An investigation of correlations between geometry, acoustic variables, and psychoacoustic parameters for French horn mouthpieces

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Because brass instrument mouthpieces are considered by musicians to be the single most important component of the instrument, a comparative investigation was made of seven French horn mouthpieces widely used by professional musicians. Acoustic parameters were obtained from both measured and computed impedance curves for the mouthpieces attached to a cylindrical tube with an overall length approximating that of the horn in B-flat. Hypothesized psychoacoustic correlates to these parameters were used by professional musicians to evaluate the mouthpieces by means of comparative testing. It was discovered that the peak amplitudes and Q values of the impedance peaks, as well as their respective variability, correlated well to the musicians' preference ratings. Based on the presented documented changes in the ratio of French horn mouthpiece cup length to throat plus backbore length throughout the twentieth century, the acoustical properties of modern designs to the older versions are compared. These results show that the average harmonics' peak amplitude has increased, while variability has simultaneously decreased, resulting in a more even envelope. Also, the impedance peak's average Q's have increased, a probable explanation for musicians' expressed preference for mouthpieces which facilitate greater pitch control. © *1999 Acoustical Society of America.* [S0001-4966(99)02906-9]

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INTRODUCTION

Until recently musical instrument design has been predominantly a heuristic procedure, but certain basic characteristics have, nevertheless, evolved for all wind instruments. Foremost among these, perhaps, is that many of the input impedance peaks should be harmonically related for each playing configuration. Such a relationship is necessary for the musician to be able to produce clear, stable notes via the feedback from the instrument's bore to a nonlinear driver. When the higher bore resonances are aligned with the harmonics of the note being played, a strong cooperative feedback condition or "regime of oscillation" is established between the components of the sound spectrum and the bore resonances.[1] Given that a suitable set of resonances exist, the mouthpiece of a brass wind instrument is considered by musicians to be the single most crucial element regarding the performance of the entire horn.[2,3] Since a mouthpiece is not only an integral part of the instrument, but the section which interfaces the musician to the instrument, it is perhaps understandable that it should have a primary role in assisting the musician to generate favorable intonation. We have chosen to study the French horn mouthpiece in detail because, in addition to its importance to the French horn, it has measurable acoustic properties which can be considered to be relatively independent of the rest of the instrument, and it is an easily changeable component of a horn.

A French horn mouthpiece consists of four parts: the rim, the cup, the throat, and the backbore, as shown in Fig. 1. The art of mouthpiece design is to create the optimized relationship of the various mouthpiece dimensions, thus assisting a competent performer in achieving superior tone quality, attack clarity, flexibility, and a comfortable resistance. That different manufacturers have attempted to achieve this end by somewhat different means is apparent by inspecting Table I. This table is a compilation of accurate measurements on 61 French Horn mouthpieces by 37 designers and 15 different manufacturers ranging from late nineteenth century through contemporary companies. Although many mouthpiece manufacturers have, in the past, exhibited such astonishingly poor quality control that nominally identical mouthpieces have occasionally differed by amounts greater than the difference between models, no attempt was made to include this variable. Only one representative sample of each model was measured. The high standard deviation for some of the variables, particularly throat length, indicates that no consensus on mouthpiece design has been achieved, even considering that some of the differences may be accounted for by the varying requirements of different styles of horn. Nevertheless, despite design variation mandated by diverse horn models, styles of music, as well as the considerable variability of personal preference, certain regularities are apparent. Approximately half of the standard deviations are less than 6%, which indicates that many of the variables are standardized across a wide spectrum of designs. Most of the differences in mouthpiece design occur in cup length, throat length, and backbore length, which vary widely although the overall length is reasonably constant.

Table II(a) presents combinations of these ratios, as

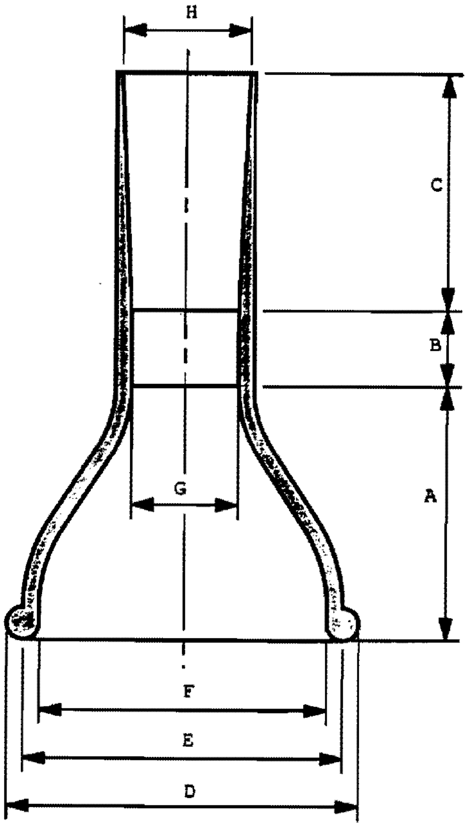

FIG. 1. The French horn mouthpiece. (A) cup length, (B) throat length, (C) backbore length, (D) cup rime o.d., (E) cup peak diameter, (F) rim inner diameter (grip), (G) throat diameter, (H) backbore end diameter.

well as several other ratios and products which have been regarded as important by manufacturers. Table II(b) shows the product-moment correlation coefficients of different combinations of the three important mouthpiece lengths and throat diameters. Note the strong negative correlations of cup versus throat length and throat versus backbore length. This may be interpreted as follows: when the throat is drilled out it becomes longer as well as wider, while the cup length and backbore length decrease by a corresponding amount. However, the negative correlation between cup and backbore length, where a positive correlation may reasonably have been expected, indicates that design procedures involve more complications than merely changing the throat diameter. This is also evidenced by the extremely strong negative correlation (−0.80) between cup length and throat plus backbore length, where a lesser correlation would be anticipated. The regularities apparent in Table I, as well as the considerable variation indicated by Tables II(a) and (b), have prompted us to attempt to determine optimum dimensions for a French horn mouthpiece which would be acceptable to professional musicians on a wide variety of contemporary horns.

Musical instrument manufacturers have long strived to produce instruments that satisfy their customers, but progress has been slow due to inherent difficulties in interpreting musicians' comments and the lack of accurate and economical methods of acoustical analysis. Although the recent introduction of computer modeling schemes has alleviated somewhat the analysis problem, there is still no firm consensus regarding the interpretation of the resultant data as they relate to musicians' preferences. Compounding the difficulty of the task is that musicians' preferences seem to have evolved or changed over the years.[4] Smithers *et al.*[5] have noted, for example, that the technical requirements of Baroque trumpeters and modern performers are not even remotely similar. More germane to the present study is the obvious evolution of

TABLE I. Mouthpiece measurements.

(Parentheticalletters refer to Fig. 1)	Number measured	Mean (cm)	Minimum (cm)	Maximum (cm)	Standard deviation	% Coeff. variation
Total length	53	6.5110	6.0198	7.2136	0.221	3.4%
Cup length (*A*) CL	43	2.9790	2.0960	4.5010	0.498	16.7%
Cup I.D. at screw joint (*F*)	28	1.6640	1.5950	1.7270	0.030	1.8%
Mouthpiece length w/o rim	45	6.1049	3.1750	6.9850	0.493	8.2%
Rim I.D. at joint (*F*)	37	1.6640	1.5950	1.7220	0.025	1.5%
Screw rim length	29	0.7520	0.5590	0.8050	0.084	11.2%
Rim face to joint depth	33	0.3250	0.2180	0.7060	0.124	38.2%
Rim O.D. (*D*)	58	2.4770	2.3500	2.6040	0.061	2.5%
Rim I.D.—grip	55	1.7400	1.6260	1.8160	0.041	2.4%
Rim full width	48	0.3530	0.2870	0.4570	0.046	13.0%
Rim peak diameter (*E*) *RPD*	43	2.0680	1.9810	2.1590	0.041	2.0%
Throat length (*B*) *THL*	43	1.0590	0.0000	4.0840	0.774	73.1%
Throat diameter (*G*) *THD*	60	0.4780	0.4090	0.5790	0.036	7.5%
Backbore end diam. (*H*) *BBED*	51	0.6350	0.5870	0.6600	0.018	2.8%
Backbore length (*C*) *BBL*	51	2.4710	0.9530	3.8100	0.543	22.0%

TABLE II. (a) Ratios of mouthpiece dimensions. (b) Product-moment correlation coefficients.

(a)	RPD/CL	THD/THL	THD_x/THL	THD^2/THL	CL/BBL	$CL/(THL+BBL)$
Number measured	39	41	42	42	41	41
Mean	0.710	0.695	0.497	0.230	1.385	0.882
Standard deviation	0.103	0.566	0.053	0.188	0.713	0.442
Coefficient variation (%)	15%	81%	69%	82%	52%	50%

(b)	
Number measured	41
Cup length versus Throat length	−0.51
Cup length versus Backbore length	−0.22
Throat length versus Backbore length	−0.58
Cup length versus Sum of throat and backbore length	−0.80
Throat diameter versus Throat length	+0.53

French horn mouthpiece designs during the course of this century, made apparent by Tables I and III. (Table III presents measurements taken on seven common mouthpieces used by musicians today; Table I is dominated by historic models currently out of favor.) This change is made even more obvious by an examination of contemporary musical compositions. Increasingly, wind instruments are being asked to perform over their entire frequency range, and sometimes even beyond the conventionally accepted compass. If a means of gauging and quantifying musicians' "preferences" and composers "requirements" could be discovered, future instruments could evolve more readily to meet these needs.

I. RATIONALE

A. Justification

In order to relate the geometry of a mouthpiece to a set of psychoacoustic variables which have meaning to a musician, it is first necessary to move from the realm of simple geometry to the acoustic domain. The air column from the entrance of the mouthpiece to the end of the bell can be regarded as a linear system whose role in tone generation may conveniently be characterized by a single function, the input impedance as a function of frequency. This function enables one to make accurate predictions about the playing characteristics of a brass instrument; the harmonics of a brass instrument's spectrum are the result of the nonlinear interaction between the player's lips and the input impedance function of the horn.[6] Oscillation is favored at a frequency where the input impedance is large and where there are several large values of impedance near integer multiples of this frequency. Thus because it is fundamental to the sound production mechanism and because it incorporates the instrument's internal geometry, the acoustic input impedance is the logical choice for objectively evaluating brass instrument mouthpieces.

To relate the input impedance to musicians' subjective evaluation, however, is considerably more difficult. It has been shown[7] that although the amplitudes and degree of harmonicity of impedance peaks are important, they are insufficient to account for the discrimination ability and strong preferences of professional musicians. It is also necessary to consider the Q's of the impedance peaks and the overall shape of the impedance peak envelope. Since the instrument's spectrum is related to this shape, and since the spectrum influences the perceived timbre, the envelope is particularly important.

For our detailed study, we selected seven mouthpieces currently in wide use among professional musicians in the United States. The pertinent geometrical variables for these mouthpieces are listed in Table III, along with the labels used to identify them in this study. Comparing the mean values of the seven mouthpieces in current use (labeled AV-NEW in Table III) with those prevalent in the early twentieth century (the mean values from Table I, identified

TABLE III. Seven mouthpieces studied.

Manufacturer	Model	Total length (cm)	Cup length (A) (cm)	THD (G) (cm)	THL (B) (cm)	BBL (B) (cm)	BB diam (H) (cm)	Cup volume (cc)	Total volume (cc)
V. Bach	VB12	6.604	2.540	0.452	1.207	2.858	0.630	3.00	3.88
Giardinelli	C8	6.096	2.223	0.508	1.655	2.223	0.660	3.90	5.08
Giardinelli	S14	6.001	2.858	0.472	0.610	2.540	0.648	3.65	4.36
Holton	MC13	6.350	2.540	0.477	1.588	2.223	0.635	3.10	3.98
Holton	MDC	6.375	2.540	0.470	1.930	1.905	0.622	3.65	4.48
King	H2	6.350	2.858	0.470	0.953	2.540	0.648	3.80	4.61
Lawson	L5	6.383	2.540	0.488	1.778	2.065	0.622	3.20	4.01
AV-NEW		6.308	2.586	0.476	1.389	2.336	0.638	3.47	4.34
AV-OLD		6.511	2.979	0.478	1.059	2.471	0.635	3.65	4.37
AV NEW/OLD		0.969	0.868	0.996	1.312	0.945	1.005	0.951	0.993

in this study as AV-OLD) it is interesting to note that the geometric parameters exhibiting the greatest change are the cup and throat lengths, as summarized in the last row of Table III (the ratio of AV-NEW to AV-OLD). (The data of Table I include the mouthpieces of Table III but the predominance of older styles yields mean values more representative of a bygone era.) In general, cup lengths have decreased while throat lengths have increased.

B. Musician consensus

For our first experiment, we chose four mouthpieces in common use by professionals in the United States. Reproductions (accurate to one-thousandth of an in.) of these mouthpieces, each having the same rim and exterior, were sent to 34 performers in major symphony orchestras across the United States. The musicians were asked to play, on their own instrument, each mouthpiece in any order and any number of times. Based on this simple test, they were requested to separate the mouthpieces, by overall preference, into two categories: "like" or "dislike." The results of this blind test appear in Table IV. Although the data make it apparent that there is considerable consensus on what is preferred and what is not, the test is not specific enough to correlate with acoustic variables.

TABLE IV. Mouthpiece preference by 34 professional musicians.

	C8	H2	MDC	L5
Number of times not liked	27	24	19	5
Number of times liked	4	4	13	27
Total number	31	28	32	32
% Preferred	12.9%	14.3%	40.6%	84.4%

C. Experimental model

Because of the importance of the input impedance, considerable effort has been devoted to determining this function for brass instruments.[8–10] In the present study, we have attempted to correlate the geometrical and acoustical parameters of French horn mouthpieces, as determined from the input impedance curves, to musicians' preferences for different designs. To limit the number of acoustic variables and to simplify the musical evaluation process, our experimental system consisted of a mouthpiece inserted into a standard 48-cm-long French horn leadpipe which was, in turn, inserted into a 1.19-cm, i.d. cylindrical tube, the entire system having a length approximating that of a B-flat French horn. Although it may seem as though a cylindrical tube is a rather poor imitation of a French horn, it has been recognized for some time[11–13] that the mouthpiece and leadpipe are the two most important sections of a French horn and their characteristics are reasonably independent of the remainder of the horn. Indeed, after the leadpipe, the balance of the horn serves mainly to fix intonation and to radiate the sound.[14] Some of the advantages of using a cylindrical tube to represent the body of a French horn are: (1) it considerably simplified the system while retaining the pertinent variables—a set of well-defined resonance peaks having approximately the same spacing as for the horn; (2) because of the small diameter, more peaks at high frequencies were present, giving the performer an extended playing range; (3) informal preliminary tests with 12 professional musicians indicated that they could consistently rank various mouthpieces by preference on the tube as well as on a horn, but the tube helped to exaggerate the pertinent differences between mouthpieces; (4) it is easier to model, it helps exaggerate the differences between mouthpieces, and musicians are better able to concentrate on properties of mouthpieces without being distracted by the French horn sound; (5) the plane wave model employed in the computer simulations to produce a calculated impedance curve is only accurate to about 600 Hz for a French horn because of the large bell while the model is accurate well beyond the frequency range of interest for the small diameter cylinder. (Figure 2 shows, for comparison, the input impedance function measured for a French Horn and for the cylindrical tube with the same mouthpiece installed.)

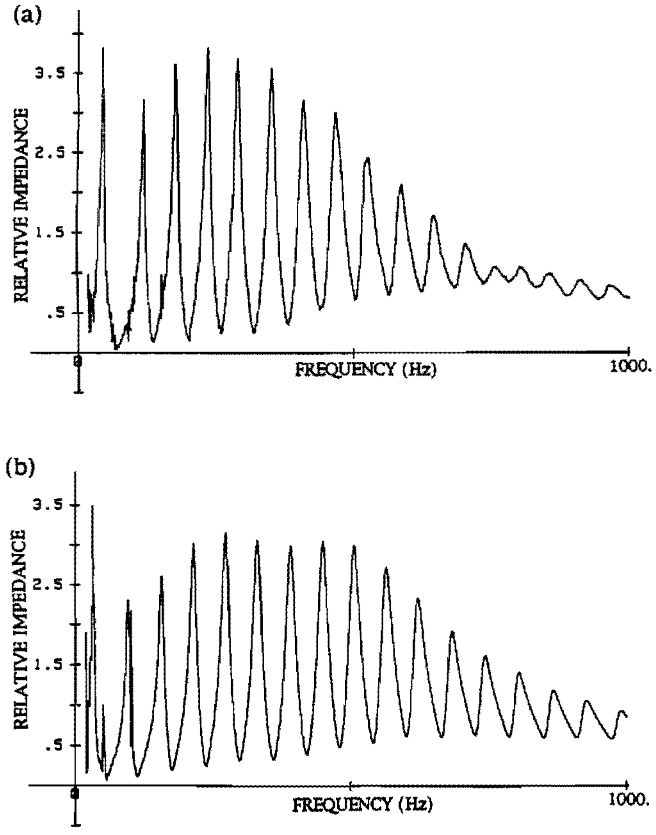

FIG. 2. Measured input impedance versus frequency for the L5 mouthpiece: (a) attached to a French horn: (b) attached to the cylindrical test instrument.

There is only one obvious disadvantage to replacing the bell flare by a cylindrical tube—harmonicity is compromised by the stretched partials. Since the advantages more than compensate for the disadvantage of stretched partials, our investigation was confined to a system consisting of a mouthpiece, leadpipe, and cylindrical tube.

TABLE VI. Mouthpiece preferences of P. Landgren.

	Like	Neutral	Dislike
Flexibility	L5, H2, MDC	C8, S14	S14, MC13, VB12
Pitch control	L5	MC13, MDC	H2, S14, C8, VB12
Ease of playing	MDC, L5	MC13, VB12	H2, S14, C8
Intonation	H2	MC13, MDC, L5	S14, C8, VB12
Tonality	L5	MC13, MDC	H2/S14, C8, VB12
Dynamic range	VB12, H2	MC13, MDC, L5	S14, C8
Attack clarity	L5	MC13, S14, MDC, C8, VB12	H2

TABLE VII. Psychoacoustic and acoustic correlates.

Psychoacoustic variable	Acoustic correlate
Flexibility	$Z_{\max}(n)/Z_{\min-\mathrm{av}}(n)$
Pitch control	$Q_n = f_n/n/Df$
Ease of playing	$Z_{\max}(n)/Z_{\min-\mathrm{av}}(n)/Q_n$
Intonation	harmonicity
Tonality	s.d. $\{Z_{\max}(n)\}_{\mathrm{av}}$
Dynamic range	$Z_{\max}(n)/Z_0$&harmonicity
Attack clarity	V_c/BBL

working hypotheses: although intonation is important, professional musicians will show preferences, even among mouthpieces having equivalent harmonicity, and musicians' subjective judgments of different aspects of various mouthpiece designs can be correlated to acoustic parameters derived from geometry or from the input impedance curves.

C. Mouthpiece preference

After the preliminary tests were completed, it was decided that it would be cumbersome to devise any detailed test which could clearly communicate the variables to be examined to a diverse group of musicians in various geographical locations. The preliminary tests showed that the mouthpiece ratings of one musician, Peter Landgren (associate principal of the Baltimore Symphony Orchestra), consistently agreed with the group consensus discussed in Sec. I B and the rankings discussed in Sec. II B. Furthermore, he is a reknowned performance teacher who is not only interested in and familiar with the psychoacoustic variables we are discussing, but someone who has been using similar terminology in his teaching. In other words, his mouthpiece rankings not only agreed with the consensus, but he understands the terminology and knows exactly what to listen for. We therefore decided to conduct the detailed analysis of the seven mouthpieces using only this one professional, Peter Landgren. He was asked to evaluate each of the seven mouthpieces according to the seven criteria listed above. He could select the unmarked mouthpieces in any order and he could return to any mouthpiece at any time in order to compare the same variable among different mouthpieces. Table VI is a summary of his comments, where for each of the seven criteria, the mouthpieces are listed in a ''like,'' ''neutral,'' or ''dislike'' column.

III. HYPOTHESIZED ACOUSTIC/PSYCHOACOUSTIC CORRELATES

Our operating assumption was that the seven psychoacoustic parameters might be identified with acoustic variables according to the scheme of Table VII. We assumed that a preferred rating for ''flexibility'' would relate to a low characteristic wave impedance Z_c, where $Z_c^2(n) = Z_{\max}(n) * Z_{\min}(n)$ over the playing range, since this should allow the performer to slip easily from one mode to the next. In conjunction with this, the ratio of $Z_{\max}/Z_{\min\text{-av}}$ should be high so that the note sounds easily and seems focused.

The playing frequency is determined by the interaction between the lips and the regime of oscillation. If the impedance peaks are reasonably well tuned, ''pitch control'' should correlate with Q_n, since the narrower the resonances, the better a note ''locks in'' and the easier it is for the musician to hold the pitch.

To a musician, ''ease of playing'' implies the sound produced relative to the effort put into producing it; that is, how much effort is required to start a note and to sustain it. Within certain limits, a high value of $Z_{\max}/Z_{\min\text{-av}}$ will yield a note which is easy to play. But a high amplitude ratio is usually accompanied by a high Q and the higher the Q the more difficult it becomes, during playing, to locate one particular impedance peak without accidentally finding its neighbors. We therefore hypothesized that ''ease of playing'' should correlate with $(Z_{\max}(n)/Z_{\min\text{-av}}(n))/Q_n$, that is, the higher the ratio, the higher the preference rating should be. The higher $Z_{\max}$ increases efficiency, while a greater bandwidth (lower Q_n) helps the musician find the resonance of choice.

Obviously, ''intonation'' should correlate indirectly with the harmonicity of the impedance peaks. For an actual French horn, the shape of the instrument is carefully designed to yield as harmonic an intonation curve as feasible, particularly in the high frequency range. The leadpipe and straight tube, however, will produce a set of modes which are stretched considerably from their values on a French horn. Despite this effect, our musician (as well as a dozen others during preliminary tests) was able to make consistent musical judgments which separated mouthpieces by preference since the amount of harmonic spreading was different for each mouthpiece.

While there does not yet exist any consensus on a measure of ''tonality'' (tone quality),[19] it was assumed to correlate with the impedance peak amplitudes, i.e., with the spectral envelope. Pratt and Bowsher[7] have shown that the nature of the spectral envelope somehow correlates with the subjective evaluation of quality, but no causal link was hypothesized. Our assumption was that even envelopes (relatively constant across most of the playing range), would be preferred to erratic envelopes or envelopes which decreased rapidly at high frequencies. A more even envelope should yield more consistent dynamics across the playing range, and should therefore be preferred by musicians. In an effort to quantify the acoustic correlate, we will define ''evenness'' as the inverse of the median deviation of $Z_{\max}(n)/Z_0$, where $Z_0 = \rho_0 c$, for each mouthpiece's spectral envelope. Thus defined, the higher the evenness coefficient (a lower median

TABLE V. Mouthpiece analysis from measured data.

Manufact.	Model	Res. freq. (Hz)	Q of Res.	V_c/BBL (cm)^2	% Deviation	$(f_r^{2x}V_c)/C$ $x\,S_{th}/L'$	% Diff. from Helmholtz	L_{e1}/L_{e2}	% Deviation	THD^2/V$_c$ (cm)$^{-1}$
V. Bach	VB12	602.3	7.74	1.05	26.1%	0.995	0.5%	4.51	9.5%	0.0675
Giardinell	C8	572.1	8.65	1.53	7.7%	1.175	17.5%	3.74	9.2%	0.0586
Giardinell	S14	593.1	7.27	1.28	9.9%	0.918	8.2%	4.20	2.0%	0.0610
Holton	MC13	617.0	7.72	1.22	14.1%	0.973	2.7%	4.43	7.6%	0.0737
Holton	MDC	585.3	6.63	1.43	0.7%	0.993	0.7%	4.14	0.5%	0.0605
King	H2	605.5	8.31	1.33	6.3%	1.015	1.5%	3.89	5.5%	0.0581
Lawson	L5	593.0	7.16	1.44	1.4%	0.730	27.0%	4.46	8.3%	0.0744

II. EXPERIMENTAL PROCEDURE

A. Acoustic Input impedance

Input impedance curves were generated by two methods: direct measurement by means of the experimental apparatus of Bruneau,[15] and calculation from physical measurements via the computer model of Plitnik and Strong.[16] The resonance frequency of each mouthpiece alone, recorded in Table V, was measured by the Bruneau apparatus. For the computer calculations the interior dimensions of each mouthpiece were measured at 3.0-mm intervals to three significant figures. Accuracy was achieved in the cup by casting a mold of the interior with nonshrinking cerro base casting metal and measuring the cast cross section at 3.0-mm intervals. The interior volume of the cup, determined from the mass and density of its casting, is recorded in Table III.

The calculated input impedance curves were used to determine directly the following acoustic parameters: an overall spectral envelope defined by the impedance maxima, the ratio $Z_{\max}(n)/Z_{\text{min-av}}(n)$ as a function of harmonic number n, where $Z_{\max}(n)$ is the magnitude of the nth impedance peak and $Z_{\text{min-av}}(n)$ is the mean of the two impedance minima adjacent to each $Z_{\max}$, Q_n as a function of harmonic number n [where Q_n is defined as $Q_n=(f_n/n)*df$ and f_n is the frequency of the nth impedance peak and df is the bandwidth at the -3 dB points], and the harmonicity of the peaks as a function of n, where harmonicity was defined as $3(f_n/f_3)-n, f_3$ being the frequency of the third impedance peak (the third peak was used as a standard because the first two peaks are not as important as the third and because accurate data are somewhat more difficult to obtain at the lower frequencies). The input impedances are all relative to the characteristic impedance of air, $Z_0=\rho_0 c$. It has been shown[17] that every complicated acoustic system has a characteristic wave impedance related to the $Z_{\max}$ and $Z_{\min}$ of the system by the simple relationship $Z_{\max}*Z_{\min}=Z_c^2$. For simple ideal systems Z_c should be equivalent to Z_0 and constant across the impedance plot; our data clearly show that this is not the case. For our system Z_c changes with frequency for every mouthpiece and the changes are different for each mouthpiece. We therefore computed $Z_c^2(n)=Z_{\max}(n)*Z_{\min}(n)$ and defined an average Z_c for each mouthpiece as the mean Z_c for the 16 impedance maxima.

B. Psychoacoustic variables

Although horn playing is a highly subjective art, both musicians and researchers have attempted to identify significant parameters which could be used to assess instruments. Farkas[4] has identified three criteria which he considers paramount: proper response, characteristic tone, and good intonation, a somewhat vague and hardly exhaustive list. For a trombone, Pratt and Bowsher[18] assessed seven subjective features: dynamic range, intonation, responsiveness, resistance, stuffiness, timbre, and flexibility. The two most critical features were shown to be timbre and responsiveness, with intonation being of only secondary concern.

For our purposes, we attempted to identify the most important subjective qualities which would most likely be influenced by the French horn mouthpiece geometry. These psychoacoustic variables, which we wished to assess, were (1) *flexibility* (the ease with which the performer can slip from resonance peak to resonance peak), (2) *pitch control* (how well the pitch "locks-in"), (3) *ease of playing* (the smoothness and consistency sensed by the player), (4) *intonation* (the facility of accurate pitch production), (5) *tonality* (the quality of the tone produced), (6) *dynamic range* (the range from the softest to the loudest tones possible, and (7) *attack clarity* (the smoothness and rapidity of the initial attack). As a preliminary test, the 7 mouthpieces were played on both the test pipe and on a French horn by 13 professional hornplayers in 3 major symphony orchestras, who were asked to comment on the above variables. (Pratt and Bowsher[18] have also shown the importance of using professional musicians in studies of this nature. While nonprofessional players had difficulty discriminating differences, a professional had no trouble quantifying his assessments of different instruments.) Typical responses were somewhat difficult to interpret, but the musicians were able to rate each mouthpiece on most of these factors, as well as assigning an overall rating. The musicians did not know which mouthpiece they were using and they were not allowed to inspect the mouthpieces. To ensure an unbiased evaluation, identical screw-on rims were used for each mouthpiece. Although only the i.d. of the rim affects mouthpiece acoustics, the size and shape of the outer elements most definitely affect the feel of a mouthpiece to a performer's lips. With the exception of intonation, the performer's comments about mouthpieces (for the other six factors) were completely consistent whether rated on a French horn or on the cylindrical tube. Confidence in using only the cylindrical tube for more detailed experiments was engendered by these preliminary trials.

We also asked the 13 musicians for an overall subjective evaluation of each mouthpiece as a means of ranking them from the most to the least preferred. In summary, we had two deviation), the more preferred the mouthpiece will be for its tonality.

"Dynamic range" is the variation from the softest to the loudest sustainable tones. Two factors would appear to be important here—the ratio of $Z_{\max}(n)/Z_0$, and the harmonicity of the peaks. Well-tuned peaks, in addition to higher peak impedances, allow for fortissimo playing.[20] Pianissimo playing is easier on small-bore instruments, which implies a higher characteristic impedance. Thus we hypothesize that the mouthpieces rated as having the best dynamic range will probably have a relatively low ratio of $Z_{\max}(n)/Z_0$ which is compensated for by relatively well-tuned peaks.

The "attack clarity," or comparative starting time of a note, is relatively easy for the musician to gauge, but considerably more difficult to relate to acoustic parameters. The player receives no feedback from the tube until the initial air pulse from his lips has traveled to the end of the system and back; the differing behavior of the performer's lips and the air column during this initial time period produces the French horn's easily identified and characteristic attack.[21] Different mouthpieces provide varying degrees of assistance in helping the musician to synchronize his lip vibration to the initially undeveloped standing wave ratio (SWR) determined by the input impedance. Indeed, it is believed[22] that brass instruments which do not start evenly are being adversely affected by premature reflections. Although the performer must rely upon his lip tension, mouth impedance, and innate sense of pitch in order to find the correct frequency without feedback, we believe that the geometry of the mouthpiece supplies some subtle aid in this endeavor. A rule of thumb long employed by French horn manufacturers is that the ratio of cup volume to the length of the backbore, V_c/BBL, is an important ratio for this purpose, and thus should be expected to remain approximately constant over a wide variety of mouthpieces. We were thus led to hypothesize that the musician's preference for attack clarity should correlate with the mean value of this ratio for all mouthpieces, and that any significant deviation from the mean would not be preferred. Although, strictly speaking, this ratio is a geometric parameter, not an acoustic correlate, we have included it in this list for completeness.

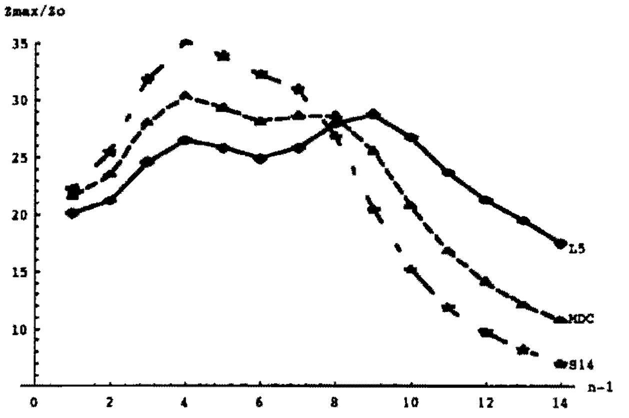

FIG. 3. Spectral envelopes of three mouthpieces.

IV. ACOUSTICAL MEASURES

The input impedance curves for the seven mouthpieces attached to the leadpipe and cylindrical tube were made using the Bruneau apparatus[15] and by computer model[16] based on accurate measurements of the system's geometry. Although the results were consistent, the somewhat idealized nature of the computer model (lack of noise) allowed a more accurate determination of the peak frequencies and bandwidths, thus allowing the data to be more easily separated when graphed. Since most of the computer generated data were used only in ratios, the idealized nature of these calculations was alleviated somewhat.

Figure 3, a graph of the spectral envelopes for several of the mouthpieces, shows that they are readily separable by this criterion. Table VIII tabulates the $Z_{\max}(n)/Z_0$ vs n, determined from the computer model data, for the seven mouthpieces currently widely used in the United States.

Figure 4 is a graph of $Z_{\max}(n)/Z_{\text{min-av}}(n)$ vs harmonic number n, constructed from the experimentally determined input impedance functions. For clarity, only three mouthpieces are plotted. In the middle register some obvious separation of the mouthpieces is apparent. Figure 5 is the Q_n vs n plot, constructed from the computer model data, for three

TABLE VIII. Impedance maxima for new mouthpieces.

n	L5	H2	MDC	MC13	S14	C8	VB12	AV-OLD	AV-NEW
1	29.16	33.15	30.60	31.97	30.37	30.60	29.65	30.61	31.14
2	20.08	23.40	21.51	22.55	22.20	21.97	20.71	21.67	21.98
3	21.17	25.67	23.47	24.77	25.44	24.81	22.36	23.95	24.13
4	24.54	30.62	28.00	29.88	31.76	30.49	26.58	28.83	29.04
5	26.45	32.77	30.31	32.91	35.01	33.26	29.18	30.89	31.73
6	25.73	31.02	29.19	32.40	33.68	31.87	28.83	29.05	30.88
7	24.86	29.31	28.06	31.91	32.09	30.44	28.50	27.25	30.03
8	25.76	29.21	28.53	33.23	30.84	29.94	30.13	26.71	30.84
9	27.87	28.43	28.56	33.74	26.76	27.32	32.19	25.22	30.84
10	28.68	24.69	25.48	30.07	20.33	21.77	31.09	21.10	27.17
11	26.70	19.74	20.63	24.15	15.06	16.50	26.70	16.50	21.73
12	23.60	15.91	16.65	19.36	11.78	13.01	22.21	13.15	17.41
13	21.16	13.41	13.99	16.15	9.72	10.79	18.97	11.04	14.55
14	19.35	11.56	12.01	13.71	8.20	9.14	16.43	9.46	12.40
15	17.40	9.90	10.73	11.55	6.94	7.73	13.98	8.69	10.49
16	15.08	8.42	8.65	–	5.93	–	11.69	7.39	9.10

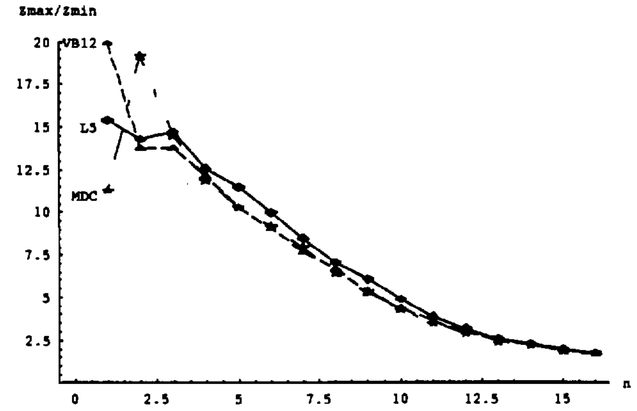

FIG. 4. Ratio of Z_{max} to $Z_{min\text{-}av}$ at each harmonic, n, for three mouthpieces, where $Z_{min\text{-}av}$ is the mean of the Z_{min}s on either side of each Z_{max} impedance peak.

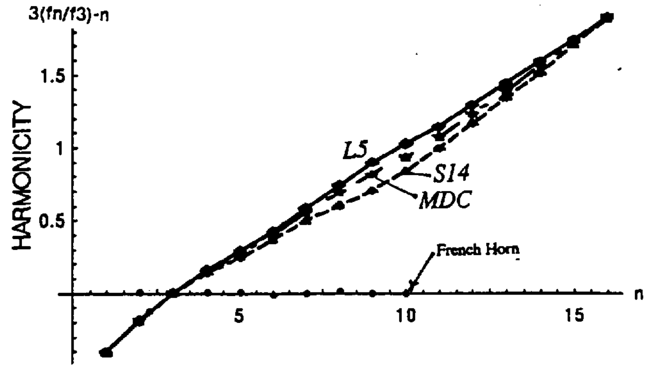

FIG. 6. Frequency deviation from integer values, defined by the third harmonic, for three mouthpieces. The points along the axis are the frequency deviations for the L5 when inserted into a French horn.

mouthpieces. The Q_n plot shows some degree of separation between mouthpieces in the high range.

Figure 6 presents the harmonicity, defined relative to the third harmonic as $3(f_n/f_3)-n$ for three mouthpieces on the tube system and for a Lawson French horn for comparison. The extensive stretching of the harmonics of the experimental system compared to the French horn is quite obvious. More subtle, but readily discernible, are the variations among mouthpieces over the playing range of our system.

Figure 7 is $(Z_{max}(n)/Z_{min\text{-}av}(n))/Q_n$ vs n for three of the mouthpieces, constructed from computer model impedance graphs. Although it has been stated[17] that, for any peak, $Z_{max}=Z_0{*}Q$ and $Z_{min}=Z_0/Q$, which implies (Z_{max}/Z_{min}) is related to Q, it is overly simplistic to assume that this ratio is exactly equal to Q^2, even for uncomplicated high Q transmission lines. (The assumption behind the assertion of equivalence seems to be that since the maximum and minimum magnitude of impedance are directly related to the SWR defined by incident and reflected signals, and since Q is the ratio of the maximum energy to the energy dissipated, it should always equal to the SWR.) Although Z_{max}/Z_{min} and Q are both determined by internal geometry and system losses, Fig. 7 indicates that the precise manner in which they vary is somewhat different. (Since Fig. 7 is constructed from computer model data, other subtle effects, such as interior shape, smoothness, the number and magnitude of discontinuities, and wall material, which also might separately influence Z_{max}/Z_{min} and Q are not present.) We can further observe that this ratio shows considerable variation among mouthpieces.

Table V lists the V_c/BBL and its percent deviation from the mean value for later consideration. Since it is widely assumed[23] that all brass instrument mouthpieces in isolation (when sealed at the rim), act as internally driven Helmholtz resonators, we calculated the following term:

$$f_r^2=V_c/(C{*}S_{th}/L),$$

where f_r is the mouthpiece's measured[15] resonant frequency, V_c is the cup volume, S_{th} is the area of the throat, and (as a reasonable approximation) $L=THL+BBL+0.6a$, where $2a$ is the end diameter of the backbore (BBED), and C is a constant. For a Helmholtz resonator, the above term is equal to 1.00. Using data from Tables III and V, our results indicate that the mouthpieces show considerable deviation from the ideal Helmholtz resonator, as indicated by the percent differences, even though there is only a 10% variation in resonant frequency among the mouthpieces studied.

V. OBSERVED PSYCHOACOUSTIC/ACOUSTIC CORELATIONS

It has been asserted[20] that the qualities of ease of playing, clear speech, and good intonation for brass instrument

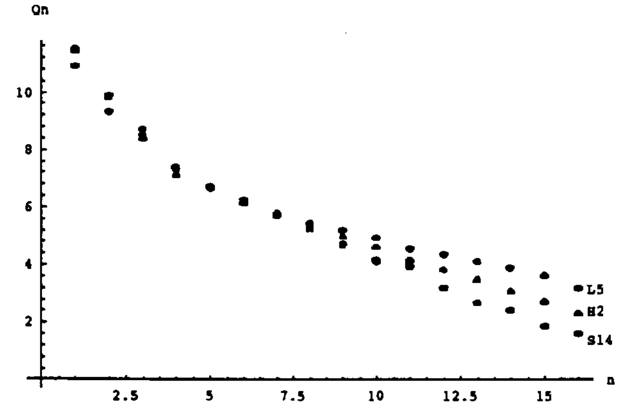

FIG. 5. Quality factor, Q_n, at each harmonic, n, for three mouthpieces.

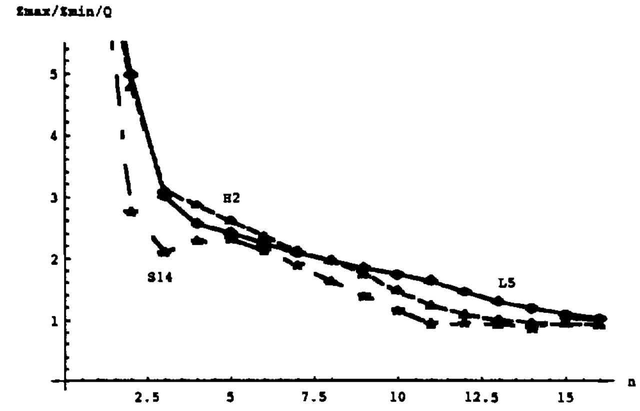

FIG. 7. Ratio of $Z_{max}(n)/Z_{min\text{-}av}(n)/Q_n$ at each harmonic, n, for three mouthpieces.

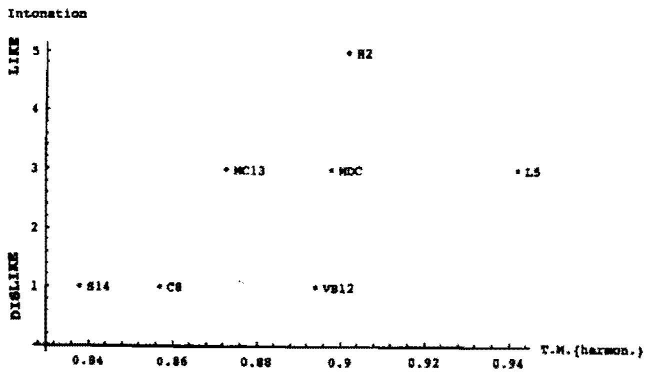

FIG. 12. Player preference for each of playing versus trimmed mean of harmonicity.

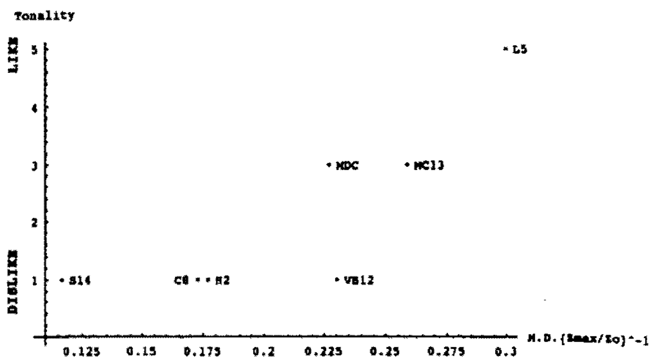

FIG. 13. Player preference for tonality versus median deviation of $\{Z/_{\max}/Z_0\}^{-1}$.

sion of these figures follows. Figure 9 indicates that the higher the "harmonic mean" of $Z_{\max}(n)/Z_{\text{min-av}}(n)$ for the partials of the experimentally determined impedance plot for each mouthpiece, the more the mouthpiece is liked for flexibility. Two notable exceptions are the MC13 which, despite its high numerical ranking was disliked, and the MDC which was liked even though its harmonic mean was quite low. For the MC13 this was undoubtedly due to its high mean characteristic impedance Z_c. (Since our data indicate that this quantity is somewhat frequency dependent, we have averaged it over all impedance peaks for each mouthpiece and recorded the results in Table IX.) The high mean Z_c indicates that it will be more difficult for the performer to slip between adjacent impedance peaks; consequently this mouthpiece will not be preferred despite the high mean $Z_{\max}(n)/Z_{\text{min-av}}(n)$. For a similar reason the VB12 is not preferred. The MDC, on the other hand, has quite a low mean Z_c, which tends to raise its flexibility preference even though the mean $Z_{\max}(n)/Z_{\text{min-av}}(n)$ is also relatively low.

Figure 10 demonstrates that although the mean Q_n ranks the mouthpieces in an approximately correct order, the correlation with "pitch control" shows a definite trend; mouthpieces with higher mean Q_n tend to be better liked. The correlation discrepancy for the pitch control parameter may be explained by considering that the perception of pitch as sensed by the player is not merely the aural feedback to his ear, but also includes how strongly the note "locks in." It would seem, then, that three factors should be important: Q_n, $Z_{\max}$, and the s.d. of $Z_{\max}$ (which is related to "tonality," i.e., the evenness of the spectral envelope). Since both the H2 and the C8 are mouthpieces with a relatively low $Z_{\max}$ and uneven spectral envelope, it is perhaps not unreasonable that they were rated poorly for "pitch control" despite their relatively high mean Q_n. If we consider, for each mouthpiece, the product of the mean Q_n and the inverse median deviation of $Z_{\max}/Z_0$ of Part E (which quantifies the unevenness of the spectral envelope), the mouthpieces are clearly ordered into three clusters which agree exactly with the "pitch control" grouping.

Figure 11 shows that "ease of playing" correlates reasonably well with the "trimmed mean" of $Z_{\max}(n)/Z_{\text{min-av}}(n)/Q_n$. (The trimmed mean is the mean of the above ratio with the first six harmonics deleted. This is desirable since the important variations between mouthpieces occur in the middle and upper frequency ranges.) That the MDC is more preferred than this ratio would indicate, and the H2 less preferred, is probably due to the surprisingly good start-up accuracy for the MDC and the unusually bad start-up accuracy exhibited by the H2.

Figure 12 indicates that the assumed correlation between "intonation" and "trimmed mean harmonicity" is less than perfect. (The trimmed mean harmonicity is the mean harmonicity without the first three or the last two partials, thus better emphasizing the differences between means.) Nevertheless, this acoustic variable orders the mouthpieces, with the exception of H2, into approximately the same basic arrangement as the preference test. Since the most preferred mouthpiece occupies an intermediate position in a harmonicity plot (such as Fig. 6), we next investigated the deviation from a least squares linear fit to the harmonicity versus mode number by calculating the rms deviation from the least squares fit for each mouthpiece. The data, incorporated into Table IX, indicate that, in general, the neutral mouthpieces show lower rms deviation while the deviation is greater for nonpreferred mouthpieces. Again, the obvious exception is the H2, with a fairly high rms deviation, but the most preferred mouthpiece for intonation. Perhaps this high deviation is offset by the decreased prominence of the higher mode peak amplitudes (see Table VIII).

Figure 13 shows that the inverse "median deviation" of $Z_{\max}(n)/Z_0$ correlates reasonably well with "tonality." That is, the more preferred mouthpieces have the lowest deviation

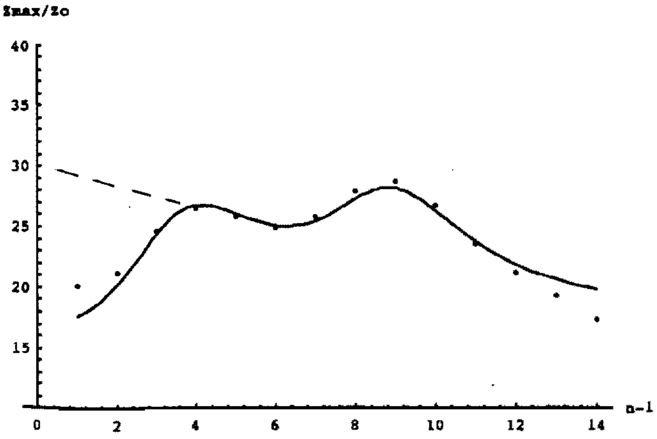

FIG. 14. Spectral envelope for L5.

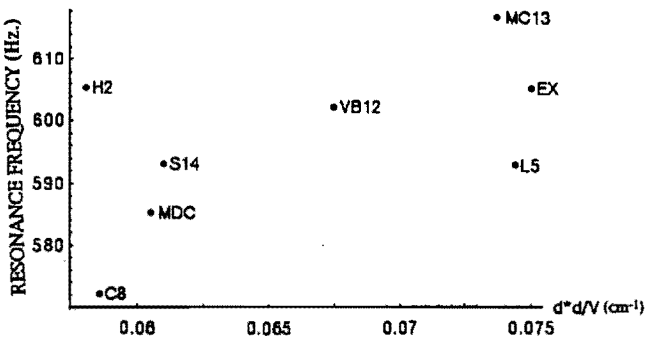

FIG. 8. Resonance frequency versus throat diameter squared divided by cup volume for eight mouthpieces.

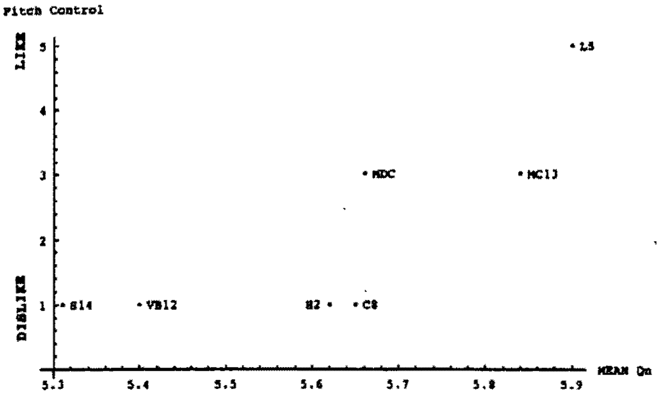

FIG. 10. Player preference for pitch control versus mean Q_n.

mouthpieces are all dominated by the relationship of total mouthpiece volume and resonance frequency. Defining a mouthpiece equivalent length at the resonance frequency as $L_{e1}=c/4^*f_r$ and defining the low frequency equivalent length, L_{e2}, as that which matches the total volume of the mouthpiece, we might expect the ratio of L_{e1}/L_{e2} to be relatively constant for all French horn mouthpieces. Our tabulated results (Table V) indicate that this is not the case, although the deviations are not, for the most part, severe. It has also been widely reported[1,23] that mouthpiece resonance frequencies are carefully chosen by adjusting cup volume and throat diameter to match the mouthpiece impedance to the instrument. It would thus seem that the ratio of throat diameter squared to cup volume, V_c, if not constant, should, at least, correlate with the mouthpiece resonance frequency. Using the tabulated d^2/V_c and f_r of Table V, we constructed Fig. 8, which indicates no apparent correlation, although it does tend to separate the mouthpieces into groups.

Comparing Figs. 3–7 to Table VI we see that, although the mouthpieces can be separated, in this form correlations with criteria of Table VII are not immediately obvious, although subtle trends are apparent. For example, in Fig. 5, the mouthpiece most preferred for pitch control clearly has the highest Q_n values. Likewise, Fig. 7 suggests that the $(Z_{\max}(n)/Z_{\text{min-av}}(n))/Q_n$ correlates with ease of playing since the more preferred mouthpieces maintain a higher ratio throughout the mid-frequency range. Figure 6 is somewhat more difficult to relate to intonation as the preferred mouthpieces are those which appear toward the center of the deviations, i.e., those with partials not stretched too much or too little (considering that they are all severely stretched by this system).

The evenness of the spectral envelope of Fig. 3 should correlate to the preferred tonality. It is apparent that L5, having lower amplitude peaks at low frequencies and higher amplitude peaks at higher frequencies, is the most even, and consequently the most preferred, mouthpiece for this criterion, under this subjective evaluation. The MC13 and MDC, which were rated neutral, have similar spectral envelopes, which are lacking somewhat in the mid-frequency range. The least preferred mouthpieces are those with high amplitude peaks at low frequencies, but which fall off rapidly at high frequencies.

No obvious correlation for the player's preference for dynamic range and attack clarity could be found with the suggested physical correlates. Indeed, an examination of the V_c/BBL data of Table V indicates that this ratio is neither extremely important, nor particularly constant.

To better compare the acoustic and psycho-acoustic parameters, we next expressed the acoustic correlates in a more quantitative, but less easily visualized, form by averaging the appropriate variable over the impedance peaks of each mouthpiece. Although this procedure may gloss over some of the fine details, it is an effective way to rank the mouthpieces so that the acoustic correlates may be objectively related to the psychoacoustic variables. This has been presented as Figs. 9 through 14, where the preferences of Table VI have been plotted versus the appropriate correlate for six acoustic parameters. (We did not include "attack clarity" because of the obvious lack of correlation.) A brief discus-

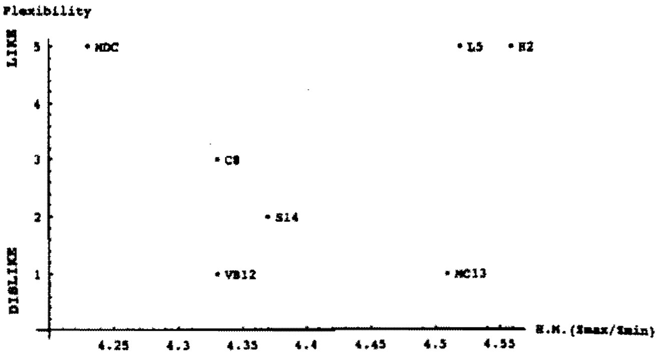

FIG. 9. Player preference for flexibility versus harmonic mean of $Z_{\max}/Z_{\min}$.

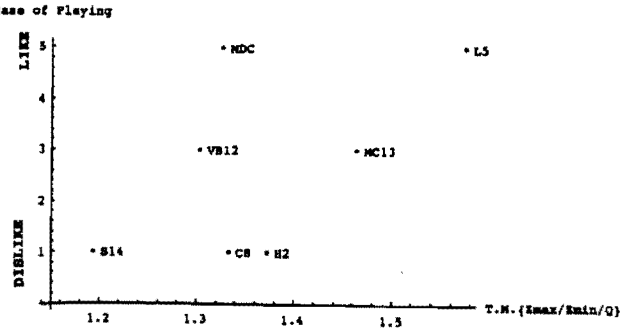

FIG. 11. Player preference for ease if playing versus trimmed mean of $Z_{\max}/Z_{\min}/Q_n$.

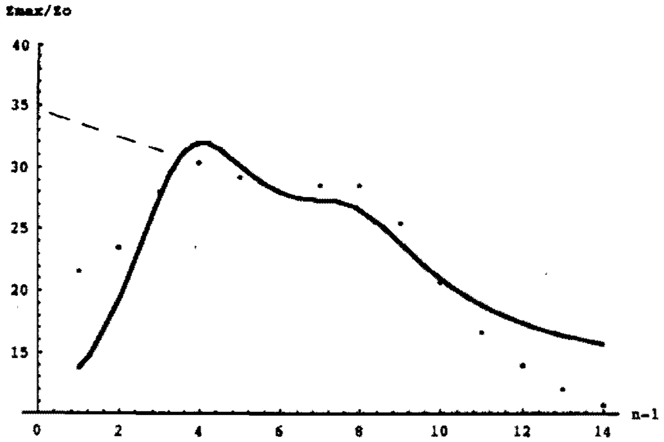

FIG. 17. Spectral envelope for MDC.

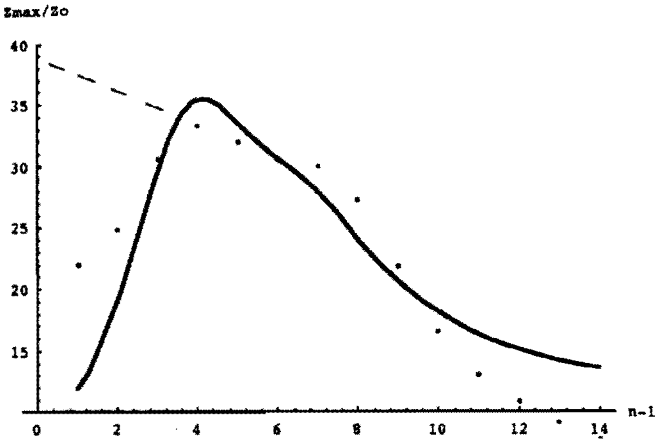

FIG. 19. Spectral envelope for C8.

lation between the z-intercept and musician's preference for tonality. Although the VB12 mouthpiece has a low Z-intercept, and therefore should have a high musician preference rating, it was disliked. This is most likely due to its strong fifth harmonic which is seriously out of tune; the "bad" intonation of one of the horn's most important harmonics ruins the otherwise excellent tonality.

Finally, the dynamic range, as summarized by the "geometric mean" of $Z_{\max}(n)/Z_0$, is presented in Fig. 22. (The geometric mean is preferred for this average because it tends to treat linear data logarithmically, which more closely approximates the manner in which this variable will be perceived.) Although the "not-preferred" mouthpieces are readily separated by their low ratio, the neutral and preferred ones cannot be separated by this variable alone. Including "harmonicity," however, helps to explain some of the discrepancies. The rms of the deviation from a linear least squares fit to the harmonicity curve for each mouthpiece shows that the L5 is at the extreme low end (least deviation), while the S14 has the greatest deviation. The H2 plots at the mid-point of the range, thus confirming our suspicion that for the test system musicians, seem to prefer this design. Perhaps a greater stretching of the harmonics is preferred for tonality, but less support for fortissimo playing is then present, thus yielding a lower preference rating for dynamic range.

VI. CONSOLIDATED PSYCHO-ACOUSTIC PARAMETERS

Since the above results indicated that there is not a one-to-one correspondence between acoustic and psycho-acoustic variables, we next investigated correlations between one of the most significant variables, $Z_{\max}(n)$, and a consolidated set of psycho-acoustic parameters. Aside from intonation, which correlates with harmonicity, but which is difficult to access on our system, we redefined the psycho-acoustic variables as follows. "*Playability*" was defined as a combination of *dynamic range, ease of playing*, and *flexibility*, while "*tonal responsiveness*" was defined as a combination of *tonality, attack clarity*, and *pitch control.*[24] Mr. Landgren was then asked to order the mouthpieces by preference according to these two criteria only, a choice rendered considerably easier by the reduced number of variables. Two additional mouthpieces were also added for his consideration. These were specially constructed mouthpieces with respective physical dimensions of the mean of the 61 mouthpieces of Table I (called AV-OLD) and the mean of the seven mouthpieces of Table III widely used today (called AV-NEW). Geometrical data on these mouthpieces have been included in Table III and the last two columns of Table VIII list their $Z_{\max}/Z_0$.

In an attempt to correlate the psycho-acoustic data with the acoustical analysis, we next found the mean $Z_{\max}/Z_0$ over

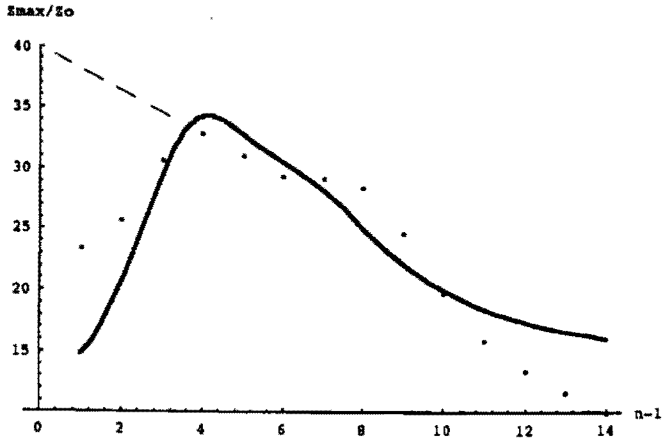

FIG. 18. Spectral envelope for H2.

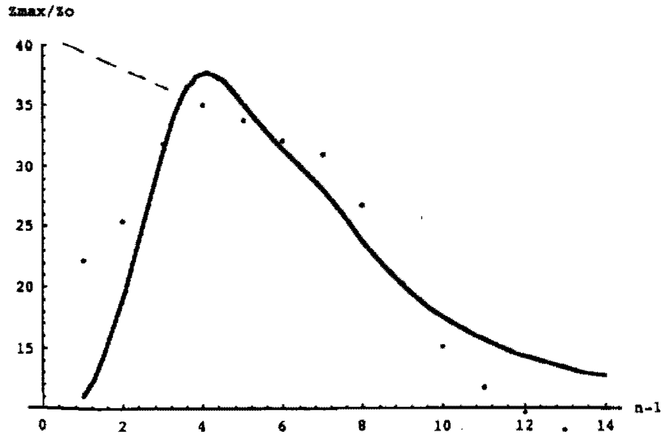

FIG. 20. Spectral envelope for S14.

TABLE IX. Computed quantities.

	L5	H2	MDC	MC13	S14	C8	VB12
Mean Z_c^2	59.59	54.73	53.32	72.03	54.40	54.07	71.53
Z_c^2 Stndrd. Deviat.	30.38	25.93	26.15	37.97	32.02	28.00	36.03
1.s. fit {harm}							
slope	0.148	0.150	0.147	0.140	0.143	0.141	0.143
y-inter.	−0.473	−0.509	−0.495	−0.461	−0.504	−0.482	−0.467
rms dev.	0.0282	0.0435	0.0392	0.0370	0.0584	0.0437	0.0352
Mean Z_{hi}	23.54	17.66	18.29	21.25	14.11	15.18	23.08
Mean Z_{lo}	24.72	29.39	27.46	29.95	30.21	29.17	26.99
Z_{hi}/Z_{lo}	0.952	0.601	0.666	0.710	0.467	0.521	0.855
C	16.78	13.50	12.17	12.69	8.67	9.91	14.91
$A(1)$	186.4	396.5	375.6	409.6	548.0	476.9	264.5
$A(2)$	176.4	115.7	153.7	237.6	126.5	133.0	242.2
$A(2)/A(1)$	0.943	0.292	0.410	0.581	0.231	0.279	0.917
Z-intercept	29.9	39.8	34.9	34.7	41.1	39.3	30.5
Q_n	5.90	5.62	5.66	5.84	5.31	5.65	5.40

and vice versa. The single exception is the VB12, which is seen to have relatively strong fifth and seventh harmonics. Since these harmonics are seriously out of tune on any natural system, they will add a strident quality to any tone played loudly. The VB12, which was rated poorly for harmonicity, is probably not preferred for tonality for precisely this reason. Table IX indicates that the mouthpieces may be similarly ordered by the ratio of the mean $Z_{\max}(n)/Z_0$ at high frequencies (impedance peaks 9–15) to the mean $Z_{\max}(n)/Z_0$ at low frequencies (the first eight impedance peaks). That is, the preferred mouthpieces have relatively high amplitude impedance peaks at high frequencies.

Following Pratt and Bowsher[5] we next investigated the nature of the spectral envelope in more detail in an attempt to identify other possible objective correlates to tonality. A visual inspection of the envelopes indicated that for most mouthpieces there seemed to be two formantlike peaks, one around the fifth partial, and one around the ninth or tenth partial. Consequently, a least squares analysis was performed to fit the impedance peaks of Table VIII by a curve having the form

$$Z(f)=C+A_1/[R+(f^2-f_1^2)^2f^{-2}]$$
$$+A_2/[R+(f^2-f_2^2)^2f^{-2}],$$

where A_1, A_2, and C are constants determined by the least squares analysis, R is a resistance term, f is the frequency, and f_1 and f_2 are the first and second "formant" peak frequencies. Figures 14 through 20 present these curves for the seven mouthpieces studied (the first impedance peak has not been included in this analysis because it is severely out of tune and seldom used) in order of decreasing importance of the second "formant." The constants A_1, A_2, and C, as determined for each mouthpiece, have been incorporated into Table IX. If the "formant" amplitude terms (A_1 and A_2) are divided, this ratio orders the mouthpieces correctly (with VB12 being the lone exception) for tonality from liked to disliked (compare Fig. 13), thus confirming the importance of the spectral envelope shape to tone quality.

To investigate the suggestion[7] that the impedance-axis intercept (defined by $n=1$ in this case) of the linear fit to the negative sloped portion of the spectral envelope (defined by peaks 5, 6, and 7, the mid-range of a horn) relates to tonality, we recorded this quantity in Table IX as the Z-intercept. Except for VB12, this quantity very clearly separates the mouthpieces into three groups. Preferred mouthpieces have an intercept value of about 30, neutral mouthpieces about 35, and unpreferred about 40. Figure 21 shows the strong corre-

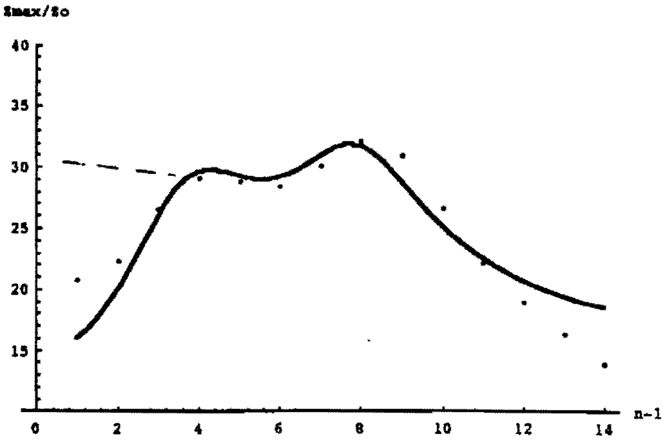

FIG. 15. Spectral envelope for VB12.

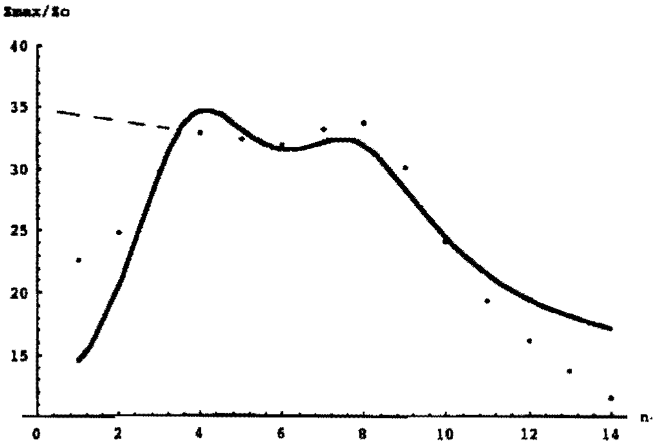

FIG. 16. Spectral envelope for MC13.

and because the mouthpiece is an easily changeable component of a wind instrument, our study was limited to a comparison of the acoustic and musical differences between various French horn mouthpiece designs attached to a "simplified" horn.

In addition to harmonicity, six other acoustic parameters, determined by geometry, were analyzed for possible correlations with psycho-acoustic factors measured by musicians' comparative evaluation testing. Although most of the correlations were reasonably good for the majority of the mouthpieces, the exceptions made it obvious that these parameters could not always be isolated and that searching for a one-to-one correspondence between psycho-acoustic and acoustic variables was counterproductive if not futile. The most important acoustic parameters seemed to be the impedance peak amplitudes, the Q_n and the overall shape of the spectral envelope. In an attempt to simplify the analysis and to include the cross correlations, we focused on the acoustic parameters $Z_{\max}(n)$. The psycho-acoustic variables were correspondingly condensed into two broad categories termed "playability" and "tonal responsiveness." Plotting the mean $Z_{\max}$ (averaged over 16 harmonics) versus standard deviation for each of the eight mouthpieces separated them into different quadrants. This correlated reasonably well with psycho-acoustic preference domains defined by the two new variables used as coordinates. Players tended to prefer mouthpiece designs which had relatively high average peak amplitudes, but coincident low variability of harmonic peaks.

Based on our documented changes in the ratio of French horn mouthpiece cup length to throat plus backbore length during the course of the twentieth century, we compared the acoustical properties of modern designs to the older versions. Our results clearly show that the average harmonics' peak amplitude ($Z_{\max}$) has increased while variability has simultaneously decreased, resulting in a more even envelope. Also, the average values of Q_n have increased, a probable explanation for the longer measured decay times. The higher Q_n values may also be associated with musicians' expressed preference for greater pitch control.

Our experiments indicate that the equivalent length concept for brass mouthpieces is an outmoded notion which is too simplistic to be accurate or useful. It has also been widely assumed that brass instrument mouthpieces can be accurately represented as Helmholtz resonators, and that the performance of a given mouthpiece is dependent upon the cup volume and throat diameter, the shape being a much less important variable.[26] Our experimental results indicate that, for the French horn, the opposite is more nearly true. Although useful as a first approximation, the Helmholtz resonator description is clearly inadequate as an accurate characterization of French horn mouthpieces. We hypothesize that it will be an equally ineffectual representation for the mouthpieces of other members of the brass instrument family.

In so far as a "consensus" mouthpiece may be identified, the AV-NEW design comes closest to being acceptable for use on a wide variety of horns in different circumstances by professional musicians. It is also interesting to note that the one mouthpiece consistently chosen in most preference categories was the L5, whose dimensions are closer to those of AV-NEW than any of the other mouthpieces in common use today.

Although we have shown that subjective judgments may be correlated to acoustic parameters derived from geometry, further investigation is needed. Future research could be directed toward more elaborate and/or more extensive player sampling data and techniques. We have determined three acoustic variables, $Z_{\max}(n)/Z_0$, Q_n, and the spectral envelope, to be particularly relevant. It is interesting to note that an important attribute of well-trained singers is the ability to maintain a uniform spectrum over wide ranges of frequency and amplitude;[27] this corresponds to our observation that a uniform spectral envelope is one of the most important characteristics of the most highly rated French horn mouthpieces.

No attempt has been made to consider how the shape of the mouthpiece may influence musician's subjective evaluations or to include, as an objective parameter, turbulence and/or vorticity as a function of shape during performance. Although it is known[7] that dc airflow will reduce the Q's of impedance maxima, thus changing the input impedance under actual playing conditions, we did not consider this effect at this time. In addition, since the sensations perceived by a performer may change as the dynamic level is varied, the selected preference variable may deviate in a corresponding manner. Clearly, there is considerable work remaining to be enacted before the intricate association between subjective qualities and the geometry of brass instruments is fully comprehended.

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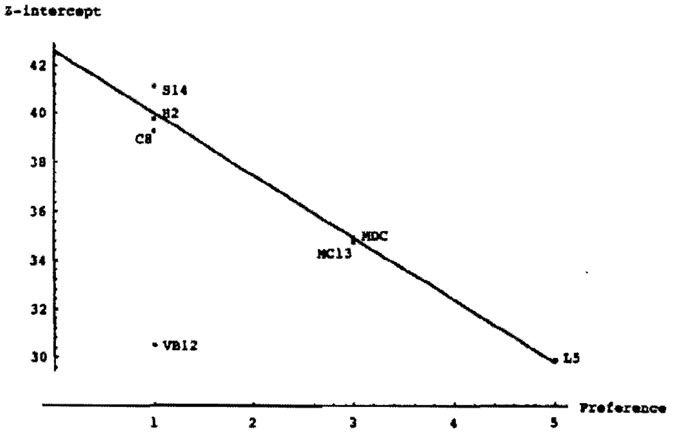

FIG. 21. Z-intercept versus musician preference for tonality.

16 harmonics, as well as the standard deviations, for each mouthpiece. A plot of the means versus standard deviations tends to separate the mouthpieces into different quadrants, as can be seen in Fig. 23, where the axes shown are the respective mean values for $Z_{\max}/Z_0$ and the standard deviation. Each quadrant may be considered as a different psychoacoustic preference domain as indicated by plotting the mouthpieces according to the consolidated criteria of playability versus tonal responsiveness, as shown in Fig. 24. Comparing Figs. 23 and 24 we see that the ordering of the mouthpieces is similar and this two-dimensional representation is more informative. Perhaps an even more accurate correlation may be obtained if the vibrational characteristics of the player's lips were incorporated, since the input impedance function alone does not adequately represent the dynamics of a player sounding the instrument. Also, it is a generally accepted truth among performers that mouthpieces tend to perform differently at different dynamics levels.

The French Horn is part of a complicated "input–output system" which includes the player's buzzing lips (the input signal) and a transfer function which relates the input to the output signal.[25] We have documented many combinations of acoustic parameters which we had hoped would help define this transfer function as well as relate geometrical and acoustical parameters to musician's perceptions. While a reasonably good correlation between the consolidated parameters and the musician's ratings was obtained, it is still unknown exactly how these variables relate to the transfer function.

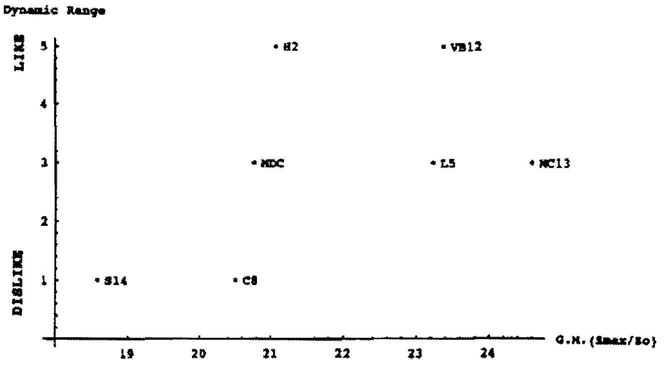

FIG. 22. Player preference for dynamic range versus geometric mean of $\{Z_{\max}/Z_0\}$.

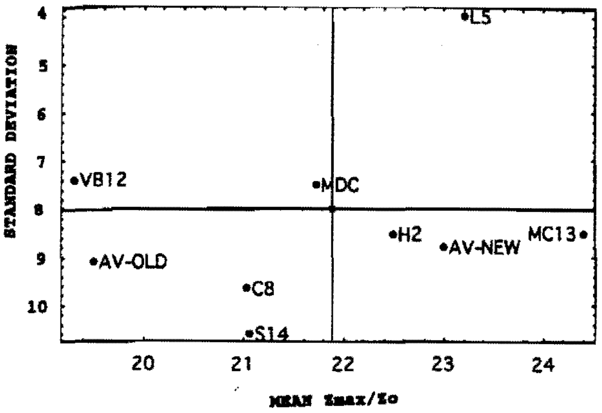

FIG. 23. Mean $Z_{\max}/Z_0$ versus standard deviation for nine mouthpieces.

Once the input signal characteristics and its transform become known it should be obvious why many of the various combinations of the impedance curves did not correlate well. Therefore we believe that in order to derive a complete understanding of the entire IO mapping system once all parameters are known, all combinations will have to be included. Although the correlations of individual parameters were not as strong as expected, we discussed the correlations in some depth because we believe the data contain important information which may be useful to future researchers. Additionally, our complete and careful documentation of the relationships between the geometric and acoustic parameter correlations will insure that future improvements can be realized quickly and easily once the entire system is mapped.

VII. CONCLUSIONS

A fundamental acoustic characteristic of well-designed brass wind instruments is that as many of the input impedance peaks as feasible should be harmonically related. This characteristic, which is interpreted by musicians as the intonation of the instrument, can be easily gauged from the input impedance function. Our investigation of the French horn was predicated on the assumption that other psycho-acoustic parameters, at least as important as intonation, may correlate with acoustic data or geometric factors. Since the mouthpiece is considered by musicians to be the single most important component regarding how the entire horn performs,

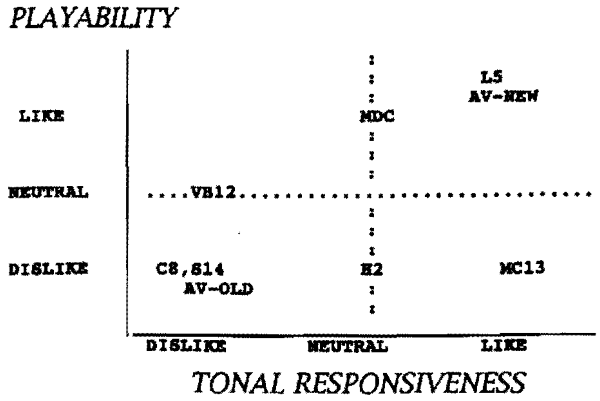

FIG. 24. Results of the two variable psychoacoustic criteria judgment test.

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