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Perturbations of Synthetic Orchestral Wind-Instrument Tones

William Strong*

Air Force Cambridge Research Laboratories, Bedford, Massachusetts 01730

Melville Clark, Jr.

Melville Clark Associates, Cochituate, Massachusetts 01763

The relative significance of spectral and temporal envelopes for the synthesis of orchestral wind-instrument tones was evaluated by exchange of spectral and temporal envelopes among the wind instruments, by creation of artificial spectral envelopes, and by perturbation of the spectral envelopes. It was found that, for the oboe, clarinet, bassoon, tuba, and trumpet, where the spectral envelope is unique as regards the frequency of its maximum and the range in which the instrument is normally played, this envelope predominates in aural significance over the temporal envelope. Where the spectral envelope is not unique—as for the flute, trombone, and French horn—the spectral envelope is equal or subordinate to the temporal one in aural significance. Interfamily confusions are fewer in those cases where the spectral envelope is of predominant importance: about 14% for the clarinet, oboe, bassoon, and tuba and about 25% for the flute, trumpet, trombone, and French horn. The ratio between identification probabilities of synthetic and natural tones is 0.97 for the oboe, 0.90 for the clarinet, 0.86 for the French horn, 0.82 for the bassoon, 0.77 for the flute, 0.75 for the trumpet, 0.69 for the tuba, and 0.62 for the trombone.

INTRODUCTION

The effects of spectral envelopes and temporal envelopes on the identification of tones simulating various orchestral wind instruments is the subject of the present work. This paper may be regarded as a sequel to a former one,[1] and we assume that the reader is familiar with it.

The earlier paper described the method used here for synthesizing tones of nine wind instruments. The method of evaluating the quality of the synthetic tones and the results of this evaluation were presented.

In order to assess the significance of some of the features used in the characterization of the synthetic tones, we perturbed and permuted the spectral and temporal envelopes. The identification of instruments under these distortions was examined to determine whether the auditor identifies an instrument on the basis of its spectral or temporal envelope.

The spectral envelopes of several instruments were also perturbed without alteration of the temporal envelopes to assess the auditory significance of various features of the spectral envelope.

I. EXPERIMENTAL PROCEDURE

There were two types of presentations to auditors. In the first, musically literate auditors attempted to identify the instrument being simulated from the perturbed tones. They were required to name one of the following instruments: trumpet, tombone, tuba, French horn, oboe, English horn, bassoon, flute, clarinet. The relative significance of the temporal and spectral envelopes was then assessed by the response of the auditors to the perturbed tones as compared with their responses to the unperturbed synthetic tones discussed in Table II in the previous paper.[1] These unperturbed tones were based on the temporal and spectral envelopes of the actual, respective instruments.

Among the nine wind instruments studied, there are three basic types of temporal envelopes:

(1) A slow-rising envelope with a large amount of amplitude and waveform modulation. This type is characteristic of the flute.

(2) An envelope having a very short rise time and a smooth, monotonic rise with time. This type is char-

* Present address: Physics Department, Brigham Young University, Provo, Utah 84601.

[1] W. Strong and M. Clark, J. Acoust. Soc. Am. 41, 39–52 (1967).

TABLE I. Probability (in percent) of naming tone presented as tone of instrument listed, with various combinations of spectral and temporal envelopes.

Synthesized tone presented: Spectral envelope	Temporal envelope	Trumpet	Trombone	Tuba	Horn	Oboe	English horn	Bassoon	Flute	Clarinet
Trumpet	Trumpet	71	2			10	10			6
	Flute	46				29	8	2	8	6
	Bassoon	58				19	21			2
	Oboe	34			2	19	27		6	12
Trombone	Trombone	6	59		10		12	10		
	Flute	8	17	2	8		25	19	19	2
	Bassoon	8	36	4	10		15	19	6	2
Tuba	Tuba		3	61	20			14		2
	Flute		8	71	8			2	6	4
	Bassoon		10	59	21			10		
French horn	French horn		13	6	54		2	19	6	
	Flute		4	2	25		6	29	31	2
	Bassoon		4		36		12	48		
Oboe	Oboe	2	2			73	13		2	9
	Flute	2				77	10			10
	Trombone	15				71	6			8
English horn	English horn	23	10		6	4	42	2	2	8
	Flute	10			8	2	46		19	15
	Trombone	29			4	6	40		2	19
Bassoon	Bassoon		6	8			21	65		
	Flute		6				8	83	2	
	Trombone		8	2			12	77		
Flute	Flute	15	2			2	4		77	
	Bassoon	36			4	4	17		27	12
	Trombone	54	8		6		8		21	2
Clarinet	Clarinet	3				5	3		2	88
	Flute	2				8	2		4	83
	Bassoon	4				8			4	83
	Trombone	8					2		2	88

acteristic of the double reeds, and of the brasses in the higher parts of their ranges.

(3) An envelope having a slightly longer rise time than that in 2, above, and exhibiting during the rise one or more blips, nonmonotonic modulations with time. This type is characteristic of all brasses, especially in the lower parts of their respective ranges.

Accordingly, tones were synthesized with the following envelopes:

- For the *flute* temporal envelope: trumpet, trombone, tuba, French horn, oboe, English horn, bassoon, and clarinet spectral envelopes.
- For the *bassoon* temporal envelope: trumpet, trombone, tuba, French horn, flute, and clarinet spectral envelopes.
- For the *oboe* temporal envelope: trumpet spectral envelope.
- For the *trombone* temporal envelope: oboe, English horn, bassoon, flute, and clarinet spectral envelopes.

In the second type of presentation, auditors, presented with pairs of synthetic tones, were asked to identify the instrument in each pair and to indicate whether the tones were the same or different. If the tones were judged to be different, the subject was required to indicate whether the first or second tone of the pair was the more natural (even though neither tone in any pair was natural, a point unknown to the subjects). The purpose of this experiment was to provide some indication of the direction in which more-natural-sounding tones may be created.

The subjects and other details of the experimental procedure were described in the earlier paper.[1]

II. RESULTS OF SINGLE-TONE PRESENTATIONS

A. Spectral and Temporal Envelopes Interchanged among Instruments

The first type of presentation was designed to determine the relative auditory significance of spectral versus temporal envelopes in controlling the timbre of various instruments. The results of this presentation

TABLE II. Probability (in percent) of naming instrument listed with various combinations of spectral and temporal envelopes for the oboe, for various note frequencies (in cycles per second).

Frequency	Trumpet	Trombone	Oboe	English horn	Bassoon	Flute	Clarinet
(a) No second peak in oboe spectral envelope, oboe temporal envelope							
232			25	63	12		
292			38	62			
370			38	62			
466	12		75	13			
593	12		75	13			
747	12		75	13			
931	25		12			13	50
Average	9		48	32	2	2	7
(b) No valley in oboe spectral envelope, oboe temporal envelope							
232	38	12	25	25			
292	12		63	25			
370	12		63	25			
466	25		63	12			
593	25		63				12
747	25		63				12
931	37		38				25
Average	25	2	54	12			7
(c) Oboe spectral envelope, trumpet temporal envelope							
212			63	37			
277			63	37			
350			75	25			
442	12		75	13			
551	12		88				
712	50		25				25
881	37		13				50
Average	16		57	16			11
(d) No valley in oboe spectral envelope, trumpet temporal envelope							
212	12	12	13	63			
277	63	12	25				
350	63		12	25			
442	75		25				
551	63		25	12			
712	75		13				13
881	88		12				
Average	62	3	18	14			2
(e) Oboe spectral envelope, oboe temporal envelope							
232		12	38	50			
292			88	12			
370			100				
466			100				
593			75	13		12	
747	12		63	13			12
931			50				50
Average	2	2	73	13		2	9

are displayed in Tables I and II. Table I summarizes the probabilities of naming the instruments listed as the sources of the tones synthesized with various combinations of spectral and temporal envelopes, averaged over all note frequencies generated.

Generally, the probabilities are greatest for naming a particular instrument if the temporal and spectral envelopes from an actual instrument are used simultaneously. As a rule, combining the spectral envelope of one instrument with the temporal envelope of another instrument reduces the probability of naming a particular instrument.

Use of a flute temporal envelope on a trumpet spectral envelope increases the probability of naming the oboe (especially) and of naming the flute (somewhat). Use of a bassoon or oboe temporal envelope on a trumpet spectral envelope substantially enhances the probability of naming a (high) double reed. The oboe temporal envelope also increases the chances of citing the flute or clarinet as the instrument producing the tone.

The results for the trombone spectral envelope are similar to those for the trumpet. Use of a flute or bassoon temporal envelope increases the chances of naming an English horn or bassoon (low double reeds), and the flute. There is the usual confusion with the French horn using trombone spectral envelopes; the confusion does not seem to be altered materially by use of a flute or bassoon temporal envelope.

As in the case for the trombone spectral envelope, the tuba spectral envelope caused the French horn as well as the tuba to be named as the tonal source, and the confusion with the horn was unaltered by the use of foreign temporal envelopes. Use of a flute temporal envelope with a tuba spectral envelope led to a greater probability of naming the tuba than the use of a tuba temporal envelope, and yielded less confusion with the bassoon. The bassoon was named about as often with the tuba spectral envelope whether a tuba or bassoon temporal envelope was used.

Identification of French horn tones was considerably impaired by use of temporal envelopes foreign to the spectral envelope. Both flute and bassoon temporal envelopes increased the probability of naming the bassoon or English horn as the source of the signals. The flute temporal envelope greatly increased the probability of naming the flute as the instrument producing the tone. Use of foreign envelopes reduced the confusion with the trombone.

We turn now to the spectral envelopes for the woodwind instruments. The probability of naming a double reed with its own spectral envelope seems to be unaltered by any foreign temporal envelope. Intrafamily confusions of the oboe and English horn are not changed; intrafamily confusions of the bassoon are reduced a little by the use of a foreign envelope. In the case of the English horn, the probability of naming a clarinet is enhanced somewhat. The use of a flute envelope with the English horn spectral envelope markedly increases the probability of naming the flute as the source of the signal, but at the expense of confusions with the trumpet. The confusions of the English horn with other instruments are about the same with any combination of spectral and temporal envelopes tried.

Temporal envelopes foreign to the flute greatly impair identification of the tones as those of the flute. A bassoon temporal envelope combined with a flute spectral envelope enhances the confusions with the trumpet, English horn, and clarinet. A trombone temporal envelope augments to the greatest extent the confusions with the trumpet.

The clarinet spectral envelope is quite resistant to perturbations in identifications from foreign temporal envelopes. Furthermore, the probabilities of any particular confusion are not changed markedly.

We turn next to a discussion of the results for each particular frequency. The conclusions are based on detailed results not presented here. Below are the detailed consequences for various spectral envelopes.

1. Trumpet

- With *flute* temporal envelopes, the enhancement of the confusions with the double reeds occurred at all frequencies but the highest one generated; the confusions with the flute and clarinet occurred only above midrange.

- With *oboe* temporal envelopes, the enhancement of confusions with the double reeds occurred over the complete range of the instrument; the confusion with the clarinet and flute occurred mostly in the upper range.

- With *bassoon* temporal envelopes, confusion was increased over the whole range of the tones generated.

2. Trombone

- With *flute* temporal envelopes, for the lowest note generated, confusion with the tuba was increased; confusion with the English horn and flute, especially, was increased over the whole range of the instrument except the lowest note; confusion with the bassoon was greatly increased for the lowest note.

- With *bassoon* temporal envelopes, confusion with the bassoon was about the same as with the trombone temporal envelopes; confusion with the English horn was increased somewhat at the extremes of the range; confusion with the French horn, clarinet, and flute was increased at the two highest notes; confusion with the tuba was markedly increased at the lowest note only.

3. Tuba

- With *flute* temporal envelopes, the probability of naming the tuba was increased over that with the tuba temporal envelope, principally by reducing the confusion with the French horn and bassoon; at the extreme high end of the tuba's range, the confusion with the flute and the clarinet was increased.

- With *bassoon* temporal envelopes, the confusions were with the same instruments and were approximately as probable as they were with the tuba temporal envelopes.

4. French Horn

- With *flute* temporal envelopes, the confusions with the flute were increased particularly in the upper half of the range of the horn; confusion with the bassoon, English horn, and trombone in the low range was increased.

- With *bassoon* temporal envelopes, confusion with the bassoon was markedly increased for all but the highest notes. Confusion with the trombone was about the same (and small), that with the English horn was increased for notes in the upper half-range.

5. Oboe

- The use of *flute* temporal envelopes gave results almost identical at any frequency with those for oboe temporal envelopes.

- With *trombone* temporal envelopes, confusion with the trumpet was increased and that with the English horn was decreased; particularly for the highest notes in both cases. The probability of naming the oboe was about the same for either the oboe temporal envelope or the trumpet envelope. For the extreme low note, there was less confusion with the English horn; for the midrange notes, there was somewhat more confusion with this instrument.

6. English Horn

- With *flute* temporal envelopes, confusion with other instruments for the lowest two notes was less—for all other notes, most decidedly greater above midrange; confusions with the trombone, French horn, and bassoon were eliminated for the lowest two notes; for the midrange notes, the confusion with the trumpet and trombone was reduced and that with the clarinet enhanced; for the highest notes, the confusion with the trombone, oboe, and trumpet was reduced, but the confusion with the flute and clarinet was increased.

- With *trombone* temporal envelopes, confusion with the trombone was eliminated, and confusion with the clarinet increased for the two highest notes only.

7. Bassoon

- With *flute* temporal envelopes, identification of the top two notes generated was improved because confusions with the English horn were greatly reduced; in the lower midrange, confusions with the tuba were eliminated.

- With *trombone* temporal envelopes, the probability of naming the bassoon was enhanced in the lower range by reducing the confusion with the trombone or tuba and in the higher range by reducing the confusion with the English horn.

8. Flute

- With *trombone* temporal envelopes, the probability of naming a flute was drastically reduced and that of naming a trumpet was greatly increased over the complete range of the flute; the probability of naming a trombone, French horn, or English horn was increased in the lower half of the range.

- With *bassoon* temporal envelopes, the probability of naming a flute was drastically reduced and that of naming the trumpet was greatly increased. The probability of naming a French horn for the midrange notes and an oboe or English horn for the mid- and low-range notes was enhanced; for the high notes, the probability of naming a clarinet was increased markedly.

9. Clarinet

- With *flute* temporal envelopes, the confusions were approximately the same, both qualitatively and quantitatively, as with the clarinet temporal envelope over the whole register of the clarinet.

- With *bassoon* temporal envelopes, the probability of naming the clarinet was increased to near perfection and was higher than that for the clarinet temporal envelope. However, in the midrange, there was a substantial confusion with the oboe for one note and, at the top note, a substantial confusion with the trumpet, both of which conditions also existed, to a lesser degree, for the clarinet temporal envelope.

- With *trombone* envelopes, the lower half-range was not always identified with the tones of the clarinet, confusions with the English horn tones existing with the clarinet temporal envelope being eliminated; the upper half-range was also improved over that obtaining with the clarinet temporal envelope, except for the very highest note, where confusion with the flute, trumpet, or oboe was somewhat augmented.

B. Perturbations of Oboe Spectral Envelope

The oboe spectral envelope has a feature unique among the envelopes of all other musical instruments,

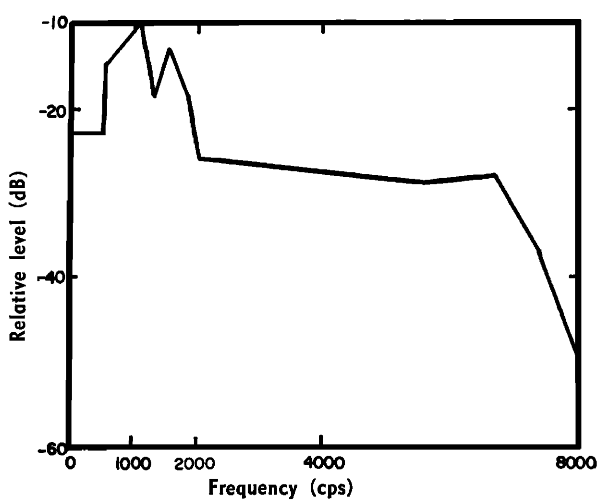

FIG. 1. Spectral envelope of oboe without the second peak.

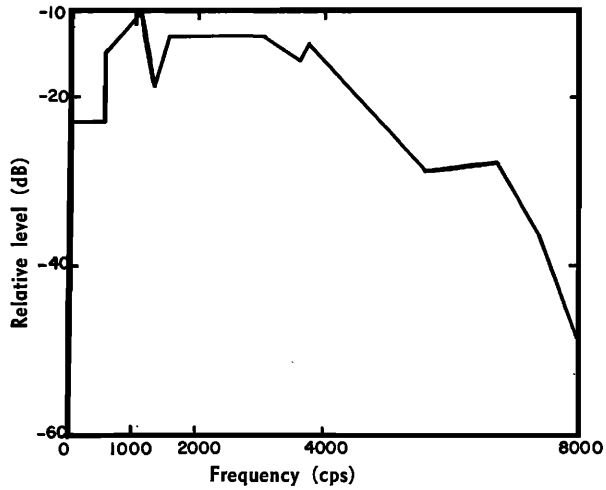

FIG. 2. Spectral envelope of oboe without the valley.

viz., two strong peaks separated by a valley at approximately 2000 cps (see Fig. 5 of our previous paper[1]). We inquire into the aural significance of the second peak and the valley by constructing tones without one or the other. The spectral envelope used for oboe tones without the second peak (at 2000 cps) is shown in Fig. 1 and that used for oboe tones without any valley (at 3000 cps) is shown in Fig. 2. Because the latter spectral envelope strongly resembles that for the trumpet, identifications were examined for both normal oboe spectral envelopes and the spectral envelope without any valley (at 2000 cps) using normal trumpet temporal envelopes.

The identifications are shown in Table II. From this table we conclude the following:

(1) Absence of a second peak (at 3000 cps) considerably impairs the identification of the oboe and produces more identifications as English horn, whose spectral envelope is not greatly different from that of the oboe without a second peak.

(2) Absence of a valley (at 2000 cps) impairs the oboe identification somewhat less than the absence of a second peak (at 3000 cps) but produces rather more identifications of the trumpet. Few such tones are identified as those of the English horn.

(3) Absence of the valley (at 2000 cps) and use of a trumpet temporal envelope greatly reduces the oboe identifications and enhances the trumpet identifications. The English horn is as often identified as the oboe in this case.

(4) Use of a trumpet temporal envelope together with a normal oboe spectral envelope increases the trumpet identifications somewhat while decreasing oboe identifications. The confusion with the English horn is the same as that with the trumpet and is not increased by use of the trumpet temporal envelope.

TABLE III. Identification, discriminability, and preference probability (in percent) for clarinet tones with and without even partials.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as clarinet	Tones in pair sound the same	Tone with even partials is natural	Tone with no even partials is natural
186	100	12	63	25
232	100		75	25
291	100		88	12
348	100	12	63	25
441	100		63	37
553	100		88	12
740	88	25	75	
996	63	13	75	12

TABLE IV. Identification, discriminability, and preference probability (in percent) for clarinet tones with and without spectral envelopes for lower and upper frequency ranges interchanged.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as clarinet	Tones in pair sound the same	Tone from normal spectral envelopes is natural	Tone from inter-spectral spectral envelopes is natural
186	100		100	
232	100	12	25	63
291	100	13	12	75
348	100		88	12
441	100		37	63
553	88	38	37	25
740	100	88	12	
996	50	25	37	38

TABLE V. Identification, discriminability, and preference probability (in percent) for flute tones synthesized by using flute and bassoon spectral envelopes.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as flute	Tones in pair sound the same	Tone from flute spectral envelope is natural	Tone from bassoon spectral envelope is natural
266	88			100
361	100		25	75
452	100		63	37
542	88	13	12	75
677	75	38	50	12
854	75	25	63	12

TABLE VI. Identification, discriminability, and preference probability (in percent) for flute tones with waveform modulation and with amplitude modulation only.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as flute	Tones in pair sound the same	Tone with waveform modulation is natural	Tone with amplitude modulation is natural
266	88	63	37	
361	100	37	63	
452	75	50	37	13
542	75	75	12	13
677	88	38	12	50
854	50	25	25	25

TABLE VII. Identification, discriminability, and preference probability (in percent) for flute tones with natural temporal envelopes for all groups of partials and with synthetic temporal envelopes for two of the three groups of partials.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as flute	Tones in pair sound the same	Tone with all natural temporal envelopes is natural	Tone with two synthetic temporal envelopes is natural
266	75	75	25	
361	75	38	50	12
452	100	38	50	12
542	63	38	50	12
677	88	12	38	50
854	50	50	12	38

TABLE VIII. Identification, discriminability, and preference probability (in percent) for bassoon tones synthesized by using bassoon and flute spectral envelopes.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as bassoon	Tones in pair sound the same	Tone from bassoon spectral envelope is natural	Tone from flute spectral envelope is natural
62	88		100	
72	88		75	25
93	100		88	12
123	88	12	50	38
154	88	12	38	50
203	63		37	63

Detailed results by note frequency are presented in Table II and reveal some interesting facts:

(1) Except for the two extreme notes, the normal oboe was identified rather accurately. The lowest note was confused with that of an English horn and the highest note with that of a clarinet.

(2) Absence of a valley (at 2000 cps) markedly increased identifications with the trumpet at all frequencies. English horn identifications below A_4 increased somewhat also.

(3) Absence of a second peak (at 3000 cps) with a normal temporal envelope increased very markedly the

TABLE IX. Identification, discriminability, and preference probability (in percent) for oboe tones synthesized by using normal and model oboe spectral envelopes.

Fundamental frequency of tones in pair (cps)	Tones in pair identified as oboe	Tones in pair sound the same	Tone from normal spectral envelope is natural	Tone from model spectral envelope is natural
232	50	12	25	63
370	75	63	12	25
466	100	12	38	50
593	88	38	37	25
747	88	50	38	12
931	63	50	25	25

identifications as an English horn below A_4; above this frequency, trumpet identifications were increased somewhat.

(4) With an oboe spectral envelope and a trumpet temporal envelope, identifications as an English horn below A_4 and as a trumpet above this note, particularly the highest two notes, were increased. At the two highest notes, the previous confusions with the flute were replaced by confusions with the clarinet.

(5) With an oboe spectral envelope having no valley (at 2000 cps) and a trumpet temporal envelope, the trumpet identifications were very greatly increased—a not surprising fact, considering the similarity of this modified spectral envelope to that of the trumpet and of the attack durations for the temporal envelopes. There were, however, still some identifications of the oboe.

III. RESULTS OF PAIRED-COMPARISON PRESENTATIONS

The results for the second type of presentation are shown in Tables III through IX. The purpose here was to determine the aurally sensitive attributes of spectral and temporal envelopes.

A. Clarinet

Two types of paired comparisons are displayed for the clarinet:

(1) Clarinet tone and clarinet tone with no even partials; results are shown in Table III. We conclude that even partials are necessary for producing natural sounding clarinet tones, since only two of the eight auditors account for 83% of the responses selecting the tones with no even partials as the natural ones.

(2) Clarinet tone, and clarinet tone with the spectral envelope for the low range (148–414 cps) and that for the upper range (440–834 cps) permuted. From the results presented in Table IV, it may be concluded that, to the degree of approximation of the spectral envelopes involved here, the difference in these envelopes is immaterial; for, of the eight tones synthesized, there was a preference displayed for only the two tones at 186 and 348 cps with the normal spectral envelopes. For those at 232, 291, and 441 cps, however, our subjects exhibited a preference for the permuted spectral envelope; for those in the other three cases no particular preference was shown. We note that the spectra are rather more poorly approximated by a spectral envelope for this instrument than is the case for the oboe and the brasses. The spectral envelope for the even partials is a poor approximation; however, since the even partials are weaker than the odd ones, this imperfection is probably of secondary importance.

B. Flute

Three types of paired comparisons were presented for the flute to test the aurally significant features of the temporal and spectral envelopes:

(1) Flute with its own spectral envelope and flute with bassoon spectral envelope. The similarity of the flute and bassoon spectral envelopes motivated this comparison. The results displayed in Table V show that the tones involving the bassoon spectral envelope seemed more natural at 266, 361, and 542 cps and that the tones involving the flute spectral envelope appeared more natural at 452, 677, and 854 cps. From this fact, we conclude that the flute and bassoon spectral envelopes are roughly equivalent for the synthesis of flute tones.

(2) Flute with waveform modulation and flute with only amplitude modulation. Flute tones with waveform modulation were achieved by modulating the partials in Group 1 with the temporal envelope of combinations of intense partials, by modulating the partials in Group 2 with the temporal envelope of combinations of medium-strength partials, and by modulating the partials in Group 3 with the temporal envelope involving combinations of the weak partials. The flute tones with only amplitude modulation were created by modulating all partials as one group with the natural temporal envelope of the flute tone itself. Our results, presented in Table VI, show that the waveform-modulated tones at 266, 361, and 452 cps were chosen as natural; that the amplitude-modulated tone at 677 cps was selected as the natural one; and that there was no definitive opinion on the tones of 542 and 854 cps. From this result, we conclude that, while waveform modulation produces a somewhat more natural tone, the difference between the two types of modulation is of secondary significance.

(3) Flute tones with natural envelopes for all three groups of partials and flute tones with temporal envelopes constructed artificially for the second and third groups of partials. The results for this test are presented in Table VII and show that the tones in the

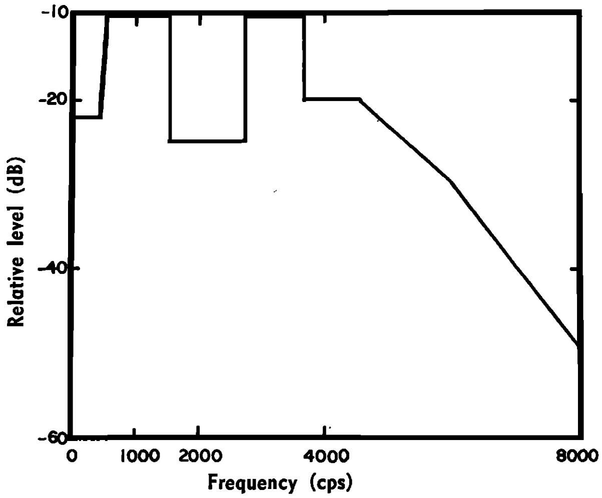

FIG. 3. Model of oboe spectral envelope.

pair sounded somewhat distinct, except for the lowest and highest ones, and that there was some preference for the tones with all natural envelopes, except for that at 854 cps. All in all, it seems that the differences are of second-order importance.

C. Bassoon

The bassoon was studied by presenting pairs of tones, each pair consisting of a bassoon tone with a bassoon spectral envelope and a bassoon tone with a flute spectral envelope. The results displayed in Table VIII show that, for the low tones with a bassoon temporal envelope, the bassoon spectral envelope produces a more-natural-sounding bassoon tone than does a flute spectral envelope. For the highest tones, it appears that the flute spectral envelope together with the bassoon temporal envelope produces slightly more-natural-sounding bassoon tones. It would seem that, for the low-frequency tones, the presence of less energy in the high partials makes the tone sound more natural; while for the high-frequency tones, there is little effect on the naturalness of the tones due to differences in the energy of the high-frequency partials.

D. Oboe

Pairs of oboe tones were presented. One member of each pair was constructed to be normal; the other, by using the model spectral envelope shown in Fig. 3. From the results presented in Table IX, we conclude that the normal oboe spectral envelope and the model spectral envelope are equivalent. Decided preference was shown for the model spectral envelope only at 232 cps and only at 747 cps for the natural envelope.

IV. SUMMARY OF RESULTS

Two tests of the quality of the synthetic tones are listed in Table X. Ideally, the probability of interfamily confusion would be 0%, and the ratio of synthetic-tone identification to natural-tone identification would be 1.0. From the results presented in this Table, we conclude that the synthetic oboe and clarinet tones are about equally natural—the former being, perhaps, slightly better than the latter. The bassoon tones are ranked third, and the tuba tones fourth. The synthetic flute, trumpet, trombone, and French horn tones are of roughly comparable quality.

TABLE X. Summary of figures of merit for synthetic wind-instrument tones.

Instrument	Probability of interfamily confusion (%)	Ratio between identification probabilities of synthetic tones and of natural tones
Clarinet	12	0.90
Oboe	14	0.97
Bassoon	14	0.82
Tuba	15	0.69
Flute	23	0.77
Trumpet	24	0.75
Trombone	26	0.62
French horn	27	0.86
English horn	52	0.56

Perturbation studies of synthetic tones indicate that:

- The spectral envelope of the *oboe* is much more important than the temporal envelope. The two strong peaks separated by a strong valley in the spectral envelope, coupled with the comparatively slow decline in spectral amplitude at high frequencies, gives the oboe a unique spectral envelope, enabling the identification of oboe tones almost independently of the temporal envelopes.

- The spectral envelope of the *clarinet* is likewise much more important aurally than the temporal. The weak, even partials and the strong, odd partials are unique to the clarinet and de-emphasize the importance of the temporal envelopes.

- The spectral envelope of the *bassoon* is more important than the temporal, perhaps because the spectral, which peaks at 550 cps, is unique in the range in which this instrument is normally played.

- The spectral envelope of the *tuba* is more important than the temporal for the reasons cited for the bassoon. The peak of the tuba spectral envelope is at 275 cps, which is lower than that of the other instruments.

- The spectral envelope of the *trumpet* is somewhat more important than the temporal; but the relative importance of the spectral envelope is much greater for the oboe, clarinet, bassoon, and tuba.

- The temporal envelope of the *flute* is more important than its spectral envelope.

- The temporal and spectral envelopes of the *trombone* and *French horn* are of comparable importance in aurally characterizing their respective instruments. The reason, in these cases and in that of the flute, is probably lack of uniqueness of the spectral envelopes of these instruments.

- The spectral envelopes for the *flute, bassoon, trombone, French horn*, and *English horn* are similar and peak within 125 cps of each other. Note, though, that the bassoon, trombone, and French horn may be played lower than the flute; although the upper registers of these instruments overlap with the lower register of the flute.

The general principle seems to emerge that, in tones for which the spectral envelope is unique with regard to the frequency of its maximum and the range in which the instrument is normally played, this envelope is predominant in aural significance to the temporal envelope. For those cases in which the spectral envelope is not unique, this envelope is of equal or subordinate importance to the temporal envelope. Furthermore, from Table X, we conclude that interfamily confusions are lower in cases where the tone tends to be identified from the spectral rather than the temporal envelope. Thus, the clarinet, oboe, bassoon, and tuba tones have a probability of interfamily confusion of only 12%–15% whereas those of the flute, trumpet, trombone, and French horn have a probability of 23%–26%, perhaps because the temporal envelopes are not so accurately known as the spectral envelopes.

Our results indicate that we achieve considerable success from formant-plus-temporal control of the partials, and that one without the other produces a case-dependent impairment of the naturalness of the timbre produced. By inference, we conclude that maintenance of fixed amplitude relationships among harmonics would lead to results inferior to those presented here.

It is noted that our test tones exceeded 0.5 sec in duration. The relative importance of spectral and temporal envelopes might be quite different for shorter tones and for those produced by ensembles of instruments, which is the most common musical situation.

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