beyond the sixth or seventh harmonic, because in that range neighboring components start falling within a critical band. A psychophysically more meaningful representation of tone spectra is obtained by listing the integrated intensity values *per critical band* (frequency intervals of roughly 1/3-octave extension) (p. 109).

The earliest devices used in recording waveforms include those such as the phonodeik, devised by Dayton C. Miller in 1909, the electromagnetic oscillograph, and the cathode-ray oscillograph. In acoustical measurement it is important to not only observe the waveform but also to determine what components or partials are present in a given sound, and the relative strength of each component. Technology in the field of musical acoustics has advanced significantly to the point that there are a number of electrical devices presently available which can determine the harmonic content of musical sounds. These are referred to as harmonic or spectrum analyzers. Such an analyzer is capable of indicating in detail the frequency distribution of any signal. The three basic types of spectrum analyzers are: (1) constant bandwidth, (2) band-rejection filter, and (3) constant-percentage bandwidth. The most sophisticated instrument presently available is a real-time analyzer which is useful because it displays the analysis instantly and automatically, via direct feeding of the signal into the analyzer.

In acoustical testing and measurement the sound under investigation is detected by a microphone, converted into a corresponding alternating electrical current, and then passed into the analyzer. A basic instrument in any acoustical measuring system is a reliable, accurately calibrated microphone. Several types of microphones are available, including condensor, electret, piezoelectric, and dynamic models.

In acoustical investigations it is highly desirable to store data for later evaluation or repetitive analysis. The most practical and widely used data-storage device is the magnetic tape recorder. Only high-quality audio tape recorders should be used, with a wide frequency response, large dynamic range, low noise, and accurate speed regulation. Vibration information fed into the tape recorder by a microphone is permanently recorded on a magnetic tape which can be replayed and the output can be fed through a frequency or harmonic analyzer and displayed on some form of read-out device. Such a device is a graphic level recorder which can be interlinked with a sound level meter, a tape recorder, or a harmonic analyzer. A strip chart provides a graphic representation of the components of each musical sound fed into a spectrum or harmonic analyzer.

Results of research by Dammann (1939), Woodward (1941), McGinnis, Hawkins and Sher (1943), Stauffer (1954), and Fletcher (1975) show that the harmonic structure of a complex tone varies with intensity. Thus, in acoustical measurement a sound level meter is often utilized to hold constant this variable. The sound level meter, a very sensitive audio-frequency voltmeter with a calibrated attenuator, indicates sound pressure levels in decibels, a single number giving the total sound-pressure level weighted by an approximation to the loudness-level sensitivity of the human ear for pure tones. For a single sound wave, moving in one direction, the intensity level and the sound-pressure level are the same.

Knowledge of the frequency of the sound being analyzed is necessary because the ear does not always respond uniformly to loudness when the frequency changes. Backus (1969) states that the pitch of a sound of a given frequency depends to some extent on its intensity (p. 112). Results of research by Stevens (1935), Cohen (1961), and Snow (1936) show that this effect seems to vary greatly from person to person and is more prevalent for pure tones than complex tones. The sound level meter does not measure loudness, only relative pressure; thus it is essential that both the sound-pressure level (SPL) and its distribution by frequency be determined in acoustical measurement. To ensure consistency of the pitch under investigation, a frequency meter called a Stroboscope is a useful instrument. Backus (1969) explicitly defines the principle and operation of such a device (p. 138).

Another variable to be considered in acoustical measurement is the experimental environment. In recording and analyzing musical sounds, it is highly desirable to provide an environment which is completely devoid of echo or reflection. Such an enclosure is called an anechoic chamber, a room specifically constructed with walls that absorb all the sound incident on them.

Thus, the quantitative analysis of musical tones is feasible via the use of highly sophisticated electronic equipment in an acoustically-controlled environment.

Statement of the Problem

The study consisted of a spectral analysis of steady state tones of five modern Boehm-system flutes constructed of different materials. A steady state tone refers to that condition in a vibration when the amplitude is constant.

The investigation sought to answer the following questions ($\alpha = .05$):

1. Do differences exist in the harmonic structure of tones produced on flutes constructed of different materials?
2. Do differences exist in the harmonic structure of tones produced on flutes constructed of the same material and made under the same written specifications by a single manufacturer?
3. Do differences exist in the harmonic structure of tones played at different intensity levels?
4. Do differences exist in the harmonic structure of tones played at various frequency levels?
5. Does the harmonic structure of a tone played on the same flute under identical conditions of intensity and frequency differ between performers?

Chapter II

REVIEW OF RELATED RESEARCH

Much can be learned about the influence of wall material on timbre from early investigations by organ builders who attempted to influence tone quality with differences in weight, density, rigidity, and potential resonance of pipe walls. Experiments with sets of pipes of like dimensions and pitch have tended to show that different materials used in construction reinforce different groups of partials.

Williams (1903) reported that the tone of metal pipes is influenced by the thickness and elasticity of the material as well as by the shape (p. 161). Miller (1909) used pipes of wood and zinc with the same internal dimensions. He concluded that the material had a decided effect on the tone quality (p. 169). Barnes (1933) reported that the thickness of the metal used in construction of organ pipes has much to do with the development of the harmonics and that thick metal causes the tone of pipes to be more foundational while pipes made with thin walls have greater harmonic development (pp. 30-31).

In a similar study, Jones (1937) concluded that the material of the walls has little effect on pitch or the quality of sound so long as the walls are hard, smooth and fairly rigid, but if the walls are thin or flexible, the material does become important (p. 47). In direct contradiction to the previous views, Glatter-Gotz (1931) investigated a large number of flue and reed pipes, analyzing the tones from pipes of various materials and shapes, and found that the material had no effect on tone quality, and that the only important factor to pipe tone was the geometrical shape (p. 99).

Lottermoser (1937) disputed this conclusion, asserting that the effect of material can easily be demonstrated by comparing the sound from an organ with tin pipes to the sound from one with zinc pipes. Describing his own experiments on four pipes of lead, zinc, tin and copper, he stated that he could detect no systematic influence of material on the total sound output from various combinations. He claimed that differences in the harmonic structure of the tones from different metals were observed, but, since the spectrum of a given combination varied with the position of the analyzing microphone, the spectrum of a tin pipe could be changed into the spectrum of a zinc pipe by moving the microphone, so the reason for the difference in sound as heard with different metals presumably arose elsewhere. With the use of a vibration pickup, he found considerable differences in the amplitudes and resonance frequencies of the wall vibrations. He concluded that these wall vibrations do not radiate significantly but do modulate the harmonics of the internal standing wave and hence account for the difference of tone owing to the wall material (pp. 129-134).

Boner and Newman (1940) conducted a study involving analysis of tones from the mouth section of a single pipe on which were mounted cylinders of various materials. Several metal tubes were used as well as cylinders of wood and one of a single layer of wrapping paper. The difference in the harmonic structure of tones produced by the various cylinders were found to be quite small, and the authors concluded that the material used in the construction of the cylinder above the upper lip of a flue pipe has very little effect on the steady state spectrum of the pipe (p. 88).

Mercer (1951) criticized the results of Boner and Newman on the grounds that their pipes were not representative of organ pipes as usually constructed, and he found it difficult to accept a conclusion so contrary to accepted views of organ builders (p. 48).

More recent studies involving organ pipes of various materials have been conducted by Jeans (1953), Lottermoser and Meyer (1962), Backus and Hundley (1966), and Levarie and Levy (1968). Jeans asserted that organ builders usually specify the precise nature of the metal or wood of which their pipes are to be built because they believe that the quality of the tone depends upon the material of the pipe. He further related this to orchestral instruments when he stated that a silver clarinet sounds very different from one made of wood, just as an orchestral flute sounds different from a penny flute. He attributed this to the formant which he found to have much to do with the characteristic timbre of the instrument. He added that some writers claimed that the timbre of the instrument is completely dominated by the formant (pp. 147-148).

Lottermoser and Meyer (1962) recorded the spectra produced on five metal pipes, identical in all respects except for the material used in their construction. Differences were found in the harmonic structure of the tones produced on the various pipes. The authors concluded that these differences were influenced by the pipe material (p. 111).

Backus and Hundley (1966) studied six organ pipes constructed of different materials. Using a sound analyzer, they examined the harmonic structure of tones produced on these pipes and concluded that the wall vibrations in organ pipes as commonly constructed have negligible influence on the steady pipe tone, and probably little on the transient buildup as well (p. 944). They further contended that the steady tone of a pipe does not depend on the material of the pipe wall (p. 945). Levarie and Levy (1968) reported that the main conditions for the creation and enhancement of harmonic vibrations are elasticity and inertia, and that every material differs in these properties (p. 89).

Numerous studies have been conducted relating to the acoustical properties of woodwind instruments. Baasch (1955) cited a study by Miller in 1926 wherein the tone of a gold flute was compared with that of other flutes made of different materials. Miller claimed that elaborate analysis of tones produced on flutes made of wood, glass, silver, and gold proves that the tone from a gold flute is mellower and richer, having a louder series of partials than flutes of other materials (p. 6).

Richardson (1929) studied the effect of tube material on the tone quality of the clarinet and concluded that the influence of the tube was twofold: (1) greater or less damping of the tone, depending upon the rigidity of the tube, and (2) enhancement of tones in certain regions of the scale depending upon the tendency of the tube to have marked natural frequencies (p. 57).

Lanier (1960) conducted a study using nine B-flat clarinets made of different materials, three ebonite, three metal, and three wooden. Through the use of a mechanical embouchure, an oscilloscope, and a sound level meter, he analyzed the tone spectra which revealed that the wooden clarinet produced stronger third and fifth partials than the ebonite and metal clarinets. Lanier concluded that the type and thickness of the material enclosing a vibrating column of air will tend to reinforce or subdue certain partials of the tone (p. 22).

The findings of Parker (1947) and Backus (1964) are in direct contradiction to those of Lanier. Parker investigated the harmonic spectra produced by wooden and metal clarinets, using a harmonic analyzer and reported that the respiratory tract and the wood or metal of which the instrument is made have no appreciable effect upon the steady-state spectra (p. 415). Backus concurred with these findings when he investigated the internal air-column vibration of a clarinet. He concluded that the material from which an instrument is made can be selected for other qualities such as dimensional stability, ease of fabrication, etc., and not because of any tone quality inherent with the material (p. 1887). In a later study, Backus (1968) investigated the resonance and mouthpiece pressure harmonic structure curves for a number of tones produced on five clarinets, two made of wood and three made of plastic. He found that the resonance curves for all five clarinets were remarkably similar, as were the harmonic structure curves, and concluded that the resonance curves for a given tone on clarinets made of different materials appear to be very much alike (p. 1281).

McCathren (1959) sought to determine the effect that the materials from which a mouthpiece is constructed has on the tone quality of a clarinet. Mouthpieces of hard rubber, crystal, and plastic were used in the study. It was found that the tone produced by the hard rubber mouthpiece contained the strongest fundamental as well as the stronger and more numerous partials. McCathren concluded that there was a great difference in the tones produced by the various mouthpieces (p. 72).

In a related study Wehner (1963*b*) sought to determine the effect of the interior shape and size of clarinet mouthpieces on intonation and tone quality. Two clarinets and two mouthpieces having the medium "French" facing and possessing identical bore size measurements were used. Brass shim stock was used in the bore to form the various tapers and rubber cement was used to make the cone airtight. The bore length was then varied with the use of red dental wax and reduced in size gradually until a measurement of 1.75 inches was reached. When the wave forms were measured with a wave analyzer, all tones which were used in the study showed a similarity in their patterns of partials. Wehner concluded that changes made in tone chamber depth sizes did not greatly affect the waveforms when measured with a harmonic wave analyzer (p. 134).

Wehner (1963*a*) reported the results of an investigation to determine if differences existed between the French and German tone qualities on the clarinet. A B-flat clarinet, with selected reeds and mouthpieces, was used. A skilled clarinetist played a single tone from four registers of the clarinet. Four tape loops each were made, first using a French-type mouthpiece and then a German-type mouthpiece. The waveform of each tone was analyzed using a harmonic wave analyzer. After examining the results of the analysis of the waveforms, Wehner concluded that the difference between the German and the French clarinet tone qualities, when measured physically, is slight if taken as an overall summation. The German tone quality is stronger in the higher frequencies and when summing the overall millivolt strength, it is stronger by .4 millivolts (p. 16). In the same study Wehner sought to determine whether well trained musicians could discriminate between the French and German tone qualities. Various tape loops were played in pairs and the judges were asked to select the French and the German timbre. The third part of the study was related, in that four records were played for the same judges, and they were asked to select the type of tone quality represented by the clarinetist on the record. After analyzing the results of testing the discrimination levels of the judges, Wehner concluded that trained musicians, in general, cannot significantly discriminate between the French and German clarinet tone quality (p. 16).

Smith and Mercer (1974) conducted an experiment directed at isolating one variable, the bore shape, in an investigation of apparent differences between the tone qualities of woodwind instruments. The same reed was used on brass cones of different apex angles. Smith and Mercer found that there was a significant change in the tone color and harmonic spectra produced by the various cones (p. 347). They observed that both the wide angled cones and instruments of similar shape, e.g., the oboe, produce spectra having formants in the 1000 Hz region, and consequently, a more penetrating tone than the narrower cones and instruments.

In a similar study, Russell (1953) sought to determine by measurement, playing test, and harmonic analysis, what relation various combinations of bore specifications, exterior body dimensions, and size and placement of the tone holes have on the musical effectiveness of the oboe. He concluded that, "If the tone of an oboe is to be aesthetically pleasing, its bore must conform to a definite pattern of deviations from a true cone, and this pattern must be one of proportion related to the true cone formed between the initial or starting diameter and the final or maximum diameter. The thickness of the body also affects slightly the tone quality and pitch . . ." (p. 66).

Benade (1959) investigated the requirements and behavior of bores which are used in woodwind instrument construction. He reported that there is a necessity for preserving a constant frequency ratio between the normal modes in all woodwinds which provides a general limitation on the types of bore which are musically useful. He concluded that the cylindrical pipe and complete cone are the only shapes which satisfy these requirements exactly (p. 137). In the same study, Benade investigated the influence of wall damping and radiation damping on the vibrational modes and their effect on the tone quality of the woodwind instruments. He concluded that on all the woodwind instruments, except for the saxophone, damping of the normal modes by the walls of the bore plays a dominant role in the playing behavior and tone quality (p. 143). Another factor investigated in the study (1959) was the influence of closed finger holes on the effective bore of the instrument and the tone quality. Benade stated that a primary concern of instrument makers is to ensure that the frequency ratio of the second to the first normal mode is integral, so that the middle register notes have acceptable intonation with respect to the low register. He contended that the tone quality, which depends on the response to all the harmonics, becomes a complicated function of the system of fingering upon which the holes are based. Benade concluded discussion of this aspect by asserting that any attempt at understanding the tone color of a woodwind instrument must concern itself closely with the actual frequencies of the normal modes, and with the damping of these modes, since the latter controls the band width. He stated that there are two means whereby a vibrating air column may lose energy. The dominant one is the friction and thermal energy transfer to the walls of the horn. The second, which is the one for which the instrument is built, is the radiative transfer of sound energy to the air outside the horn by way of the open tone holes and bell (p. 142).

Fajardo (1973) conducted a scientific investigation into the tonal properties of the flute head joint using a Tektronix scope with a frequency analyzer and memory storage. His contention was that the material of the body of the flute has very little effect on its tone quality, but the material and various dimensions (wall thickness, taper and hole size) of the headjoint have a significant and decisive influence on the tone (p. 46). The same headjoint made of linen phenolic material, similar to formica, was used with an inexpensive metal flute made of nickel alloy called German silver and with a wooden flute. The tones produced were judged subjectively, via aural discrimination, and objectively by means of a harmonic analyzer. Musically trained persons could not tell the difference between the two flutes. The data proved through harmonic analysis that the phenolic head joint eliminated the third harmonic with both the metal and wooden flutes as compared to when both were played with their own headjoints (p. 49). Fajardo drew the conclusion that a head built of a suitable plastic would permit a body of relatively inexpensive metal to sound like the more expensive flutes built entirely of silver or gold. Fajardo made no reference to the use of a sound level meter in the experimental procedures. It has been proven in previous research studies that the intensity level of a tone affects the harmonic content.

Benade and French (1965) investigated the acoustical properties of the flute headjoint and concluded that while the tone color of a flute is determined in part by the same parameters that control its intonation, it is not possible to analyze tone color meaningfully unless resonance properties of the complete instrument are known over the whole spectral domain (p. 679). They contended that a knowledge of the detailed nature of the regeneration mechanism that sustains the oscillations is necessary, and that if a study deals only with the headjoint, it is premature to attempt a discussion of tone color (p. 680).

Significant investigations into the effects of materials used in the construction of flutes have been conducted by Coltman, a physicist and flutist. In a recent study (1971), two experiments were conducted, based on aural discrimination. The first was directed toward determining whether listeners could discriminate among three flutes constructed of different materials, when played by the same performer. In the second test, four different flutists, all reasonably skilled, were asked to play three different flutes. They were then asked to identify the material from which each was made, without being able to observe which instrument they were playing. Coltman reported that no evidence was found that experienced listeners or trained players can distinguish between flutes of like mouthpiece material whose only difference is the nature and thickness of the wall material of the body, even when the variations in the material and thickness are very marked (p. 523).

The bodies of the flutes used in Coltman's study were constructed of thin silver, heavy copper, and wood. They were, however, not considered representative examples of the modern concert flute, in that they were only thirteen inches long, keyless, and had plastic head joints only two inches long. Embouchure hole specifications were not reported and the use of a sound level meter was not mentioned. For some of the experimental tasks, the flutes were mounted on a round metal plate at points where the head joints joined the bodies, so that the performers could rotate the plate to play the different flutes without knowing which one they were playing. This unnatural arrangement in playing conditions would seem to be restrictive to the performer.

Numerous studies have been conducted in recent years relating to other acoustical principles involved in wind instrument performance. Aspects of embouchure formation, intensity levels, and vibrato have been investigated.

Klein and Gerritsen (1975) investigated the tone qualities of two tones of the same pitch played on a modern metal flute by the same player. The flutist used a different embouchure formation for each of two tones, played in pairs. Three registers of A-natural tones were played in pairs, first, with a relaxed embouchure with a circular aperture, then with a tight embouchure in which the lips were tensed back at the corners of the mouth forming an elongated aperture. A high-quality crystal microphone, connected to an oscilloscope equipped with a camera was used in the experiment. A photograph was taken of each pair of tones. The photographs were projected and copied onto graph paper. The results of the Fourier analysis demonstrated that a correlation does exist between tone quality and the amplitude of the contributing harmonic components (p. 736). The difference in tone quality was produced by controlling the size and shape of the flutist's lip opening.

In a study conducted by Neverdeen (1973), frequencies of flute tones performed by various players were compared with passive resonances, with and without the lip partly covering the embouchure hole. It was found that the part of the embouchure hole covered by the lip is approximately constant for all frequencies; however, the exact magnitudes of both frequency shift and lip coverage appear to depend on the player. Neverdeen found that a comparison of the calculated and measured passive resonances for flutes with uncovered embouchure hole did not yield completely satisfactory results. Differences varied over the entire compass of the flute range, but in a significantly different way for two virtually identical flutes (p. 22). He related these findings to a study wherein the influence of wall vibration on sound generation in two different recorders was investigated. The flexural resonance curves were measured for both a recorder considered to be a good specimen and one considered inferior. It was found that the damping, as obtained from the width of the resonance curves, was .011 for the superior recorder and .016 for the inferior one. Neverdeen stated that the wall vibrations can be coupled with air vibrations in some way, and that any exhaustive discussion of a flute's blowing mechanism should also include effects of its wall vibrations (p. 22).

Researchers have investigated the extent to which the harmonic structure of tones produced on wind instruments varies with changes in intensity. McGinnis, Hawkins and Sher (1943) investigated tones throughout the entire range of the clarinet. Three sound levels of each tone, i.e., 78, 84 and 92 db, were measured by a General Radio sound level meter. A piezo-electric pressure microphone was placed about three inches from the bell of the clarinet and on a line with its axis. A harmonic wave analyzer was used to measure the relative physical intensity of the harmonics present in the tones. The results showed that the playing of a *pp* tone always resulted in an almost pure sine curve on the screen of the oscilloscope, showing it to consist almost entirely of the fundamental. The authors concluded that the harmonic content of tones produced on the clarinet becomes simpler from the lowest to the highest pitch and changes in the intensity affect the waveform of tones in the chalumeau register more than those in the clarion or altissimo registers (pp. 234-236).

In a study by Fletcher (1975), four experienced flutists played concert C-natural in three different registers using the same flute. The tone in each register was played at three different dynamic levels, i.e., fortissimo, mezzo forte, and pianissimo. The sounds produced by each of the four players in the study were recorded and systematically analyzed. The results showed that in the lowest register of the flute, in loud playing, the fundamental is lower in level of predominance than either the second or third harmonics, and may be lower than the fourth or fifth harmonics as well. When the playing is soft in this octave, the level of the fundamental is the same as for loud playing but the relative levels of all higher harmonics are decreased.

For the middle octave of the flute, the fundamental becomes the dominant partial for both loud and soft playing, though second and third harmonics are within

10 db in relative level. The sound pressure level of the fundamental changes little with dynamic level and most of the change is represented by changes in the upper partials.

In the third octave the fundamental is clearly dominant and all upper partials are more than 10 db below it in relative level. The fundamental changes considerably with dynamic level, though still not as much as do the upper partials. Fletcher asserted that, "If we were to seek to describe a formant for flute tone on the basis of these measurements, then we would in fact need different formants for loud and soft playing" (p. 235).

The previous findings related to the effect of intensity on the harmonic structure of a tone are corroborated by conclusions drawn from experiments by Dammann (1939), Woodward (1941), Lehman (1964), Stauffer (1954), and Clark (1964).

Small (1967) investigated aspects of the clarinet tone quality through the use of oscilloscopic transparencies. His objective was to use the photographs as a teaching aid, whereby analysis of the transparencies would serve as a method by which clarinet tone quality might be (a) perceived, (b) compared, (c) diagnosed, (d) corrected, and (3) better understood by students and teachers (p. 11). He concluded that the procedures developed in the study were of value as a teaching aid. Small advocated the need for further research into the analysis of tone quality of wind instruments, and emphasized, in particular, the possibility of future research into aspects of vibrato.

Fletcher (1975) dissected the various components of flute vibrato using a wave analyzer whose bandwidth was much larger than either the amplitude-modulation frequency (the pulsation frequency) or the frequency deviation in the vibrato. The data showed that flute vibrato consists largely of variation in amplitude of the upper partials of the tone, causing a periodic variation both in loudness and, more importantly, in timbre (p. 236).

Chapter III

PROCEDURES

The study consisted of a spectral analysis of three tones played at two intensity levels by two performers on five flutes constructed of different materials. Three trials of each performance task were conducted. Thus, the design of the study was as follows: 2 performers x 3 frequencies x 2 intensities x 5 flutes x 3 trials = 180 total performance tasks.

An example of the design depicting all performance tasks as performed by one player on a single flute is represented schematically in Figure 2, page 34.

Selection of Flutes

Five modern Boehm-system flutes constructed of different materials were used in the study. The materials represented included sterling silver, white gold, 14 karat gold, and palladium. Two sterling silver flutes, bearing consecutive production serial numbers and possessing identical specifications of manufacture, were tested under the same conditions of frequency, intensity, performer and wall material. This was to determine whether two flutes, assumed to be identical, produce the same or similar tonal spectra.

Performer No. 1--Flute No. 1

a_1	b_1	b_1	b_1
a_2	b_1	b_1	b_1
a_1	b_2	b_2	b_2
a_2	b_2	b_2	b_2
a_1	b_3	b_3	b_3
a_2	b_3	b_3	b_3

a = intensity (2 levels)
b = frequency (3 levels)

Figure 2. An Example of the Design of the Study

All the flutes were produced by the same manufacturer, Muramatsu Flutes, Inc., and were the standard French model (open hole) with a low B foot joint. The five flutes tested were all produced during the same series of manufacture and were cast with the same internal and external measurements. The specifications such as the length of the instrument, the length and internal configuration of the headjoint, the size and shape of the embouchure hole, the size and shape of the tone holes, the placement of the tone holes, and the diameter of the bore were held as uniformly as possible.

Measurements of such specifications were made on each flute by the researcher, using a vernier caliper constructed to facilitate measurement of a curved wall. Measurements of wall thickness were taken at each end of the headjoint and at the body and foot joint of each flute. The diameter of the bore was determined in a similar manner. Two measurements were taken at the headjoint to determine the diameter of the bore, one at the end where the plug is inserted, and one at the open end. These are given respectively in the information contained in Figure 3, page 36. The weight of each flute was obtained using a set of double-pan balancing scales and weights, calibrated in grams. Measurements and specifications of each flute are also given in Figure 3.

No.	Brand	Serial Number	Material Used in Construction	Thickness of the Wall (in inches)	Diameter of the Bore (in inches)	Weight (in grams)
1	Muramatsu	25296	Sterling Silver	.015	.664/.743	441.2
2	Muramatsu	25295	Sterling Silver	.015	.664/.743	441.6
3	Muramatsu	21149	Palladium	.015	.664/.743	438.4
4	Muramatsu	18314	White Gold	.015	.664/.743	529.6
5	Muramatsu	14871	14 Karat Gold	.015	.664/.743	503.2

Figure 3. Specifications of the Flute

Due to the softness and malleability of pure gold, it is usually alloyed with other metals such as iridium to obtain the required hardness in flute construction. White gold is an alloy of gold decolorized by the addition of palladium. The density and elasticity of these metals is given in Figure 4, page 38.

Selection of the Performers

Serving as performers in the study were Ervin Monroe, recording artist/clinician and principal flutist in the Detroit Symphony Orchestra, and the researcher, an Assistant Professor of Music (flute) at Appalachian State University, Boone, North Carolina.

Performance Tasks

The performance tasks consisted of three frequencies played at two intensity levels by two performers on five different flutes. Three trials were conducted on each tone at a single intensity level by each performer. The performance tasks included extremes of dynamic and pitch ranges. A total of 180 tasks were performed for purposes of analysis.

In the case of intensity, preliminary tests revealed that the range from 70 to 100 decibels approached the limits of what is possible on the flute. Intensity and loudness, however, are terms which are not interchangeable, i.e.,

	DENSITY (in gm/cm^3)	ELASTICITY Young's Modulus in lbf/in^2
STERLING SILVER	10.5	11×10^6
GOLD (pure)	19.3	12×10^6
PALLADIUM	12.2	18×10^6
IRIDIUM	22.4	75×10^6

Figure 4. Density and Elasticity of Metals

intensity refers to the physical property of sound, while loudness is a psychological phenomenon perceived by the listener. Intensity can be measured objectively, while loudness is a subjective sensation of the magnitude of a sound.

Frequency plays a significant role in the intensity/loudness relationship. Previous research by Fletcher and Munson (1933), Schneider et al. (1972), and Molino (1973) reveals that the human hearing mechanism's sensitivity to changes in intensity varies with frequency. Equal loudness curves show that the sensitivity of the ear tends to decrease considerably toward the low and very high frequencies. Thus, the tones of performance tasks 1-3 and 7-9 were held at 85 decibels, which was determined to represent the *forte* dynamic level for both G_4 (392 Hz) and G_5 (784 Hz). The tones of performance tasks 4-6 and 10-13 were held at 75 decibels, which was considered to represent the *piano* dynamic level for these frequencies. The decibel levels determined to represent the *forte* and *piano* dynamic levels for G_6 (1568 Hz) were increased to 95 and 85 decibels, respectively, due to the human hearing mechanism's sensitivity or subjective perception at this frequency level.

The frequencies for performance tasks 1-18, which represented three registers of the range of the flute, were G_4 (392 Hz), G_5 (784 Hz), and G_6 (1568 Hz). The system used to designate the octaves is that which has been adopted by the Acoustical Society of America. The performers held each tone at the specified decibel level for four to five seconds. A sound level meter was used to measure this variable for control purposes. The performers did not use vibrato when performing the tasks. Each performer, flute and task number was announced by the performer prior to initiating each tone. This procedure was followed to ensure synchronization of all final records. An audio tape recording was made of all final records. An audio tape recording was made of all performance tasks. An example of the performance tasks is presented in Figure 5, page 41.

Physical Environment

The study was conducted in the anechoic chamber and adjacent electronic laboratory at The Center for Acoustical Studies of North Carolina State University, Raleigh, North Carolina. The chamber, a suspended room within a room, measured 18 feet square and 12 feet high. All walls, the floor and ceiling were lined with triangular-shaped polyurethane foam panels which were supported by batting. Housed inside the anechoic chamber were two high-quality condensor microphones, a sound-level meter mounted on a tripod, and a table which held the frequency meter and the five flutes, each of which was assigned a number, one through five. A single performer was the only individual present within the anechoic chamber during
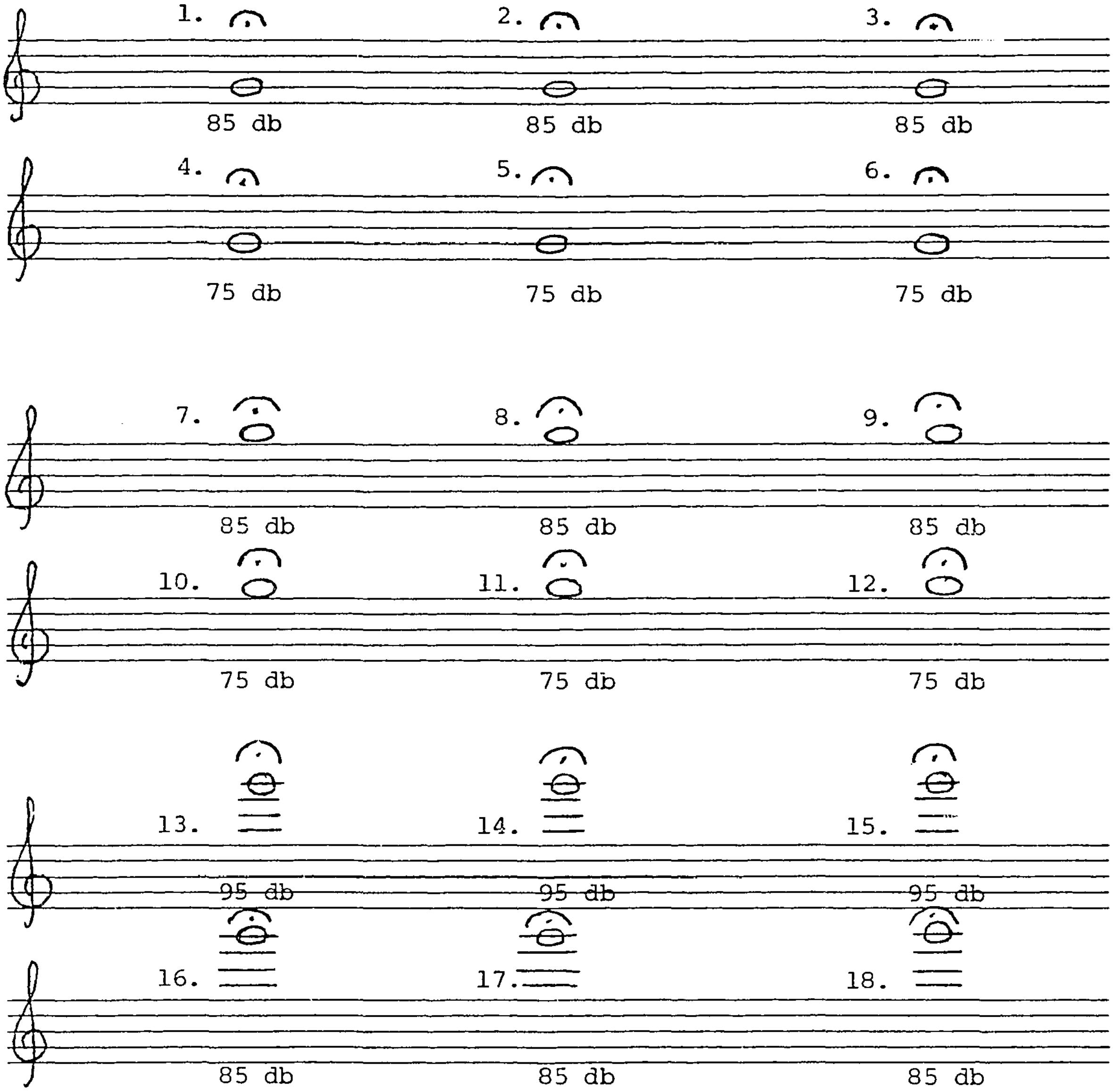
Figure 5. The Performance Tasks

performance of the tasks. Individuals present in the adjacent electronic laboratory during the investigation included two research technicians employed by The Center for Acoustical Studies, an assistant to the researcher, and the other performer.

Instrumentation and Technique

Prior to beginning the performance tasks, the performers were permitted to "warm up" and carefully tune each of the five flutes inside the anechoic chamber. A *Korg* tuner was used to check intonation. During the performance tasks, each performer was situated in a normal playing position equidistant from two high-quality calibrated condensor microphones, which were placed eight feet from the performer and seven feet apart. The place where the performer was to be situated during the performance tasks was marked with strips of masking tape affixed to the floor. Directionality of the sound emitted from the flute proved to be a significant factor during the investigation. A careful balance between the two microphones was calibrated before each performer began the performance tasks. Due to the difference in height between the two performers, the taller of the two was seated on a high stool such as a double bass player uses, in order to replicate the position of the shorter performer during performance of the tasks. A careful check of the calibrations of all the electronic equipment was conducted to ensure consistency of this variable. Once this was attained, a single performer was the only individual present within the anechoic chamber.

A sound level meter mounted on a tripod was positioned two feet in front of the performer at eye level. A music manuscript of the performance tasks was placed just beneath the sound level meter in view of the performer. Six inches to the right and slightly in front of the performer was the table holding the five flutes, positioned so that the player could change flutes without changing playing position. This arrangement was held constant throughout the performance of all tasks.

Signals from the condensor microphones were channeled into a real-time spectrum analyzer which was housed inside an electronic laboratory adjacent to and connected with the anechoic chamber. The analyzer, which detected and computed the mean of 32 samples or pictures of the tonal spectra for a given tone in three seconds, covered a frequency range of 20-20,000 Hertz. A linear graph plotter (recorder) was linked with the spectrum analyzer to produce a "print-out," a graphic representation of the components of each musical sound channeled into the analyzer. An example of the plot or "print-out" of the tonal spectra is presented in Appendix B, page 83.

Activity within the anechoic chamber was visually monitored through a clear glass observation window which connected the chamber and the electronic laboratory, in the event that problems arose during the investigation. An audio recording of all performance tasks was made using a high-quality tape recorder. A complete listing of all equipment used in the study is contained in Appendix C, page 85).

Chapter IV

DATA ANALYSIS AND RESULTS

The information produced by the spectrum analyzer was recorded by a linear graph recorder. The tonal spectrum for each tone investigated was plotted on an individual chart such as that illustrated in Appendix B. The amplitude of the partials, indicated in relative decibel level, was plotted along the vertical axis. The frequencies of the spectral components, indicated in Hertz, were plotted along the horizontal axis.

Quantification of the Data

The spectra were examined to determine the strength and number of partials in each tone investigated under each condition of intensity, performer and wall material. The information from the plots was converted and quantified. The -0 to -60 decibel scale reflected the relative decibel level and served as a logarithmic reference point in voltage output. A calibration tone was established to determine the absolute decibel level of the partials present in each tone. It was determined that 94 decibels was the peak amplitude in calibrating the absolute decibel level. A transparency grid was used to convert the relative decibel levels of the partials to absolute levels.

Analysis of the Data

The individual and mean strengths of the partials for each tone, derived from three trials under the same conditions of intensity, performer and wall material, were calculated. The mean strengths of the partials for each tone played under the same conditions of intensity and wall material by both performers combined, i.e., a composite total of all six trials, were also calculated. These data are presented quantitatively in Tables 1 through 18 of Appendix D. The quantified data are presented in bar graph form in Tables 19 through 30 of Appendix D for purposes of visual examination.

Since the present investigation involved several independent variables, i.e., frequency, intensity, performer and flute, as well as several dependent variables, i.e., the various partials present within the tonal spectra, a multivariate analysis of variance of a four-way factorial design was utilized. In the multivariate analysis of variance the total sum of products was partitioned according to the independent variables into between groups and within groups sums of products. Multivariate methods take into account the correlations among the dependent variables.

A 2 x 3 x 2 x 5 factorial design was utilized to determine differences between the tonal spectra of all five flutes tested. For a comparison of the tonal spectra of only the two sterling silver flutes, a 2 x 3 x 2 x 2 factorial design was used.

The general linear models procedure was employed, which insures that the analysis for each dependent variable brings into use every possible observation, and tests the significance of main effects and interactions (crossed effects).

The inconsistent and sparse presence of the upper partials within the tonal spectra, particularly for the higher frequencies tested, resulted in insufficient data and degrees of freedom considered feasible for analysis beyond the fourth partial.

The *Statistical Analysis System* program package, 1979 edition, SAS Institute, Inc., Raleigh, North Carolina, was employed. The .05 level of probability was chosen for significance testing. Results of the multivariate analysis of variance of the four-way factorial designs are found in Tables 31 through 39 in Appendix D.

Observations and Results

Observations based on a visual examination of the graphically-represented data and the results of a four-way multivariate analysis of variance are presented in the following pages.

Differences between the Five Flutes

The number and amplitude of partials present in the tonal spectra of the five flutes used in the study varied.

The data contained in Tables 25 through 30 reveal that the fundamental was generally the strongest partial at all intensity and frequency levels investigated, and was the partial which varied the least in amplitude between flutes. The lower, stronger partials tended to vary less between flutes than the upper, weaker partials. In general, there was a gradual decrease in the number and amplitude of partials from the fundamental to the upper partials, i.e., a sloping off in amplitude and presence, sequentially. This was observed in the tonal spectra at all intensity and frequency levels with the exception of flute number three, made of palladium. At the higher intensity level of all three frequencies investigated, an upper partial tended to occur equal to or higher in amplitude than a lower partial within the tonal spectrum.

The number of partials within a tone consistently decreased with an increase in frequency. The number of partials present in a tone consistently decreased with a decrease in intensity. The greatest difference between the tonal spectra of the five flutes existed in the number and amplitude of the upper partials present in the tones investigated. The data in Tables 25 through 30 reveal that the greatest variation between flutes in the number of partials present in a tone occurred in the tonal spectra of G_4 (392 Hz) at the *piano* level (75 db) and G_5 (784 Hz) at the *forte* level (85 db). The least variation in this respect occurred in the tonal spectra of the highest frequency investigated, G_6 (1568 Hz). The variation between flutes in the mean strength of a single partial for a given tone ranged from exact duplication to 20 decibels for the first three partials, and up to 37 decibels for the upper partials, an example of which may be found in Table 3.

The information in Figure 6, page 50, represents a comparative analysis of the tonal spectra of the five flutes used in the study. The data indicated that when considering the total amplitude of all partials present in a composite tone, the tonal spectra of the sterling silver flute number one consistently possessed the strongest total amplitude of all partials present at the higher intensity level of all frequencies investigated, and at the lower intensity of G_6 (1568 Hz). The tonal spectra of the flute number two, also constructed of sterling silver, possessed the strongest total amplitude at the lower intensity level of the two lower frequencies investigated. Although the tonal spectra of flute number one possessed the strongest total amplitude of partials at the higher intensity levels, it proved to be the weakest in total amplitude at the lower intensity level of G_5 (784 Hz).

The data in Figure 7, page 51, represent the total amplitude of all partials present in each composite tone investigated in the study. The range of variation between flutes in the total amplitude of partials present in a tone

Frequency--392 Hz (G$_4$)			Frequency--784 Hz (G$_5$)			Frequency--1568 Hz (G$_6$)		
	High Intensity (85 db)	Low Intensity (75 db)		High Intensity (85 db)	Low Intensity (75 db)		High Intensity (95 db)	Low Intensity (85 db)
Flute No. with *Most Number* of Partials Present	1,2,4,5	Equal (but varied)	Flute No. with *Most Number* of Partials Present	4	Equal (but varied)	Flute No. with *Most Number* of Partials Present	Equal	Equal
Flute No. with *Least Number* of Partials Present	3	Equal (but varied)	Flute No. with *Least Number* of Partials Present	1,2,3,5 (but varied)	Equal (but varied)	Flute No. with *Least Number* of Partials Present	Equal	Equal
Flute No. with *Strongest Total Amplitude* of All Partials Present	1	2	Flute No. with *Strongest Total Amplitude* of All Partials Present	1	2	Flute No. with *Strongest Total Amplitude* of All Partials Present	1	1
Flute No. with *Weakest Total Amplitude* of All Partials Present	5	4	Flute No. with *Weakest Total Amplitude* of All Partials Present	3	1	Flute No. with *Weakest Total Amplitude* of All Partials Present	4 & 5	5

Figure 6. A Comparative Analysis of the Flutes

Frequency--392 Hz (G_4)

Flute Number	High Intensity (85 db)	Low Intensity (75 db)	Difference between Intensity Levels
1	380	214	166
2	383	226	157
3	355	209	146
4	377	206	171
5	347	224	123
	range = 36	range = 20	

Frequency--784 Hz (G_5)

Flute Number	High Intensity (85 db)	Low Intensity (75 db)	Difference between Intensity Levels
1	218	142	76
2	213	167	46
3	179	143	36
4	207	155	52
5	197	161	36
	range = 39	range = 25	

Frequency--1568 Hz (G_6)

Flute Number	High Intensity (95 db)	Low Intensity (85 db)	Difference between Intensity Levels
1	181	153	28
2	174	145	29
3	168	135	33
4	168	145	23
4	172	120	52
	range = 13	range = 33	

Figure 7. A Comparison of Total Amplitude of Partials between Flutes, Intensity Levels, and Frequency Levels

was generally less at the lower intensity level than at the higher intensity level of the same frequency. The least variation between flutes in the total amplitude of all partials present in a composite tone occurred for the frequency 1568 Hz (G_6) at the higher intensity level, with a range of only 13 decibels. The most variation between flutes in this respect occurred for the frequency 784 Hz (G_5) at the higher intensity level, with a range of 39 decibels.

A summary of the multivariate analysis of variance of the 2 x 3 x 2 x 5 factorial design is presented in Figure 8, page 53. A significant difference was found between the tonal spectra of the five flutes for the partials number one ($p < .0139$), two ($p < .0001$), and four ($p < .0105$). No significant effect ($p > .05$) was found for partial number three. Further analysis revealed that the interaction of performer and flute was significant for partials number one ($p < .0343$) and three ($p < .0003$), but not significant for partials two and four ($p > .05$).

All main effects of performer, frequency, intensity, and flute were significant ($p < .05$) for every partial with two exceptions, i.e., performer for partial number two ($p > .05$) and flute for partial number three ($p > .05$).

Source	Partial #1	Partial #2	Partial #3	Partial #4
A (Performer)	$p < .0001$	NS	$p < .0001$	$p < .0001$
B (Frequency)	$p < .0001$	$p < .0001$	$p < .0001$	$p < .0001$
C (Intensity)	$p < .0001$	$p < .0001$	$p < .0001$	$p < .0001$
D (Flute)	$p < .0139$	$p < .0001$	NS	$p < .0105$
A x B	NS	$p < .0115$	$p < .0001$	NS
A x C	$p < .0083$	NS	NS	NS
A x D	$p < .0343$	NS	$p < .0003$	NS

Figure 8. MANOVA Summary of the 2 x 3 x 2 x 5 Factorial Design

Differences between the Two Silver Flutes

The number and amplitude of partials present in the tonal spectra of the two sterling silver flutes differed, as evidenced in the data contained in Tables 25 through 30. The number and amplitude of partials in the tonal spectra of both flutes tend to decrease with an increase in frequency. The fundamental and the lower, stronger partials tend to vary less than the upper, weaker partials.

The information contained in Figure 6 shows that the tonal spectra of flute number one possessed the strongest total amplitude of partials present in the composite tones of all frequencies tested at the higher intensity level, and at the lower intensity level of G_6 (1568 Hz). The tonal spectra of flute number two possessed the strongest total amplitude of all partials present in the composite tones of G_4 (392 Hz) and G_5 (784 Hz) at the lower intensity level.

The data in Figure 7 reveal that the difference in total amplitude of all partials present between the two intensity levels of the same frequency was greater in the tonal spectra of flute number one for the two lowest frequencies investigated, while a slightly greater difference was observed in the tonal spectrum of flute number two for G_6 (1568 Hz). Differences between the two flutes in the total amplitude of partials present in the spectra were consistently greater at the lower intensity level than at the higher intensity level of the same frequency.

A summary of the multivariate analysis of variance of the 2 x 3 x 2 x 2 factorial design is presented in Figure 9, page 56. The analysis showed no significant difference ($p > .05$) between the tonal spectra of the two sterling silver flutes. The main effects of frequency and intensity were found to be significant ($p < .0001$) for all partials. The main effect of performer was significant for partials number one ($p < .0005$) and three ($p < .0043$), but not for partial number two ($p > .05$).

The interaction of performer and frequency was significant for all partials ($p < .0091$, $p < .0251$, $p < .0152$, respectively). The interaction of performer and intensity was significant for only partial number one ($p < .0012$), while the interaction of performer and flute was significant for only partial number three ($p < .0001$).

Differences between Intensity Levels

In general, the number and amplitude of partials in the tonal spectra of each of the frequencies investigated decreased consistently with a decrease in intensity. The fundamental was most often the strongest partial in amplitude at both intensity levels, and varied the least. Generally, the lower, stronger partials varied less in number and in amplitude than the upper, weaker partials for the same frequency at both intensity levels.

The data in Figure 7 show that the range of variation between flutes in total amplitude of all partials present

Source	Partial #1	Partial #2	Partial #3
A (Performer)	$p < .0005$	NS	$p < .0043$
B (Frequency)	$p < .0001$	$p < .0001$	$p < .0001$
C (Intensity)	$p < .0001$	$p < .0001$	$p < .0001$
D (Flute)	NS	NS	NS
A x B	$p < .0091$	$p < .0251$	$p < .0152$
A x C	$p < .0012$	NS	NS
A x D	NS	NS	$p < .0001$

Figure 9. MANOVA Summary of the 2 x 3 x 2 x 2 Factorial Design

in a composite tone was less at the lower intensity level than at the higher intensity level of the same frequency, in general. The range of variation between the five flutes was only 20 decibels for G_4 (392 Hz) and 25 decibels for G_5 (784 Hz). The exception occurred for the frequency 1568 (G_6), where the range of variation between flutes was less at the higher intensity level than at the lower intensity level.

The greatest difference between two intensity levels of the same frequency in total amplitude of all partials occurred in the tonal spectra for G_4 (392 Hz). For a single flute, the most difference in this respect occurred in the tonal spectra of the white gold flute number four for the frequency 392 Hz (G_4), where a difference of 171 decibels was observed. The least difference in total amplitude of partials between two intensity levels of the same frequency occurred in the tonal spectra of G_6 (1568 Hz). For a single flute, the least difference in this respect occurred in the tonal spectra of the white gold flute number four for the frequency 1568 Hz (G_6), where a difference of only 23 decibels was evident.

Results of the multivariate analysis of variance of the 2 x 3 x 2 x 5 factorial design, summarized in Figure 8, showed that the main effect of intensity was significant for all partials ($p < .0001$). Interaction of performer and intensity was found significant for only partial number one ($p < .0083$).

Differences between Frequency Levels

The number of partials present in the spectra of tones held at the same intensity level decreased consistently with an increase in frequency. Tables 25-30 and Figure 7 show that a greater difference in the number and amplitude of partials present in two tones held at the same intensity level occurred between the lower two frequencies than between G_5 (784 Hz) and G_6 (1568 Hz). The greatest difference occurred between G_4 (392 Hz) and G_5 (784 Hz) at the *forte* level (85 db).

A greater difference in total amplitude of partials between two tones held at the same intensity level occurred between the frequencies of 392 Hz (G_4) and 784 Hz (G_5). The greatest difference in this respect ranged from 150 to 176 decibels at the *forte* level (85 db). The least difference occurred at the lower intensity level between G_5 (784 Hz) and G_6 (1568 Hz) with a range of only 8 to 41 decibels.

A summary of the multivariate analysis of variance of the 2 x 3 x 2 x 5 factorial design, found in Figure 8, revealed that the main effect of frequency was significant for all partials ($p < .0001$). Interaction between performer and frequency was found to be significant for partials number two ($p < .0115$) and three ($p < .0001$), but not significant for partials number one and four ($p > .05$).

Differences between Performers

The data in Tables 1 through 24 reveal that the tonal spectra produced on all flutes by both performers varied less in the number and amplitude of the lower partials than in that of the upper partials. The fundamental was consistently the partial which varied the least in amplitude between performers as well as from trial to trial by a single performer.

The tonal spectra produced by performer number two generally possessed a greater number of partials than that of performer number one. The tonal spectra of performer number one generally possessed greater amplitudes of the lower, stronger partials than that of performer number two. The number and amplitude of the upper, weaker partials were greater in the spectra of performer number two. A greater variation between performers in the number and amplitude of partials present existed in the tonal spectra of G_4 (392 Hz) and G_5 (784 Hz) than that of G_6 (1568 Hz).

The data in Tables 1 through 18 reveal that variation in the amplitude of each partial present in a tone played under the same conditions from trial to trial by the same performer ranged from exact duplication to a difference of nine decibels for the first three partials. A difference of as much as 48 decibels from trial to trial was evidenced for the upper partials. Variation in the amplitude of each partial in a tone played under the same conditions between performers ranged from exact duplication to a difference of 13 decibels for the first three partials. Such a difference between performers for the upper partials was observed to be as much as 45 decibels.

Tables 1 through 18 reveal that the upper partials were not consistently present in tones of the same frequency played under identical conditions from trial to trial by the same performer. This inconsistency was apparent in the tonal spectra of both performers.

Results of the multivariate analysis of variance of the 2 x 3 x 2 x 5 factorial design, summarized in Figure 8, revealed that the main effect of performer was significant for all partials ($p < .0001$) except number two. The interaction of performer and frequency was found significant for only partials number two ($p < .0115$) and three ($p < .0001$), while interaction of performer and intensity was significant for only partial number one ($p < .0083$).

The analysis revealed that the interaction of performer and flute was significant for only partials number one ($p < .0343$) and three ($p < .0003$). No significant difference was found for the second partial ($p > .05$) for the main effect of performer nor for the interaction of performer with either intensity or frequency.

Chapter V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

A review of the woodwind pedagogical literature revealed that the relationship between wall material and the tone quality of the flute has long been a source of disagreement among musicians, instrument makers, and physicists. Much that has been written on the subject has been based on theory and conjecture. Previous research studies of the influence of wall material on the timbre of the flute have involved either flutes which do not resemble the modern-day flute, or only a single flute which is investigated via the use of an oscilloscope or wave analyzer.

The present investigation consisted of a systematic examination and analysis of the tonal spectra of five modern Boehm-system flutes constructed of different materials and produced with the same specifications by a single manufacturer. The questions of concern in the study involved the influence of wall material, intensity level, frequency level, and the performer on the harmonic structure of tones produced on each flute used in the investigation.

Two professional flutists played a sustained tone using no vibrato on three frequencies representing three registers of the flute range, at two intensity levels corresponding to the *forte* and *piano* dynamic levels, on each of the five flutes. Three trials were conducted for each pitch at a single intensity level by each performer. All performance tasks were conducted within an anechoic chamber which housed two high-quality condensor microphones, a sound level meter to control the intensity level, a frequency meter used to tune the flutes, and the five flutes used in the study. An electronic laboratory adjacent to and connected with the anechoic chamber housed a real-time spectrum analyzer into which the signals from the microphones were channeled, two amplifiers, a graphic recorder and a high-quality tape recorder. Graphic representations of the tonal spectra and an audio tape recording of all performance tasks were obtained.

The tonal spectra plotted by the graphic recorder were examined to determine the strength and number of partials present in each tone investigated under each condition of intensity, performer, and wall material. The information derived from the plots was quantified, and the individual and mean strengths of the partials for each tone, derived from three trials under the same conditions, were calculated and presented quantitatively and graphically for purposes of visual examination.

A multivariate analysis of variance of a four-way factorial design was utilized. The general linear models procedure was employed to test the significance of main effects and interaction (crossed effects). The *Statistical Analysis System* program package was used, and the .05 level of probability was chosen for significance testing.

Conclusions

Based upon the results of the multivariate analysis of variance of the 2 x 3 x 2 x 5 factorial design, the following conclusions were drawn ($\alpha = .05$):

1. A significant difference is found between the five flutes for the partials number one ($p < .0139$), two ($p < .0001$), and four ($p < .0105$); however, the analysis reveals that the interaction of performer and flute is significant for partials number one ($p < .0343$) and three ($p < .0003$), but not significant for partials number two and four. It appears that the performer influences the harmonic structure of tones played on flutes constructed of different materials.

2. Although a significant difference ($p < .0001$) is revealed between intensity levels for all partials, the interaction of performer and intensity is significant for partial number one ($p < .0083$), but not for partials number two, three and four. There is reason to suspect that the performer influences the harmonic structure of tones played at different intensity levels.

3. A significant difference ($p < .0001$) exists between frequency levels for all partials; however, the interaction

of performer and frequency is significant for partials number two ($p < .0115$) and three ($p < .0001$), but not for partials number one and four. It seems the performer influences the harmonic structure of tones played at various frequency levels.

4. A significant difference ($p < .0001$) is found between performers for the partials number one, three, and four. Thus, there is reason to believe the performer influences the harmonic structure of a tone played on a flute.

5. Variation between performers is evidenced by the amount of interaction when comparing changes in significance from main effects to crossed effects.

Based upon the results of the multivariate analysis of variance of the 2 x 3 x 2 x 2 factorial design, the following conclusions were drawn ($\alpha = .05$):

1. No significant difference ($p > .05$) is found between the two sterling silver flutes for all partials; however, the analysis shows that the interaction of performer and flute is significant for partial number three ($p < .0001$). It appears that the performer influences the harmonic structure of tones played on the same flute.

2. The main effects of frequency and intensity are found significant ($p < .0001$) for all partials. The interaction of performer and frequency is significant for all partials ($p < .0091$, $p < .0251$, $p < .0152$, respectively),

while the interaction of performer and intensity is found significant for only partial number one ($p < .0012$). It appears the performer influences the harmonic structure of tones played at various frequency and intensity levels on the same flute.

3. The second partial seems to be least affected by the main effect and the interaction of performer.

4. Variation between performers is evidenced by the amount of interaction when comparing changes in significance from main effects to crossed effects.

Based upon a visual examination of the graphically-represented data derived from this investigation, the following observations are presented.

The number and strength of partials present in the spectra of a given tone varied between flutes constructed of different materials. The fundamental was generally the strongest partial present at all intensity and frequency levels and tended to vary the least between flutes. The number and strength of partials in a tone decreased sequentially from the fundamental to the upper partials. This does not lend support to the findings of Fletcher (1975), who reported that in the lowest register of the flute, in loud playing, the fundamental is lower in level of predominance than either the second or third harmonics.

The tonal spectra of the five flutes differed more in the number and strength of the upper partials than in that of the lower partials present in a tone. The greatest variation between flutes in the number of partials present in a tone occurred in the spectra of G_4 at the *piano* level, while the least variation occurred in the spectra of G_6. Variation between the five flutes in the mean strength of a single partial for a given tone ranged from exact duplication to 20 decibels for the first three partials, and up to 37 decibels for the upper partials.

In general, there was less variation between the five flutes in the total strength of partials present at the *piano* level than at the *forte* level of a given frequency. The least variation between flutes in the total strength of partials occurred in the tonal spectra of the highest pitch investigated, G_6, at the *forte* level, with a range of only 13 decibels. The greatest variation between flutes in this respect occurred for G_5 at the *forte* level, with a range of 39 decibels.

The tonal spectra of the first flute, constructed of sterling silver, consistently possessed the greatest total strength of partials for all tones performed at the *forte* level, as well as for G_6 at the *piano* level. The tonal spectra of the second flute, which was also constructed of sterling silver, possessed the strongest total amplitude of partials for G_4 and G_5 at the *piano* level. It is possible that this was due to the inherent qualities of the flutes themselves, or perhaps this can be attributed to the fact that the physical vitality of the performer was most likely at its peak during the performance of the tasks on the first two flutes tested. The element of physiological fatigue may explain the weaker amplitude of partials present in the tonal spectra of the subsequent flutes investigated.

The number and strength of partials present in the tonal spectra of the two sterling silver flutes differed for the same frequency played under identical conditions of intensity and performer. The total amplitude of partials present for the same frequency at different intensity levels was greater in the spectra of flute number one for the lowest two frequencies only. Differences between the two flutes in the total amplitude of partials present were consistently greater at the lower intensity level of the same frequency.

The number and strength of partials present in a tone of the same frequency increased with an increase in intensity, i.e., there were more and stronger partials present at the *forte* dynamic level than at the *piano* dynamic level of the same pitch. The data from the present study support the findings of Dammann (1939), Woodward (1941), Stauffer (1954), and Fletcher (1975) which showed that the harmonic structure of a complex tone varies with intensity.

The fundamental varied the least for all frequencies at all intensity levels. In general, the range of variation between flutes in total amplitude of all partials present in a composite tone was less at the lower intensity level than at the higher intensity of the same frequency. There was a greater difference in the total strength of partials between the *forte* and *piano* levels of a low pitch than between these two dynamic levels of a high pitch. For a single flute, the most difference in this respect occurred in the spectra of the white gold flute for G_4, where a difference of 171 decibels was observed. The least difference occurred in the spectra of the same flute for G_6, where a difference of only 23 decibels was evidenced.

The number of partials present in a tone held at the same intensity level decreased with an increase in frequency, i.e., fewer partials were present in high tones than in low tones. The greatest difference occurred between G_4 (392 Hz) and G_5 (784 Hz) at the *forte* level (85 db). A greater difference in total strength of partials occurred between tones of the first and second registers than between tones of the second and third registers, when played at the same intensity level. The variation ranged from 150 to 176 decibels at the *forte* level between the lower two frequencies, and only 8 to 41 decibels between the upper two frequencies at the *piano* level.

The tonal spectra of a given tone played under identical conditions of frequency, intensity, and flute differed between performers. A greater variation between performers in the number and amplitude of partials present in a tone existed in the tonal spectra of G_4 (392 Hz) and G_5 (784 Hz) than in that of G_6 (1568 Hz). The amplitude of each partial present in a tone played under the same conditions from trial to trial by the same performer ranged from exact duplication to a difference of nine decibels for the first three partials, and up to 48 decibels for the upper partials. Variation in amplitude of each partial played under identical conditions between performers ranged from exact duplication to a difference of 13 decibels for the first three partials, and up to 45 decibels for the upper partials. In addition, the upper partials were not consistently present in tones of the same frequency played under identical conditions from trial to trial by the same performer. Performer variability is evidenced in the visual examination of the data derived from this study.

Recommendations for Further Research

Based upon the findings of the present investigation, the following recommendations for further research are warranted:

1. The present study involved the investigation of only steady-state tones produced on flutes constructed of different materials. Radocy and Boyle (1979) discuss the significance of the onset behavior (initial transience, attack, rise time) of a tone produced on a musical instrument (pp. 54-55). Further study of these aspects of a tone seems warranted.

2. The findings of the present investigation reveal the influence of the performer on the harmonic structure of tones produced on the flute. A replication of this study, using an artificial blowing mechanism, i.e., a regulated source of compressed air such as the one used by Coltman (1966), might produce interesting results.

3. A subject of concern in a study such as the present, is that of possible preconceived notions or prejudice held by the performer regarding the attributes of a specific instrument. In the present study the performers were aware of which flute they were playing during the performance tasks. A blindfold could not be used since it was essential that the performer visually monitor a sound-level meter to hold the intensity level constant. The element of human prejudice or preconceived notions could be eliminated through the use of an artificial blowing mechanism.

4. The results of previous research by Klein and Gerritsen (1975), Coltman (1966), and Benade (1965) have revealed that the size and shape of the opening in the flutist's lips influence the tone quality. These variables may be held constant through the use of an artificial blowing mechanism.

5. Although the five flutes used in the study were produced with the same written specifications by a single manufacturer, minute internal differences may have occurred during the production process. The results of research by

Wimberley (1980) and Monroe (1978) reveal that exact specifications in headpiece and body construction may vary somewhat during manufacture, and that the shape and size of the embouchure hole as well as the height and angle of the chimney wall may vary by measurements of .00005". The contention is that no headpiece is ever duplicated exactly, due to the process of soldering the chimney to the main tube and the fine-finishing of the embouchure hole. A study using the same headpiece on several flute bodies might produce interesting results.

6. Further research into the relationship between the physical characteristics of timbre, such as are investigated in this study, and the subjective characteristics of a musical tone is warranted. A test of aural discrimination involving a group of trained listeners, perhaps all flutists, would prove interesting to determine whether such musicians could discriminate between tones produced on modern flutes constructed of different materials.

Implications of the Study

The findings of the present study indicate that performer variability seems to play a significant role in the harmonic structure of a tone produced on a flute. Variation in the tonal spectra between performers and from trial to trial by a single performer indicates that a slightly different harmonic structure is produced each time a tone is played on the flute.

Today, a performer may be called upon frequently to produce contrasts in timbre on a single flute within a composition to facilitate the demands of various styles of music, thus necessitating the versatility of the embouchure. Though the artificial blowing mechanism may be a more reliable sound source than that of the human performer, many questions may arise related to aspects of flute performance such as the use of vibrato and contemporary techniques.

The objective data derived from this study must be viewed in relation to the intrinsic subjectivity within the realm of aesthetics. Human performance and aesthetic judgments are not always consistent. The performance of music on the flute in today's society involves a strong human element which contributes to the identity of music as an art form.

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APPENDIX A

BIBLIOGRAPHY OF RELATED ACOUSTICAL RESEARCH STUDIES AND TEXTS

APPENDIX A

Bibliography of Related Acoustical Research Studies and Texts

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APPENDIX B

AN EXAMPLE OF THE GRAPHIC REPRESENTATION OF THE TONAL SPECTRA

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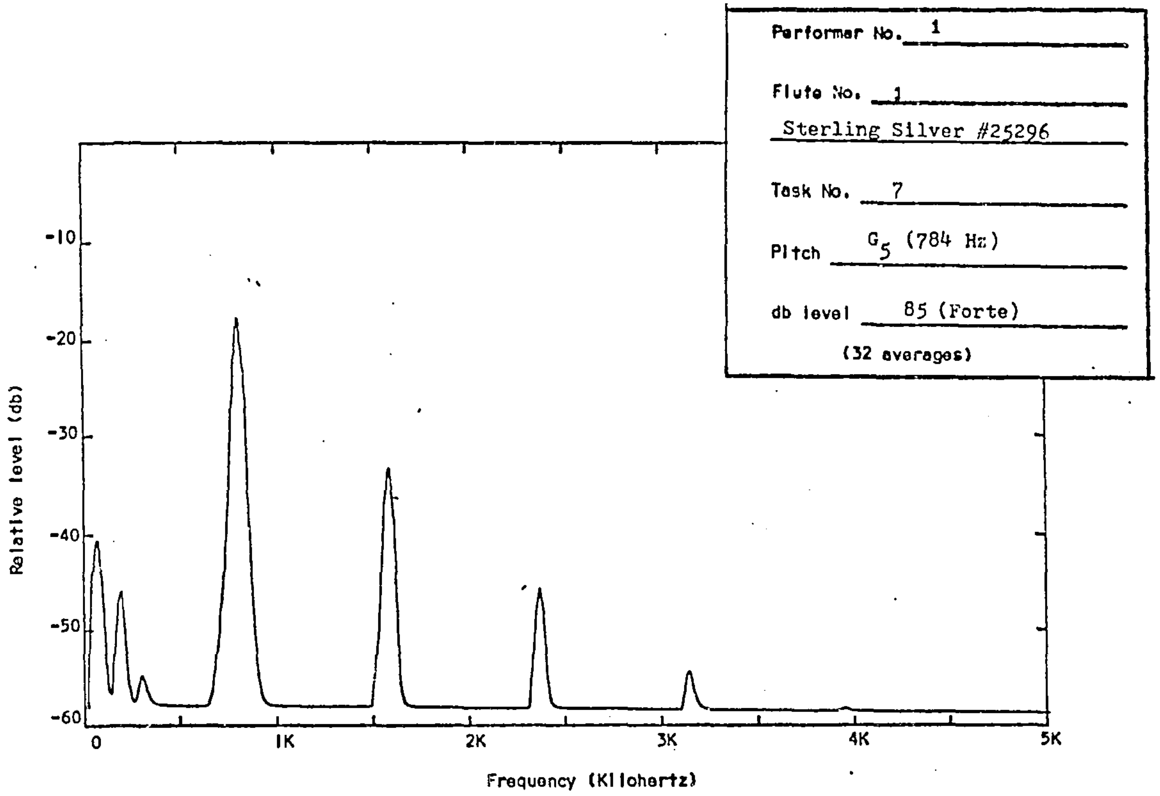
AN EXAMPLE OF THE GRAPHIC REPRESENTATION OF THE TONAL SPECTRA



Performer No. 1

Flute No. 1

Sterling Silver #25296

Task No. 7

Pitch G_5 (784 Hz)

db level 85 (Forte)

(32 averages)

Spectrascope Model SD 330A
Real Time Analyzer
30 HZ bandwidth

MFE Plotamatic 715 M
x-y plotter

24 March 1980
NCSU

APPENDIX C

LIST OF INSTRUMENTATION

APPENDIX C

List of Instrumentation

1. *Spectral Dynamics* Real-Time Analyzer, Model SD 330 A; constant narrow bandwidth, 30 Hertz resolution, provides digital samples of 500 points within a block; computes the mean of 32 samples of a steady state tone in three seconds; analysis range of 20-20,000 Hz.
2. *Brüel & Kjaer* Microphone Amplifier, Type 2603; Meter Range = 80 db, Range Multiplier = 0.
3. *Brüel & Kjaer* Measuring Amplifier, Type 2607; Frequency Range = 20-20,000 Hz; Input Section Attenuator = 3mV.
4. *Brüel & Kjaer* Random Incidence Type one-half inch Condensor Microphones (Two); Model 4134.
5. *MFE Plotamatic, 715M x-y Plotter.*
6. *Nagra, Type IV-S* Tape Recorder.
7. *Scotch* Professional Mastering Tape 207, High Output/ Low Noise.
8. *Quest Electronics 215* Sound Level Meter, ANSI S1.4, Type 2-IEC R 123; db range 40-130; linear weighting.
9. *Kanon* Stainless Steel Hardened Caliper, measures 1000ths inch.
10. *Harvard Trip* Double-Pan Balancing Scales; 2Kg-5lb capacity; Serial Number AB 7414.
11. *OHAUS* Weights, 10-1000 grams range.
12. *Korg* Tuning Standard, Model WT-10A; Reading Range: A = 435 ∿ 450 Hz, Six Octaves; Pitch = 12 tempered chromatic scale; Accuracy = 3 Cent (Chromatic Interval = 100 Cent).
13. Anechoic Chamber: walls, floor and ceiling lined with polyurethane material and supported by batting; dimensions: 18' x 18' square x 12' high.

14. 180 plots or "print-outs" of the tonal spectra.

APPENDIX D

TABLES

Table 1

Strength of the Partials for the Pitch G_4 (392 Hz) at *Forte* (85 db) by Performer No. 1 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	68	70	62	53	53	46	45
	69	72	56	51	54	44	44
	69	71	57	49	52	46	44
2	70	71	61	58	55	52	0
	71	71	60	58	55	52	40
	70	71	59	57	54	52	0
3	70	71	57	58	54	52	0
	69	68	56	48	50	47	0
	70	65	54	52	48	44	0
4	70	66	62	60	46	51	41
	68	67	53	52	50	49	0
	69	69	60	56	52	52	0
5	69	65	54	53	52	46	0
	69	64	52	51	50	0	0
	69	67	60	50	51	40	0

Table 2

Strength of the Partials for the Pitch G₄ (392 Hz) at *Forte* (85 db) by Performer No. 2 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	68	63	64	52	58	54	0
	68	69	60	64	48	45	48
	66	68	58	60	44	0	43
2	70	67	64	61	57	52	0
	69	69	56	62	47	47	44
	69	68	56	62	38	46	47
3	70	65	65	60	58	50	0
	68	65	67	52	58	45	0
	69	68	67	53	56	55	0
4	68	66	57	63	52	43	40
	70	67	64	61	58	50	0
	70	66	67	54	55	54	36
5	69	68	63	62	42	54	41
	69	68	63	60	46	53	0
	69	68	60	62	44	52	0

Table 3

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G$_4$ (392 Hz) at the *Forte* Level (85 db)

Partial No.	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	69	67	68	70	69	70	70	69	70	69	69	69	69	69	69
2	71	67	69	71	68	70	68	66	67	67	66	67	65	68	67
3	58	61	60	60	59	60	56	66	61	58	63	61	55	62	59
4	51	59	55	58	62	60	53	55	54	56	59	58	51	61	56
5	53	50	52	55	47	51	51	57	54	49	55	52	51	44	48
6	45	33	39	52	48	50	48	50	49	51	49	50	29	53	41
7	44	30	37	13	30	22	0	0	0	14	25	20	0	14	7

Table 4

Strength of the Partials for the Pitch G₄ (392 Hz) at *Piano* (75 db) by Performer No. 1 for Three Trials

	Partial Number						
Flute Number	1	2	3	4	5	6	7
	66	57	38	40	38	0	0
1	66	56	37	38	0	0	0
	66	58	36	38	0	0	0
	65	54	45	42	0	0	0
2	66	56	45	44	0	0	0
	66	55	44	37	41	0	0
	64	53	45	43	0	0	0
3	65	56	45	37	0	0	0
	64	52	40	0	0	0	0
	65	54	41	40	0	0	0
4	65	52	41	40	0	0	0
	64	48	42	40	0	0	0
	64	53	48	43	0	0	0
5	63	53	41	0	0	0	0
	65	55	45	40	0	0	0

Table 5

Strength of the Partials for the Pitch G_4 (392 Hz) at *Piano* (75 db) by Performer No. 2 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	61	52	51	46	0	0	0
	62	54	53	49	0	0	0
	62	53	53	47	0	0	0
2	63	53	51	43	40	0	0
	66	58	53	51	0	0	0
	64	52	48	44	0	0	0
3	62	47	50	44	0	0	0
	63	47	51	40	40	0	0
	64	50	52	37	36	0	0
4	64	52	52	44	0	37	0
	64	52	54	40	37	0	0
	66	51	54	0	43	0	0
5	63	52	52	46	0	37	0
	64	53	52	44	0	40	0
	64	57	53	48	0	42	0

Table 6

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G_4 (392 Hz) at the *Piano* Level (75 db)

	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
Partial No.	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	66	62	64	66	64	65	64	63	64	65	65	65	64	64	64
2	57	53	55	55	54	55	54	48	51	52	52	52	54	54	54
3	37	52	45	45	51	48	43	51	47	42	53	48	45	52	49
4	39	47	43	41	46	44	27	40	34	41	28	35	28	46	37
5	13	0	7	14	13	14	0	25	13	0	12	6	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	40	20
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7

Strength of the Partials for the Pitch G_5 (784 Hz) at *Forte* (85 db) by Performer No. 1 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	76	60	48	40	0	0	0
	76	58	56	37	0	0	0
	74	58	54	41	0	0	0
2	75	66	57	38	0	0	0
	73	64	54	42	0	0	0
	73	61	52	40	0	0	0
3	74	59	56	0	0	0	0
	73	52	54	0	0	0	0
	74	58	48	0	0	0	0
4	74	58	58	38	0	0	0
	72	64	55	36	0	0	0
	72	57	58	0	0	0	0
5	72	63	55	0	0	0	0
	72	61	55	0	0	0	0
	73	61	52	0	0	0	0

Table 8

Strength of the Partials for the Pitch G_5 (784 Hz) at *Forte* (85 db) by Performer No. 2 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	73	66	57	42	0	0	0
	72	65	57	0	0	0	0
	71	60	57	0	0	0	0
2	74	68	52	0	0	0	0
	74	63	52	0	0	0	0
	71	64	54	0	0	0	0
3	70	58	50	0	0	0	0
	71	51	55	0	0	0	0
	70	0	52	0	38	0	0
4	72	60	57	0	41	0	0
	72	62	52	0	0	0	0
	72	59	50	0	0	0	0
5	71	66	54	0	0	0	0
	73	61	56	0	38	0	0
	72	62	58	0	0	0	0

Table 9

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G_5 (784 Hz) at the *Forte* Level (85 db)

Partial No.	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	75	72	74	74	73	74	74	70	72	73	72	73	72	72	72
2	59	64	62	64	65	65	56	36	46	60	60	60	62	63	63
3	53	57	55	54	53	54	56	52	54	57	53	54	54	56	55
4	39	14	27	40	0	20	0	0	0	25	0	13	0	0	0
5	0	0	0	0	0	0	0	13	7	0	14	7	0	13	7
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10

Strength of the Partials for the Pitch G_5 (784 Hz) at *Piano* (75 db) by Performer No. 1 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	68	50	0	0	0	0	0
	68	50	0	0	0	0	0
	68	51	36	0	0	0	0
2	67	56	49	0	0	0	0
	68	55	53	0	0	0	0
	68	54	51	0	0	0	0
3	66	52	46	0	0	0	0
	66	52	44	0	0	0	0
	67	53	45	0	0	0	0
4	65	52	44	0	0	0	0
	65	52	44	0	0	0	0
	63	53	42	0	0	0	0
5	66	54	46	0	0	0	0
	65	53	48	0	0	0	0
	65	52	45	0	0	0	0

Table 11

Strength of the Partials for the Pitch G_5 (784 Hz) at *Piano* (75 db) by Performer No. 2 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	60	46	44	0	0	0	0
	61	46	42	0	0	0	0
	62	50	46	0	0	0	0
2	66	51	44	0	0	0	0
	64	50	43	0	0	0	0
	66	47	44	0	0	0	0
3	63	47	46	0	0	0	0
	64	0	37	0	0	0	0
	65	40	0	0	0	0	0
4	62	52	36	0	0	0	0
	65	48	39	0	0	0	0
	66	47	37	0	0	0	0
5	63	50	46	0	0	0	0
	63	49	45	0	0	0	0
	62	46	44	0	0	0	0

Table 12

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G_5 (784 Hz) at the *Piano* Level (75 db)

	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
Partial No.	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	68	61	65	68	65	67	66	64	65	64	64	64	65	63	64
2	50	47	49	55	49	52	52	29	41	52	49	51	53	48	51
3	12	44	28	51	44	48	45	28	37	43	37	40	46	45	46
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 13

Strength of the Partials for the Pitch G_6 (1568 Hz) at *Forte* (95 db) by Performer No. 1 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	77	57	44	0	0	0	0
	76	37	48	0	0	0	0
	77	48	46	0	0	0	0
2	74	51	45	0	0	0	0
	76	50	45	0	0	0	0
	75	57	46	0	0	0	0
3	77	46	46	0	0	0	0
	77	42	45	0	0	0	0
	76	45	49	0	0	0	0
4	77	52	40	0	0	0	0
	75	50	43	0	0	0	0
	76	40	48	0	0	0	0
5	75	48	45	0	0	0	0
	74	48	47	0	0	0	0
	75	43	47	0	0	0	0

Table 14

Strength of the Partials for the Pitch G_6 (1568 Hz) at *Forte* (95 db) by Performer No. 2 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	81	56	56	0	0	0	0
	80	56	56	0	0	0	0
	75	59	54	0	0	0	0
2	76	43	55	0	0	0	0
	82	48	45	0	0	0	0
	78	51	48	0	0	0	0
3	70	46	50	0	0	0	0
	76	44	52	0	0	0	0
	74	46	44	0	0	0	0
4	73	44	48	0	0	0	0
	75	47	45	0	0	0	0
	72	50	50	0	0	0	0
5	78	51	50	0	0	0	0
	73	49	53	0	0	0	0
	74	46	50	0	0	0	0

Table 15

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G_6 (1568 Hz) at the *Forte* Level (95 db)

	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
Partial No.	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	77	79	78	75	79	77	77	73	75	76	73	75	75	75	75
2	47	57	52	53	47	50	44	45	45	47	47	47	46	49	48
3	46	55	51	45	49	47	47	49	48	44	48	46	46	51	49
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 16

Strength of the Partials for the Pitch G_6 (1568 Hz) at *Piano* (85 db) by Performer No. 1 for Three Trials

Flute Number	Partial Number						
	1	2	3	4	5	6	7
1	69	44	36	0	0	0	0
	68	46	35	0	0	0	0
	71	46	0	0	0	0	0
2	69	44	38	0	0	0	0
	68	40	42	0	0	0	0
	68	0	43	0	0	0	0
3	68	44	0	0	0	0	0
	69	44	36	0	0	0	0
	68	45	0	0	0	0	0
4	68	45	35	0	0	0	0
	70	42	35	0	0	0	0
	68	38	0	0	0	0	0
5	66	0	36	0	0	0	0
	69	42	0	0	0	0	0
	66	37	0	0	0	0	0

Table 17

Strength of the Partials for the Pitch G_6 (1568 Hz) at *Piano* (85 db) by Performer No. 2 for Three Trials

	Partial Number						
Flute Number	1	2	3	4	5	6	7
1	68	46	38	0	0	0	0
	68	53	42	0	0	0	0
	68	55	46	0	0	0	0
2	67	49	43	0	0	0	0
	62	47	36	0	0	0	0
	66	47	36	0	0	0	0
3	66	36	40	0	0	0	0
	65	44	36	0	0	0	0
	64	46	37	0	0	0	0
4	66	43	42	0	0	0	0
	64	43	38	0	0	0	0
	70	49	48	0	0	0	0
5	68	0	42	0	0	0	0
	68	40	36	0	0	0	0
	64	43	43	0	0	0	0

Table 18

Mean Strengths of the Partials in Absolute Decibel Level for the Pitch G_6 (1568 Hz) at the *Piano* Level (85 db)

Partial No.	Flute No. 1			Flute No. 2			Flute No. 3			Flute No. 4			Flute No. 5		
	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean	Perf. 1	Perf. 2	Mean
1	69	68	69	68	65	67	68	65	67	69	67	68	67	67	67
2	45	51	48	28	48	38	44	42	43	42	45	44	26	28	27
3	24	42	36	41	38	40	12	38	25	23	43	33	12	40	26
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 19

A Comparison of Performers: Mean Strengths of the Partials for the Pitch G4 (392 Hz) at *Forte* (85 db)

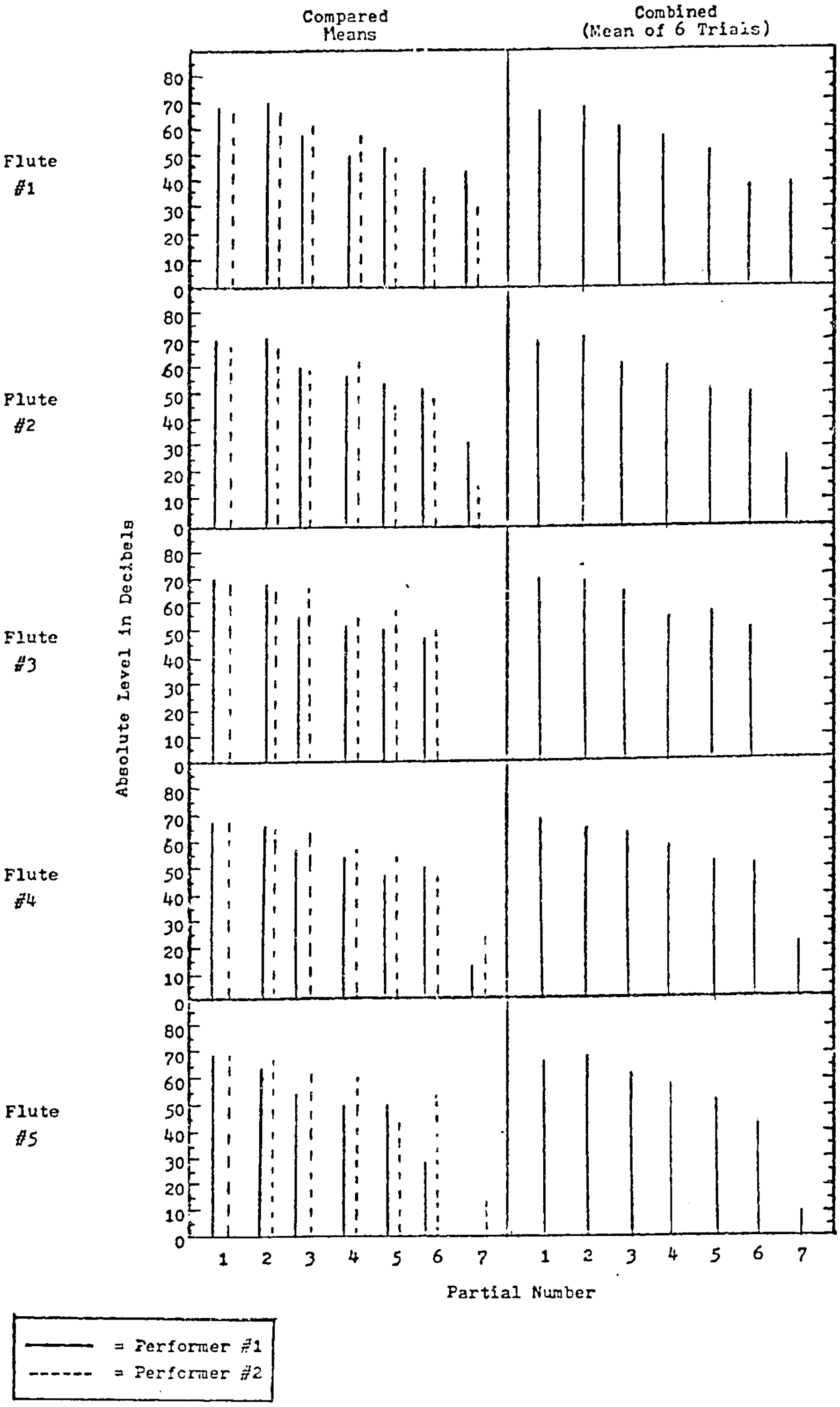


Table 20

A Comparison of Performers: Mean Strengths of the Partials for the Pitch G4 (392 Hz) at *Piano* (75 db)

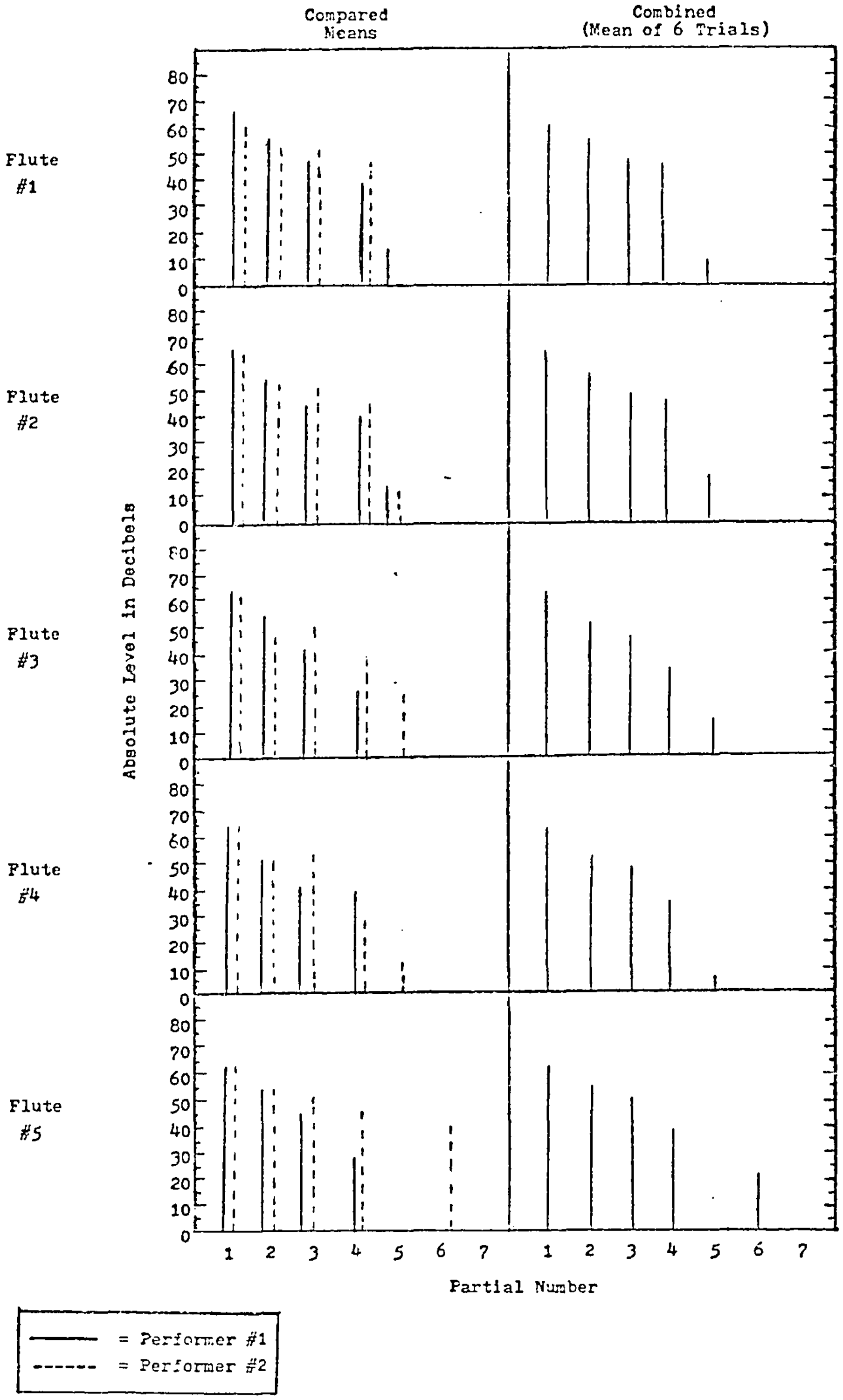
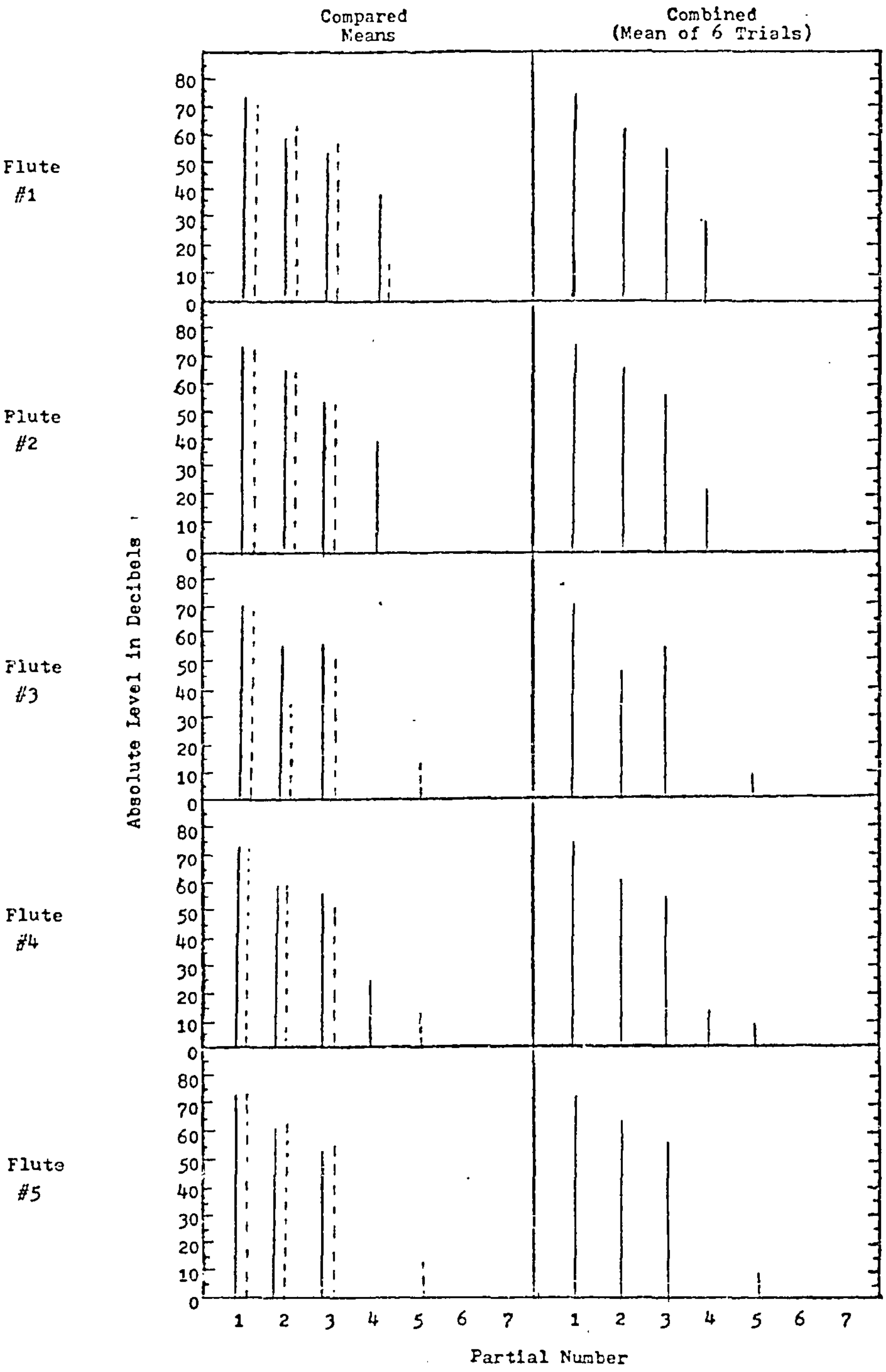


Table 21

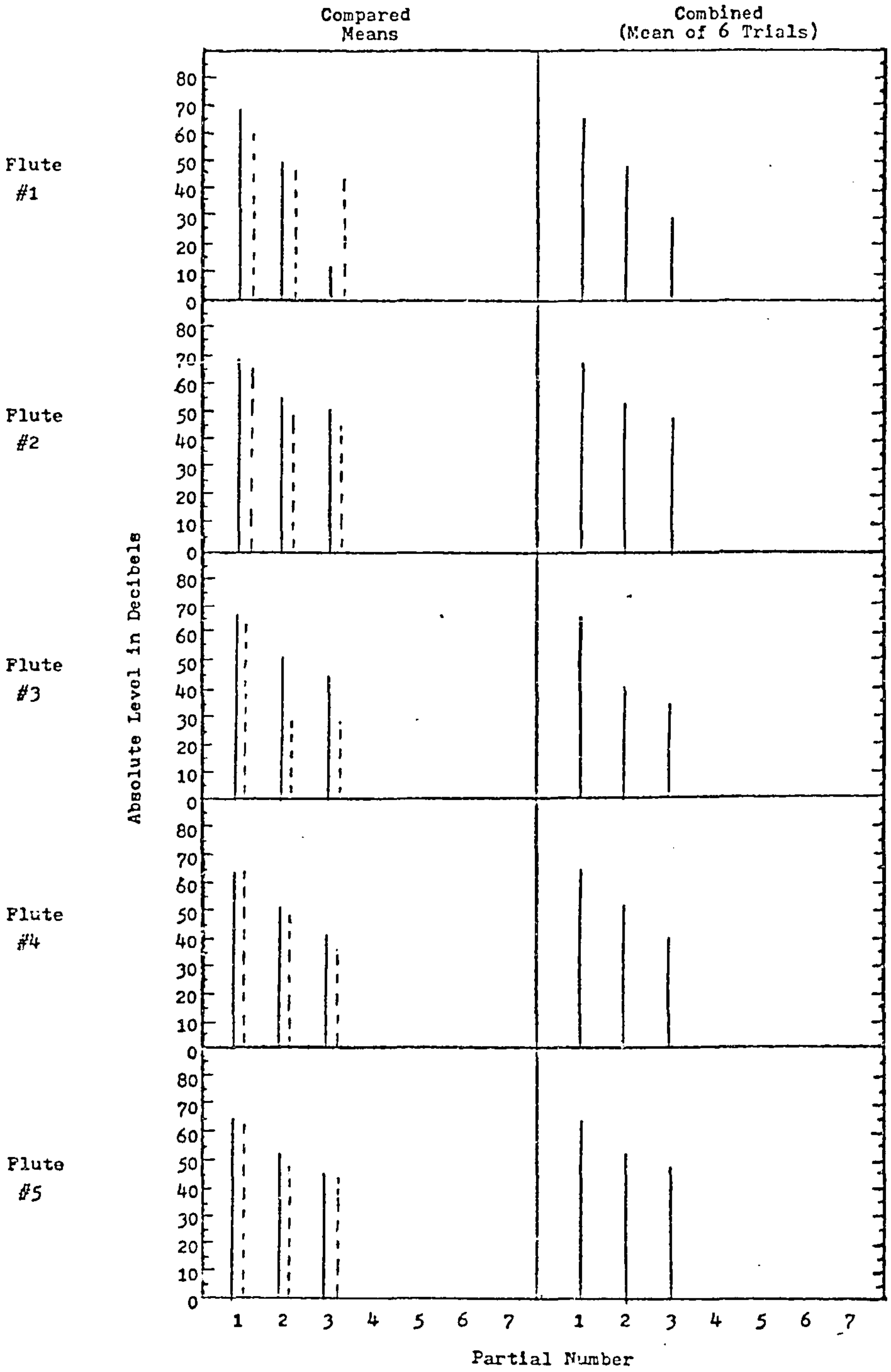
A Comparison of Performers: Mean Strengths of the Partials for the Pitch G_5 (784 Hz) at *Forte* (85 db)



——— = Performer #1
------ = Performer #2

Table 22

A Comparison of Performers: Mean Strengths of the Partials for the Pitch G5 (784 Hz) at *Piano* (75 db)



——— = Performer #1
------ = Performer #2

Table 23

A Comparison of Performers: Mean Strengths of the Partials for the Pitch G_6 (1568 Hz) at *Forte* (95 db)

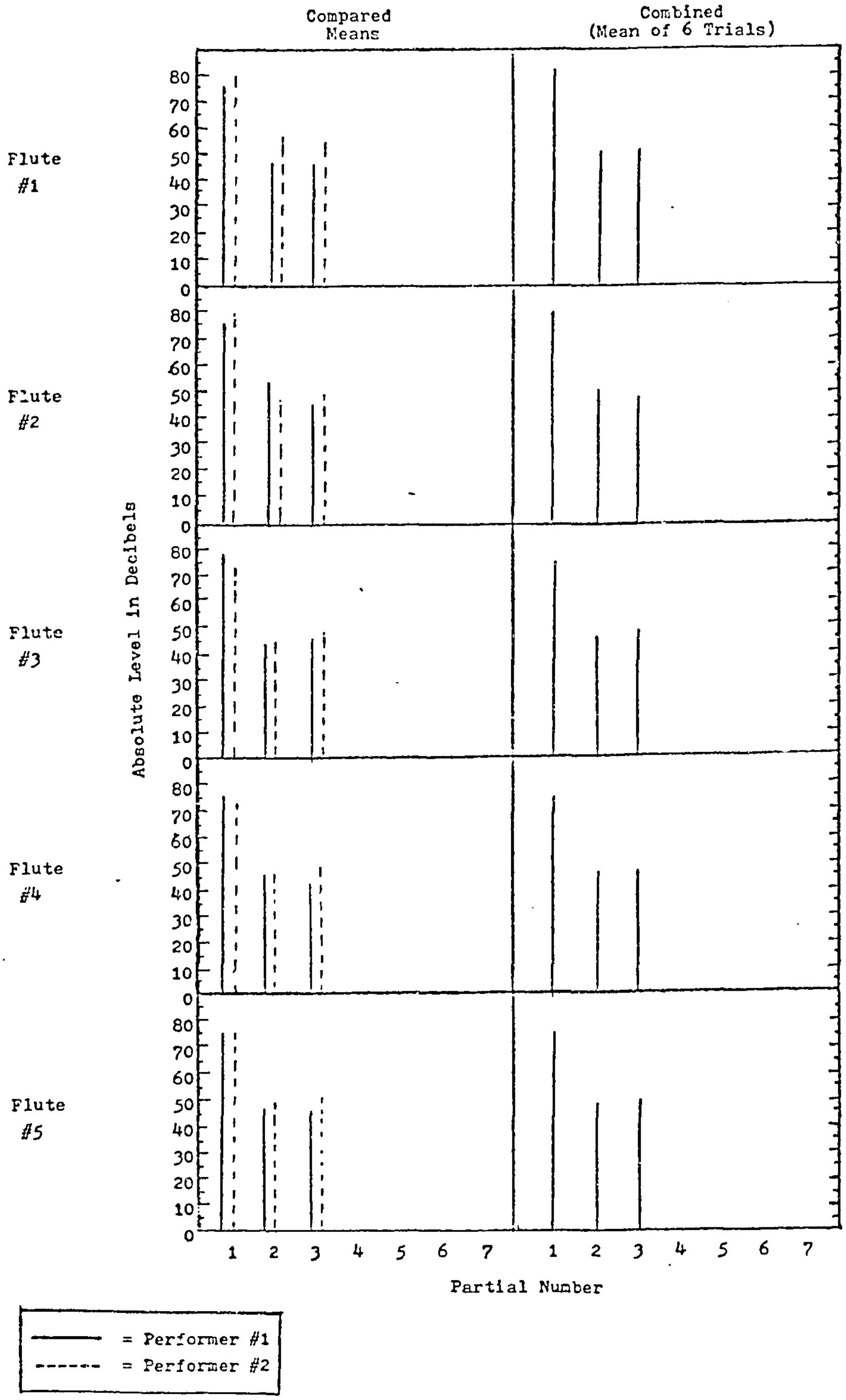
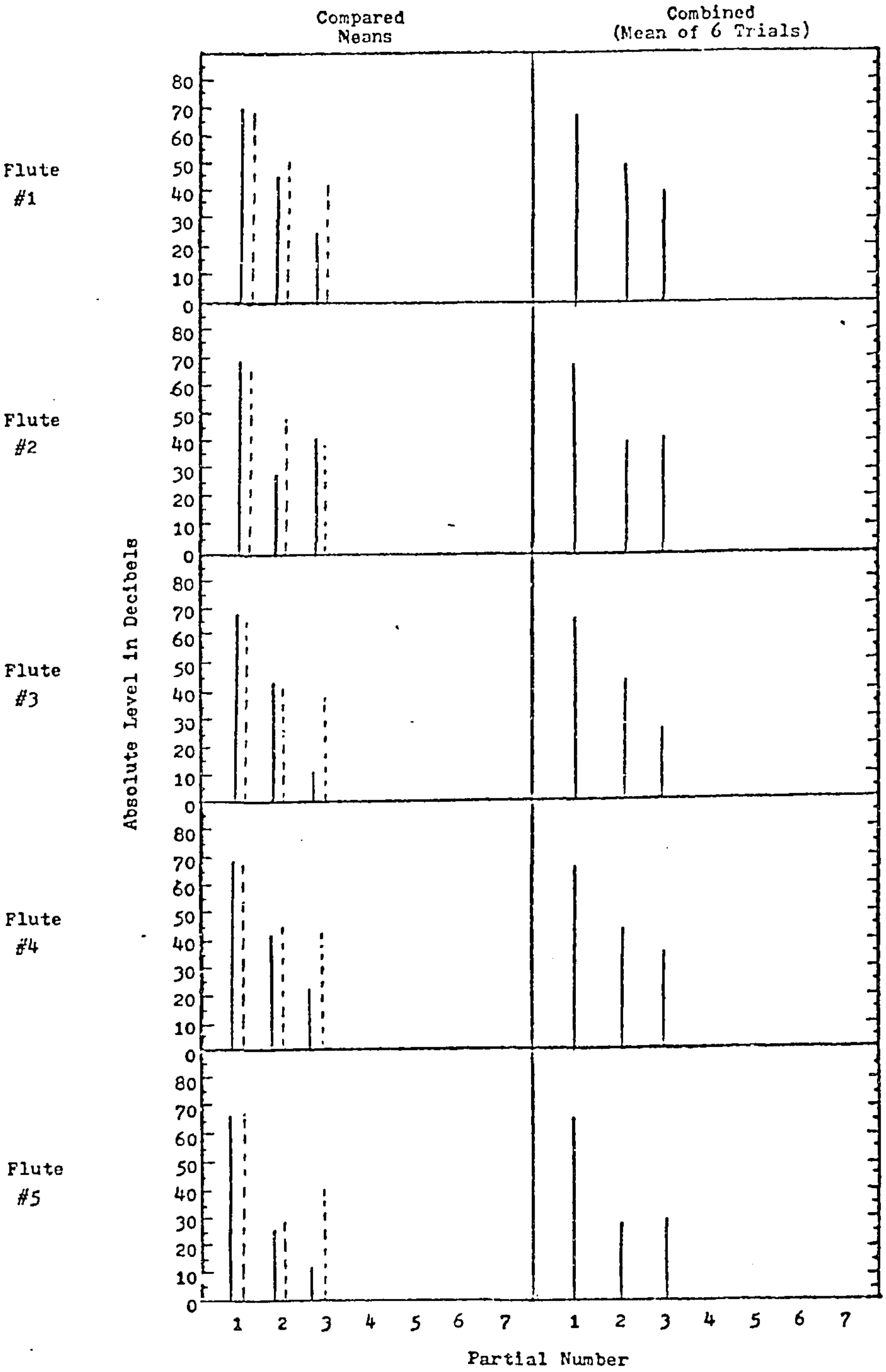


Table 24

A Comparison of Performers: Mean Strengths of the Partials for the Pitch G₆ (1568 Hz) at *Piano* (85 db)



———	= Performer #1
- - - - - -	= Performer #2

Table 25

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G_4 (392 Hz) at *Forte* (85 db)

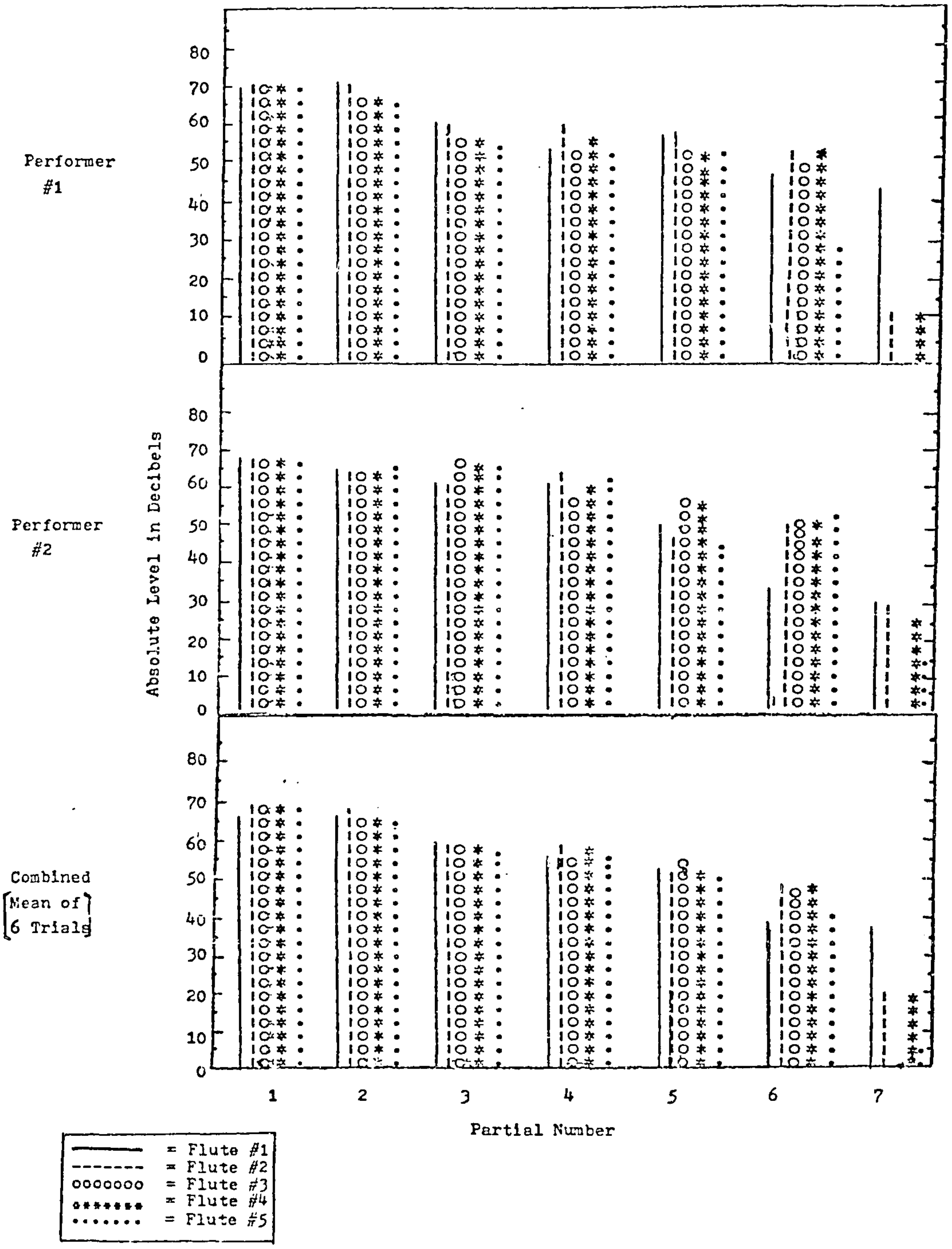


Table 26

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G$_4$ (392 Hz) at *Piano* (75 db)

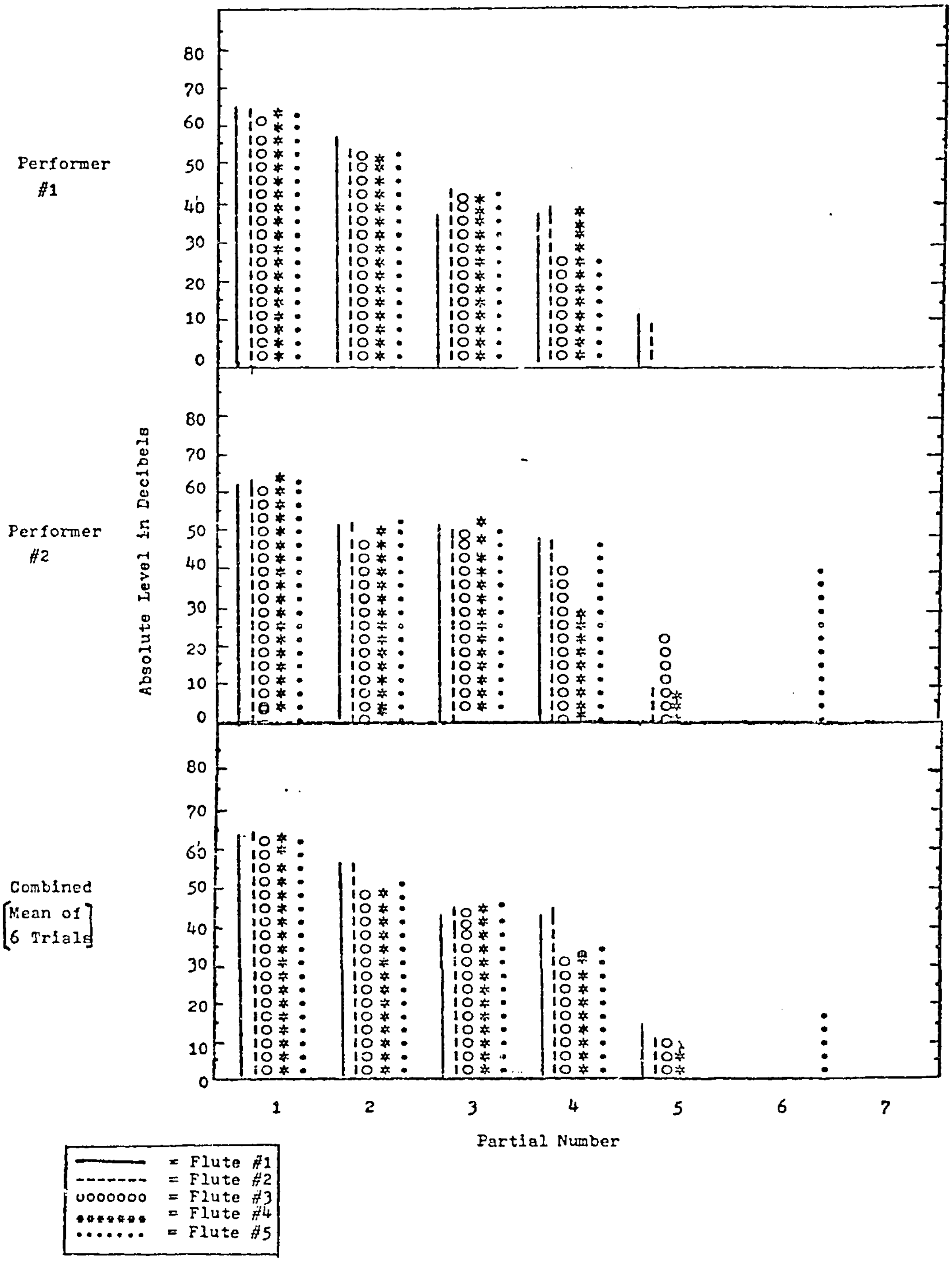


Table 27

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G_5 (784 Hz) at *Forte* (85 db)

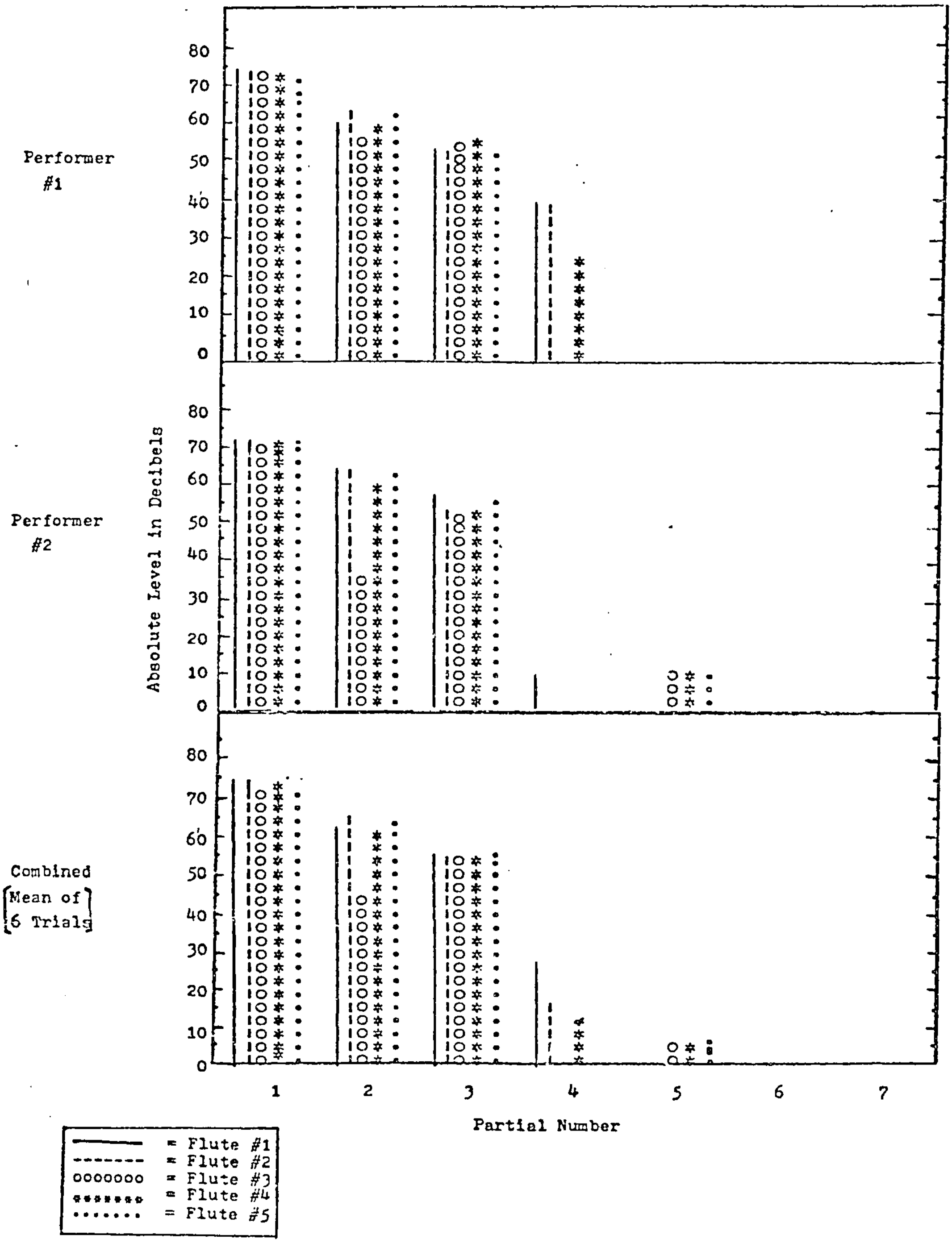


Table 28

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G_5 (784 Hz) at *Piano* (75 db)

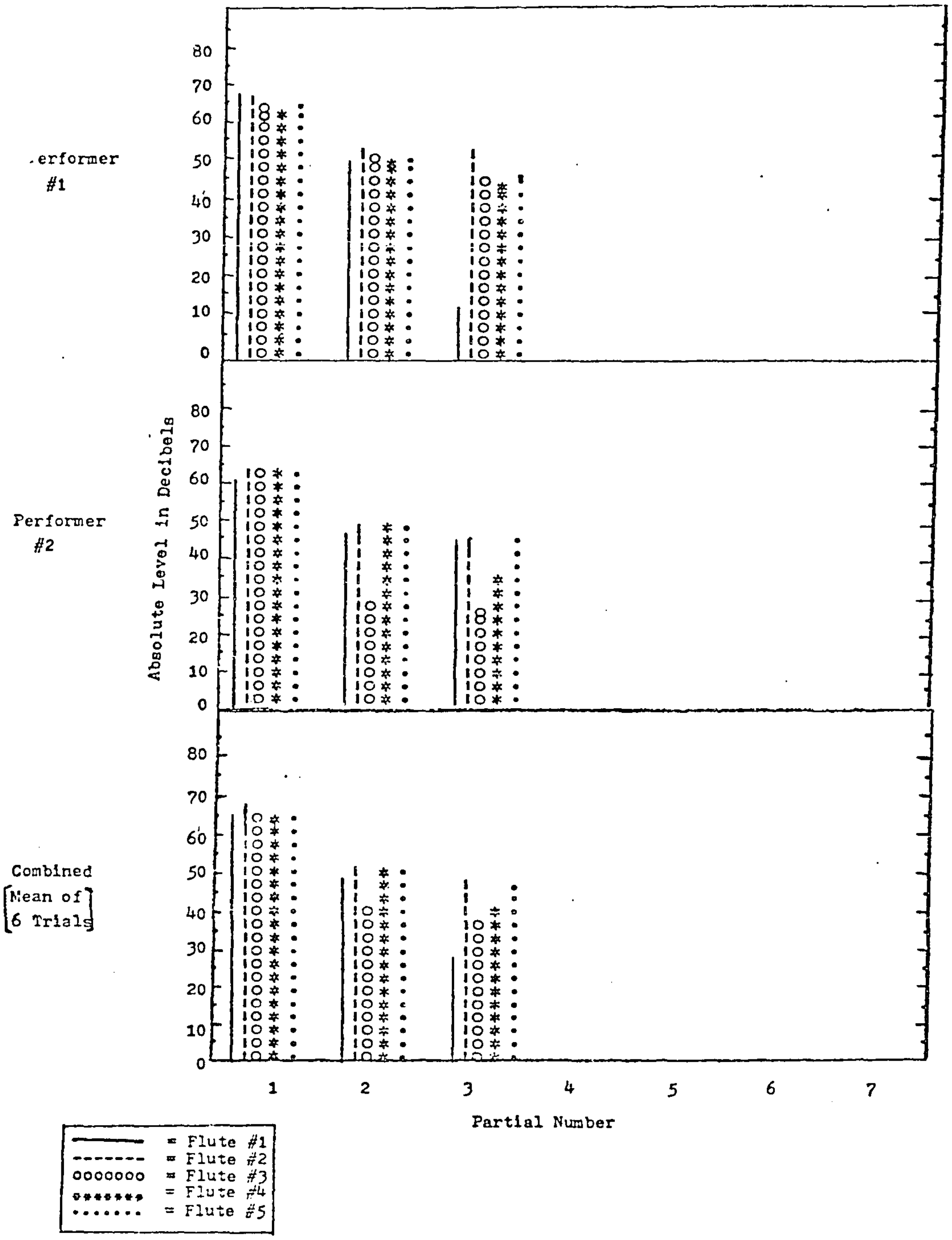


Table 29

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G_6 (1568 Hz) at *Forte* (95 db)

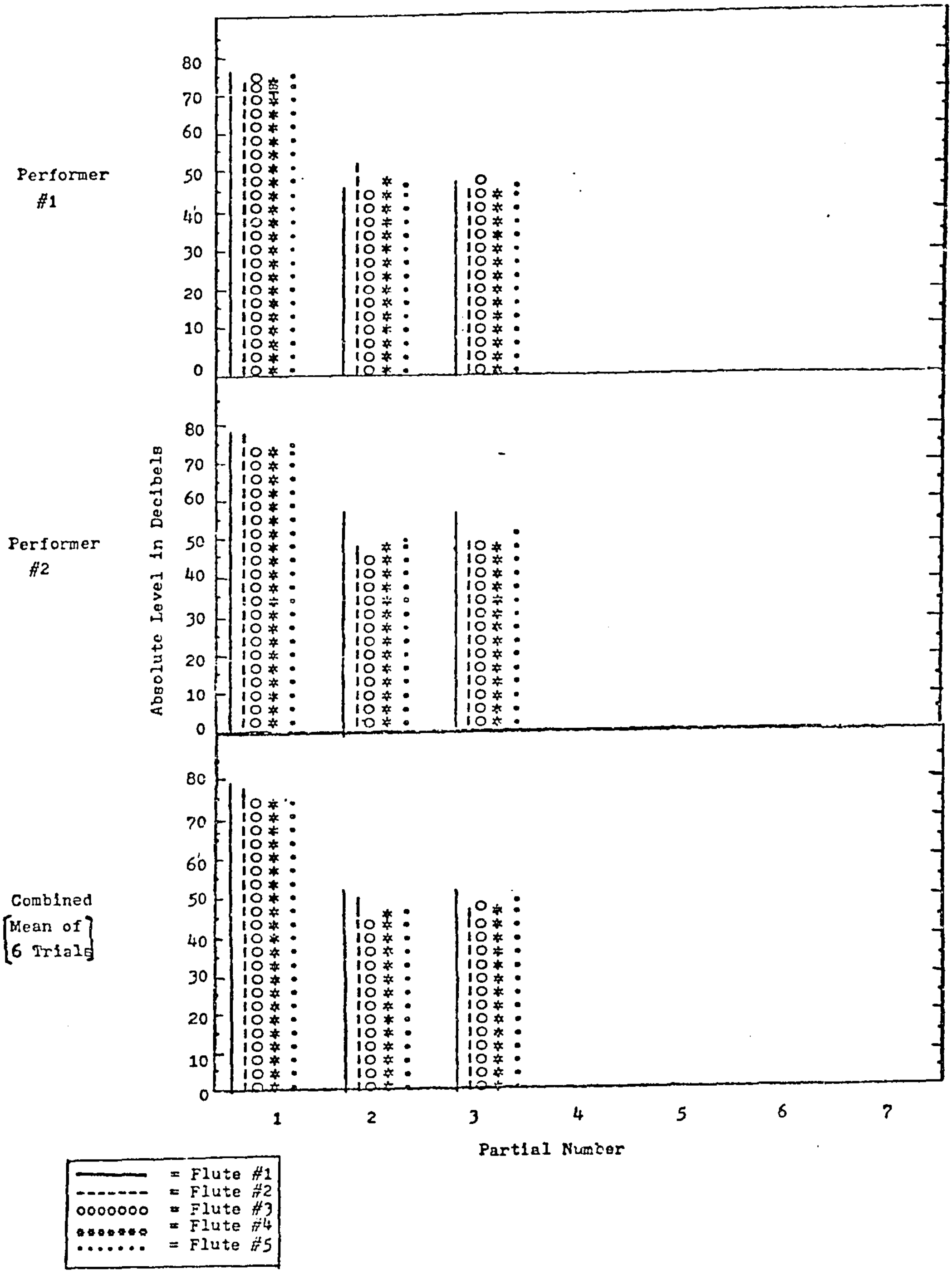


Table 30

A Comparison of Flutes: Mean Strengths of the Partials for the Pitch G_6 (1568 Hz) at *Piano* (85 db)

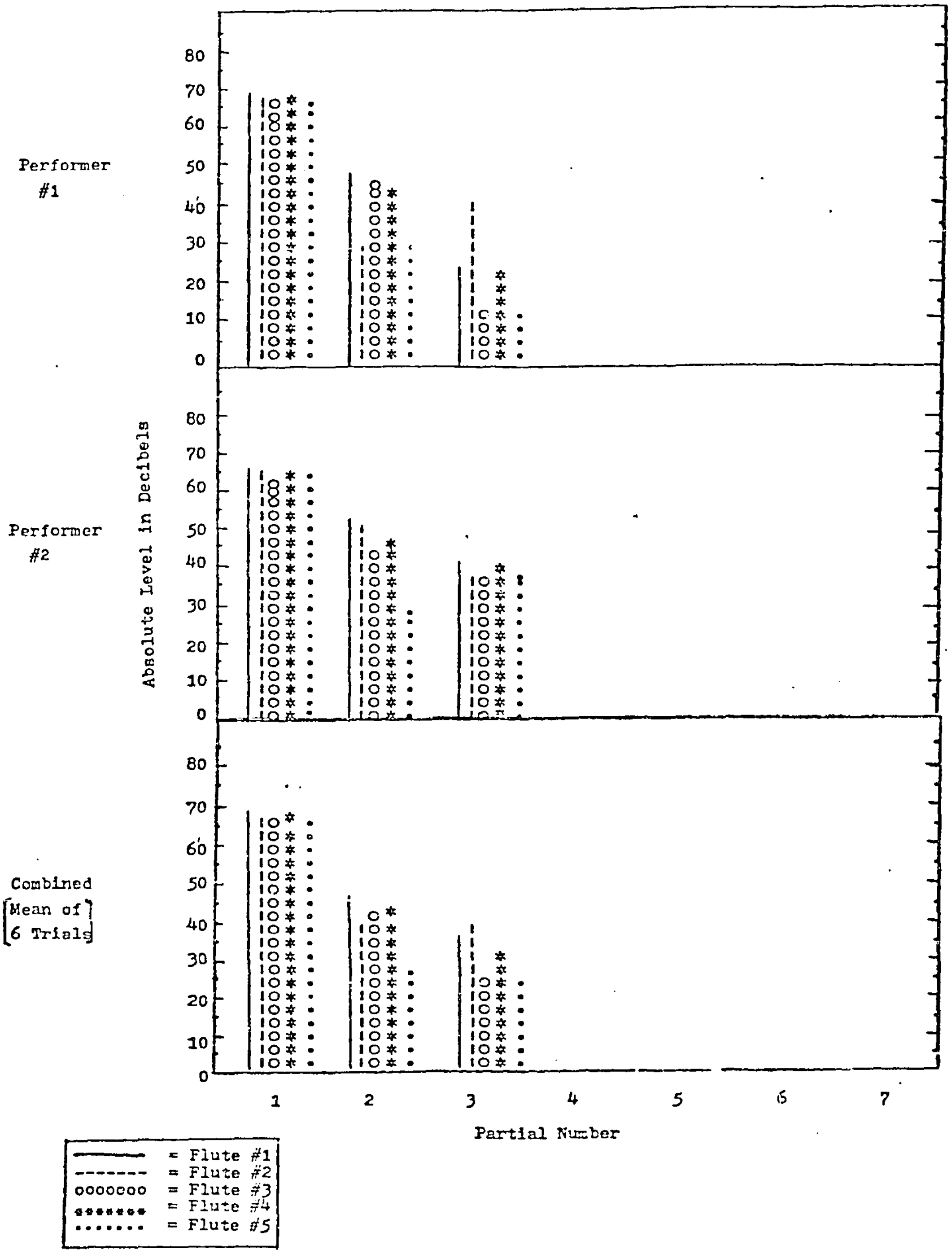


Table 31

Multivariate Analysis of Variance of the 2 x 3 x 2 x 5 Factorial Design: Dependent Variable = Partial 1

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	92.4500	92.4500	29.89	.0001
B (Frequency)	2	728.6111	364.3056	117.80	.0001
C (Intensity)	1	2240.1389	2240.1389	724.37	.0001
D (Flute)	4	39.9667	9.9917	3.23	.0139
A x B	2	15.6333	7.8167	2.53	.0830
A x C	1	22.0500	22.0500	7.13	.0083
A x D	4	32.9667	8.2417	2.67	.0343
Error	164	507.1778	3.0926		
Corrected Total	179	3678.9944			

Table 32

Multivariate Analysis of Variance of the 2 x 3 x 2 x 5 Factorial Design: Dependent Variable = Partial 2

Source	d.f	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	11.9481	11.9481	.75	.3868
B (Frequency)	2	5874.6130	2937.3065	185.13	.0001
C (Intensity)	1	4195.0981	4195.0981	264.40	.0001
D (Flute)	4	433.5634	108.3909	6.83	.0001
A x B	2	145.7867	72.8934	4.59	.0115
A x C	1	36.2892	36.2892	2.29	.1324
A x D	4	112.7816	28.1954	1.78	.1360
Error	159	2522.7543	15.8664		
Corrected Total	174	13332.8343			

Table 33

Multivariate Analysis of Variance of the 2 x 3 x 2 x 5
Factorial Design: Dependent Variable = Partial 3

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	259.0763	259.0763	23.47	.0001
B (Frequency)	2	2583.5361	1291.7680	117.05	.0001
C (Intensity)	1	4990.5792	4990.5792	452.19	.0001
D (Flute)	4	43.0261	10.7565	.97	.4232
A x B	2	559.5168	279.7584	25.35	.0001
A x C	1	.8596	.8596	.08	.7806
A x D	4	252.0748	63.0187	5.71	.0003
Error	155	1710.6410	11.0364		
Corrected Total	170	10399.3099			

Table 34

Multivariate Analysis of Variance of the 2 x 3 x 2 x 5 Factorial Design: Dependent Variable = Partial 4

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	631.2748	631.2748	64.69	.0001
B (Frequency)	1	538.3617	538.3617	44.00	.0001
C (Intensity)	1	2843.7741	2843.7741	290.53	.0001
D (Flute)	4	143.6573	35.9143	3.67	.0105
A x B	1	1.0269	1.0269	.10	.7473
A x C	1	3.3327	3.3327	.34	.5621
A x D	4	77.1080	19.2770	1.97	.1129
Error	52	508.9948	9.7884		
Corrected Total		4747.5303			

Table 35

MANOVA Summary Table: 2 x 3 x 2 x 5 Factorial Design

Source	Partial #1	Partial #2	Partial #3	Partial #4
A (Performer)	$p < .0001$	NS	$p < .0001$	$p < .0001$
B (Frequency)	$p < .0001$	$p < .0001$	$p < .0001$	$p < .0001$
C (Intensity)	$p < .0001$	$p < .0001$	$p < .0001$	$p < .0001$
D (Flute)	$p < .0139$	$p < .0001$	NS	$p < .0105$
A x B	NS	$p < .0115$	$p < .0001$	NS
A x C	$p < .0083$	NS	NS	NS
A x D	$p < .0343$	NS	$p < .0003$	NS

Table 36

Multivariate Analysis of Variance of the 2 x 3 x 2 x 2 Factorial Design: Dependent Variable = Partial 1

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	51.6806	51.6806	13.31	.0005
B (Frequency)	2	402.5833	201.2917	51.84	.0001
C (Intensity)	1	975.3472	975.3472	251.18	.0001
D (Flute)	1	1.6806	1.6806	.43	.5131
A x B	2	39.3611	19.8055	5.07	.0091
A x C	1	45.1250	45.1250	11.62	.0012
A x D	1	13.3472	13.3472	3.44	.0685
Error	62	240.7500	3.8830		
Corrected Total	71	1769.8950			

Table 37

Multivariate Analysis of Variance of the 2 x 3 x 2 x 2 Factorial Design: Dependent Variable = Partial 2

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	.9016	.9016	.05	.8278
B (Frequency)	2	1956.6744	978.3372	51.79	.0001
C (Intensity)	1	1876.4514	1876.4514	99.33	.0001
D (Flute)	1	.8363	.8363	.04	.8341
A x B	2	148.0400	74.0200	3.92	.0251
A x C	1	3.4861	3.4861	.18	.6690
A x D	1	35.2375	35.2375	1.87	.1770
Error	61	1152.3728	18.8914		
Corrected Total	70	5174.0000			

Table 38

Multivariate Analysis of Variance of the 2 x 3 x 2 x 2 Factorial Design: Dependent Variable = Partial 3

Source	df	Sum of Squares	Mean Squares	F Value	PR > F
A (Performer)	1	113.7817	113.7817	8.83	.0043
B (Frequency)	2	847.2578	423.6289	32.87	.0001
C (Intensity)	1	1990.8865	1990.8865	154.48	.0001
D (Flute)	1	8.2816	8.2816	.64	.4260
A x B	2	115.8557	57.9433	4.49	.0152
A x C	1	1.2300	1.2300	.10	.7585
A x D	1	247.5935	247.5935	19.21	.0001
Error	59	760.3596	12.8875		
Corrected Total	68	4085.2464			

Table 39

MANOVA Summary Table: 2 x 3 x 2 x 2
Factorial Design

Source	Partial #1	Partial #2	Partial #3
A (Performance)	$p < .0005$	NS	$p < .0043$
B (Frequency	$p < .0001$	$p < .0001$	$p < .0001$
C (Intensity)	$p < .0001$	$p < .0001$	$p < .0001$
D (Flute)	NS	NS	NS
A x B	$p < .0091$	$p < .0251$	$p < .0152$
A x C	$p < .0012$	NS	NS
A x D	NS	NS	$p < .0001$