Naval Submarine Medical Research Laboratory

NSMRL Report 1165 10 December 1990

CONTRIBUTIONS OF ENVELOPE INFORMATION
TO CLASSIFICATION OF BRIEF SOUNDS

Thomas E. Hanna

Released by:
R. G. Walter, CAPT, DC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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NSMRL REPORT 1165

OFFICE OF NAVAL RESEARCH
RESEARCH WORK UNIT 61153N - RR4209.001-ONR4424207

Approved and released by

R. G. Walter

R. G. WALTER CAPT, DC, USN
Commanding Officer
NavSubMedRschLab

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SUMMARY PAGE

THE PROBLEM

To identify the potential relevance of the signal envelope for aural classification.

THE FINDINGS

Listeners were trained to classify a set of sounds into eight categories. Classification was almost as good in subsequent tasks where listeners classified signal envelopes or signals created by modulating a tone with the signal envelopes. Classification of signals created by modulating a tonal-complex or broadband noise was markedly worse, probably due to interaction of sidebands from nearby carrier frequencies.

APPLICATION

These results indicate that further investigation of envelope features and aural sensitivity to these features would further our understanding of aural classification of brief complex sounds.

ADMINISTRATIVE INFORMATION

This investigation was conducted under Office of Naval Research Work Unit 61153N-RR4209.001-ONR4424207. It was submitted for review on 18 January 1990, approved for publication on 10 December 1990, and designated Naval Submarine Medical Research Report 1165.

ABSTRACT

Listeners were trained to classify a set of sounds into eight categories. Classification was almost as good in subsequent tasks where listeners classified signal envelopes or signals created by modulating a tone with the signal envelopes. Classification of signals created by modulating a tonal-complex or broadband noise was markedly worse, probably due to interaction of sidebands from nearby carrier frequencies. These results suggest the importance of envelope cues for aural classification. Further investigation of envelope features and aural sensitivity to these features would further our understanding of aural classification of brief complex sounds.

Most psychoacoustic research has concentrated on describing the auditory system's ability to detect signals or to discriminate small changes in simple stimuli such as tones or bands of noise. More recently, increasing attention is being paid to the auditory system's ability to classify sounds so that we can better understand the acoustic features that underlie aural recognition of complex real-world sounds. Many acoustic features are potentially available within the auditory system, but an analysis of some of these features can be simplified by considering one aspect of the acoustic waveform - the amplitude envelope. The signal envelope is an amplitude-time function that describes the signal's amplitude variation distinct from the spectral content. Thus, for example, a two-tone signal consisting of 500 and 504 Hz would produce a "beating" sensation due to its periodic 4 Hz amplitude variation, as would a two-tone signal consisting of 800 and 804 Hz or any pair of frequencies separated by 4 Hz.

Using two-tone complexes, Buus (1983) has shown that the auditory system can discriminate envelope fluctuations up to at least 640 Hz. Using a noise carrier modulated by the speech envelope, Van Tassell et al. (1987) have shown that envelope frequencies less than 200 Hz (and possibly higher) provide the information needed for the discrimination of certain speech features. The present study examines the role of the envelope for the perception of nonspeech sounds.

METHOD

Signals. Fifty one-second segments were extracted from digitized recordings of underwater sounds. Each segment contained an event with a duration ranging from tens to hundreds of milliseconds. Each event was approximately centered within the one-second sample. The recordings had been digitized at a 12.5 kHz sampling rate with 12 bits of linear encoding of amplitude. A preliminary classification of the fifty events into eight categories was performed based on transcripts of the recording sessions and in consultation with two experienced sonar operators who listened to the recordings in their original context (prior to extraction). For each of the eight categories, three exemplars were chosen that represented good-quality samples with minimal ambiguity regarding the accuracy of the classification.

Classification performance was measured using the original set of fifty signals and four other sets that were derived from the signal envelopes of the original set. Envelopes were extracted from the digitized signals using the Interactive Laboratory System (ILS) from Signal Technology Inc. In the first of the envelope conditions, the fifty envelopes were used as signals, i.e., the envelope was presented as a time waveform; in the second condition, the envelopes were used to modulate a multitonal complex consisting of tones with approximately one-third octave spacing; in the third condition, the envelopes were used to modulate a broadband noise carrier; and in the fourth condition, the envelopes were used to modulate a 3-kHz tonal carrier.

Apparatus. For the condition with the original set of signals and for the first of the envelope conditions, the sounds were presented over 16-bit digital-to-analog converters with a 12.5 kHz sampling rate. Stimuli were low-pass filtered at 5 kHz. All filters in this experiment had asymptotic rejection rates of 115 dB/octave.

In the modulated-carrier conditions, the envelope was presented over 16-bit digital-to-analog converters and low-pass filtered at 5 kHz (3 kHz for the tonal carrier). The carriers for the three conditions were: 1) a tonal-complex, consisting of 500, 650, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000, and 5000 Hz tones (with arbitrary starting phases), which was presented over a second digital-to-analog converter, 2) broadband noise, generated from a white-noise generator and filtered from 0.5 to 5.0 kHz, and 3) a 3-kHz tone, generated from an oscillator. The carrier was multiplied by the envelope and filtered from 0.5 to 5.0 kHz (0 to 6 kHz for the tone carrier).

In all conditions a programmable attenuator was used to adjust the amplitude of each signal to a comfortable listening level. In addition, the programmable attenuator was used to randomize stimulus levels over a 15-dB range to minimize the use of amplitude as a classification cue. An electronic switch gated the stimuli with 20-ms, sine-squared ramping. Stimuli were presented to the right earphone of a Sennheiser HD430 headset.

<u>Procedure</u>.

Table I shows the order of the training and testing phases.

Table I

Order of training and testing.

Initial training
Training for condition 1 (original signals)
Testing for condition 1
Training for condition 2 (envelopes)
Testing for condition 2
Retesting of condition 1 (exemplars only)
Training for condition 3 (modulated tone complex)
Testing for condition 3
Retesting of condition 1 (exemplars only)
Training for condition 4 (modulated noise)
Testing for condition 4
Retesting of condition 1 (exemplars only)
Training for condition 5 (modulated tone)
Testing for condition 5

Initial training: On each trial, one stimulus was presented and the listener classified it using the letters A-H to designate the eight categories. The correct response was displayed after each response. Only the exemplars from categories one through four were presented within half of the blocks and only exemplars from categories five through eight were presented within the other blocks. These reduced sets were used to facilitate the learning of category labels. Listeners had at least 670 trials for each of these two stimulus sets by which time they had attained stable performance. Following initial training, condition-specific training and testing occurred for the five conditions sequentially.

Condition-specific training: For each condition, listeners were trained with the full set of eight categories. Only the three exemplars from each category were presented during this training, and correct-answer feedback was given on each trial. One day of training, consisting of at least 720 trials, was conducted prior to switching to the test condition.

Testing: Each of the fifty stimuli was presented once within a block of fifty trials. If an exemplar was presented, correct-answer feedback was given. However, if the stimulus was one of the twenty-six stimuli that was not an exemplar (such stimuli will be called probe stimuli), no feedback was given. Normally thirty-six blocks of fifty trials were administered during the test phase. These blocks were run over two days.

All listeners were tested simultaneously which prevented counterbalancing the conditions across listeners. Conditions were run in the following order: original sonar signals, envelopes, modulated tone-complex, modulated noise, and modulated tone. Before each of the modulated-carrier conditions, listeners were retested on the original set of signals for one session (approximately 864 trials) to monitor performance in this baseline condition. Only exemplars were used for retesting.

Listeners. Three paid volunteers and the author (identified as L2 in the Tables) served as listeners. Each had normal hearing sensitivity (less than 15 dB HL at octave frequencies from 250 to 8000 Hz). The author had been involved in the stimulus preparation and was very familiar with the signals prior to testing. The other three subjects had never heard these sounds prior to this experiment.

RESULTS

Table II shows percent correct on the original signals. Performance is stable except for a small improvement for L1. L4's performance is markedly poorer than the other three listeners -- even after thousands of trials with these signals L4 only achieved 65% correct while the other three listeners got more than 90% correct.

Table II

Percent correct classification on initial and retested conditions using the original signals for each of four listeners. The three retestings were prior to each of the modulated carrier conditions.

	Listeners			
	L1	L2	L3	L4
Initial test	89.4	99.6	88.4	65.4
First retest	95.6	--	91.1	70.8
Second retest	94.6	--	--	65.4
Third retest	96.6	--	--	64.1

Table III shows the percent correct on the 24 exemplars and the percent correct for 18 of the probe stimuli for each condition. Eight of the probe stimuli were eliminated from this analysis because they were poor recordings or contained artifacts that created ambiguity about which event was to be judged. Five of these eight stimuli had been identified in a previous study (Hanna, 1989); three additional stimuli with similar problems were identified after examining listeners' responses to the original (unaltered) signals of the present study. The inconsistency of listeners' responses to these stimuli was clearly attributable to the quality of the signal. Apparently three of these stimuli were not identified in the previous study due to those two listeners' prior familiarity with the signals.

Table III

Percent correct classification of exemplar and probe signals in each of the five conditions and for each of four listeners.

Exemplars:

	Listeners			
	L1	L2	L3	L4
Original	89.4	99.6	88.4	65.4
Envelope	84.7	--	76.6	51.1
Modulated tone	85.8	91.9	--	27.0
Modulated complex	69.3	--	--	20.0
Modulated noise	66.4	57.7	--	--

Probes:

	Listeners			
	L1	L2	L3	L4
Original	69.4	82.6	67.9	45.8
Envelope	65.4	--	57.7	37.8
Modulated tone	60.1	69.5	--	18.4
Modulated complex	41.5	--	--	20.2
Modulated noise	40.7	36.0	--	--

Percents correct on the probe stimuli are roughly 20% less than on the exemplars. This difference is presumably a reflection of the fact that the clearest and least ambiguous signals were used as exemplars. It appears that, for each condition, listeners appropriately generalize the categories to the probe stimuli even though they have never been given feedback about the probe stimuli. This result indicates that listeners are learning categories rather than simply learning arbitrary assignments of category labels to each of the exemplar stimuli.

With two minor exceptions, performance on the five conditions is rank-ordered similarly for each listener and for both exemplar and probe stimuli. Classification is best on the original (unaltered) set of signals, followed by the envelope condition, the modulated tone condition, the modulated tonal-complex condition, and the modulated broadband-noise condition. Listener 4 is noticeably worse than the other three listeners, particularly for the modulated-carrier conditions.

Performance in the envelope condition was almost as good as for the original signals. Percent correct was only 4-14% worse when the envelope was presented as the signal. Moreover, the envelope signals sounded remarkably similar to the original signals. For two of three listeners for which a comparison is possible, performance on the modulated-tone condition is also almost as good as for the original signals. For these two listeners (L1 & L2), percent correct was only 4-13% worse with the modulated tone. The other listener (L4) was the one that did poorly (near chance) in all of the modulated-carrier conditions. All listeners showed a marked decrement with the modulated tonal-complex and the modulated noise carriers. Percent correct was 20-46% worse in these two conditions than for the original signals. Although performance was noticeably worse for these two conditions it should still be noted that L1 & L2 still got 36-69% percent correct with these signals (versus chance performance of 12.5%).

Table IV shows the pattern of errors made by L1 for whom we have data for all conditions. This table shows the percentage of times each response was given to the exemplar signals from each of the eight categories. For the envelope and modulated-tone conditions, categories 3, 6, and 8 are the ones that show the largest decrements relative to the original signals. Most of the increase in errors is attributable to these three categories. These results suggest that the envelope does not contain all of the information by which listeners distinguished categories 3, 6, and 8. For the modulated tonal-complex and modulated noise conditions, decrements are found for categories 1, 3, 4, 6, 7, and 8. The errors among stimuli from categories 1, 3, 6, and 8 are common. These errors include those made in the envelope and modulated-tone conditions as well as additional errors involving categories 1, 4, and 7. Thus, the conditions do not idiosyncratically degrade the signals--the conditions may be rank-ordered not only by overall level of performance but also by the types and amount of information that are affected in the various conditions. The information lost (or masked) in the modulated-tonal-complex and modulated-noise conditions is in addition to that lost (or masked) in the envelope and modulated-tone conditions.

We analyzed the patterns of errors using Multidimensional Scaling (MDS) in order to identify perceptual dimensions underlying the classification of these sounds (Kruskal & Wish, 1978). MDS is a scaling technique that places stimuli in a multidimensional space such that the closeness of two points in the space is correlated with the perceived similarity of the two stimuli. For our data, the similarity, S(i,j), of stimuli i and j was defined as:

$$S(i,j) = \sum_{k=1}^{8} p(i,k)p(j,k) \qquad (1)$$

where p(i,k) is the probability that stimulus $\underline{i}$ will be called category $\underline{k}$.

Table IV

Confusion matrix for L1 for each of the five conditions. Each entry represents the percentage of times this listener gave a particular response to exemplar signals from a given category.

Original signals:

Signal cat.	Response 1	2	3	4	5	6	7	8
1	99	-	-	-	-	-	-	1
2	1	64	31	1	-	-	3	-
3	-	8	80	3	-	1	8	-
4	-	-	-	96	-	-	4	-
5	-	-	-	-	100	-	-	-
6	-	-	-	4	1	92	1	3
7	-	-	-	1	-	-	99	-
8	-	-	1	3	-	10	-	86

Envelope:

Signal cat.	Response 1	2	3	4	5	6	7	8
1	94	-	-	1	-	4	-	1
2	-	75	20	-	-	4	1	1
3	2	19	70	2	-	5	3	-
4	1	-	-	98	-	-	1	-
5	-	-	-	-	100	-	-	-
6	5	-	1	-	-	72	-	23
7	-	2	-	-	-	-	98	-
8	1	-	3	6	-	19	-	72

Modulated tone:

Signal cat.	Response 1	2	3	4	5	6	7	8
1	96	-	2	-	-	2	-	-
2	1	87	7	1	-	1	3	-
3	5	13	68	-	-	10	1	3
4	-	-	-	100	-	-	-	-
5	-	-	-	-	100	-	-	-
6	2	2	7	-	-	76	4	9
7	-	-	-	-	-	-	100	-
8	3	15	16	-	-	7	-	59

Modulated tonal-complex:

Signal cat.	Response 1	2	3	4	5	6	7	8
1	67	3	18	-	-	1	1	10
2	4	75	21	-	-	-	-	-
3	13	16	44	1	-	4	2	20
4	-	-	-	92	1	-	-	7
5	-	-	-	4	95	1	-	-
6	5	3	14	3	-	44	7	24
7	1	6	13	1	1	1	77	-
8	1	-	3	21	-	11	2	62

Modulated broadband-noise:

Signal cat.	Response 1	2	3	4	5	6	7	8
1	61	6	15	-	-	11	1	6
2	7	88	1	2	-	-	2	-
3	13	10	39	13	-	14	4	6
4	3	-	1	78	2	4	2	10
5	-	-	-	1	98	-	1	-
6	10	6	18	5	-	46	4	11
7	6	9	3	-	-	1	81	-
8	10	2	4	16	-	22	4	41

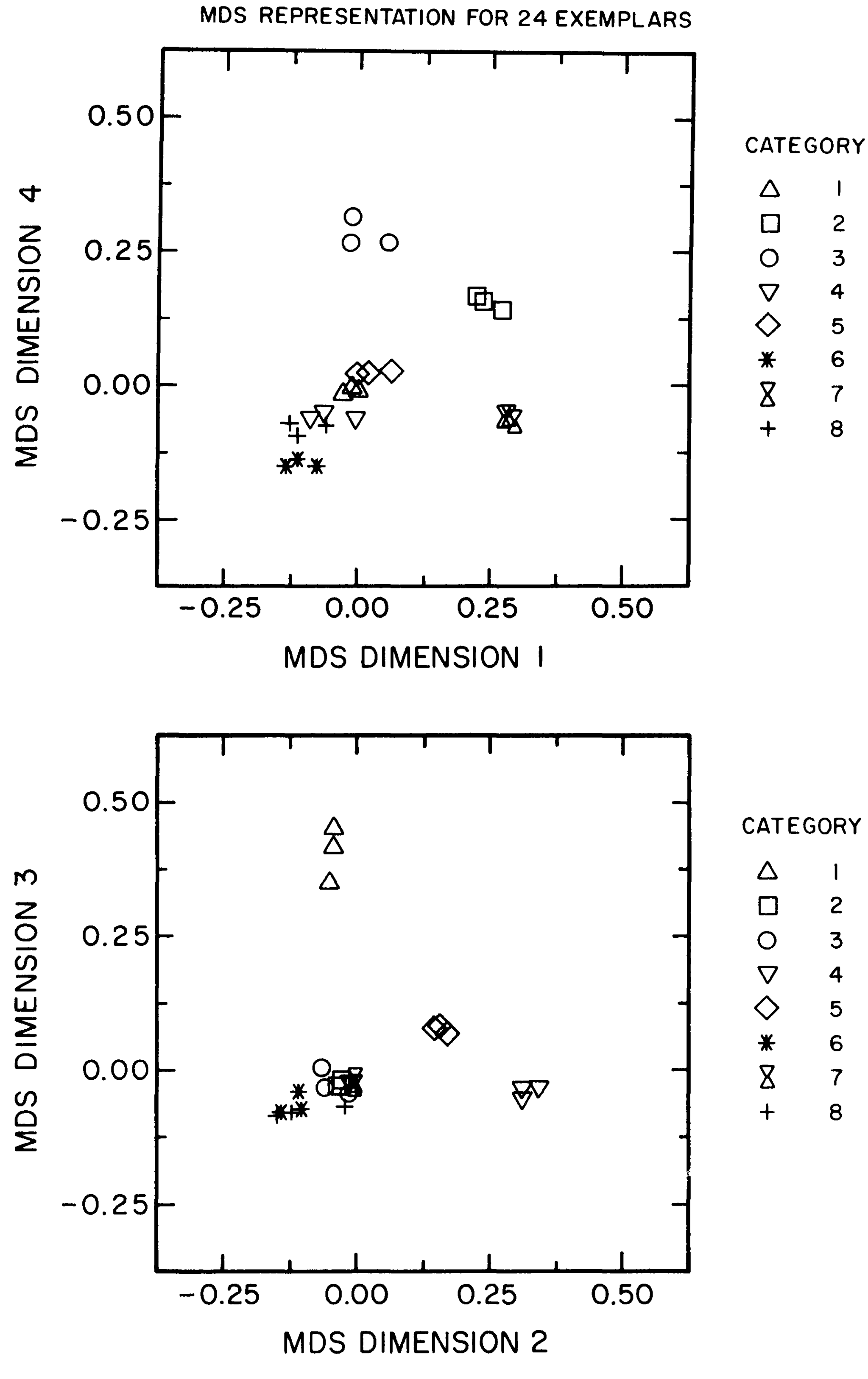

Figure 1. SINDSCAL representation for the twenty-four exemplars. Fig. 1a plots values on Dimension 4 vs. values on Dimension 1; Fig. 1b plots values on Dimension 3 vs. values on Dimension 2. The different symbols represent the eight different stimulus categories. Three exemplars from each category are shown.

This summed crossproduct corresponds to the probability that the two stimuli would be given the same category label, assuming independent responses to each. Similarity matrices defined by Eq. 1 were constructed separately for each listener and condition. A SINDSCAL MDS analysis (Carroll & Chang, 1970) of these fourteen matrices (corresponding to condition by listener entries in Table III) produces a common perceptual space and a weightings space that indicates differential weighting of the dimensions for the fourteen similarity matrices.

A four-dimensional solution accounted for 61.3% of the variance. Higher-dimensional solutions provided only a moderately better fit (65.4% and 67.3% for five- and six-dimensional solutions, respectively). Decreasing the dimensionality to three caused a larger change in explained variance, down to 52.2%. Using the typical criterion for dimensionality, we took the relatively sharp decrement in explained variance as dimensionality decreased from four to three as an indication that four dimensions are appropriate to describe the data. This solution uses about 256 parameters (4 dimension values for 50 stimuli plus 4 weights for 14 matrices) to predict 5600 data values (8 response probabilities for 50 stimuli for 14 matrices). Repeated analyses with different starting configurations gave similar results.

Figure 1 shows the obtained SINDSCAL representation. Figure 1a plots values on MDS dimensions 1 and 4; Figure 1b plots MDS dimensions 2 and 3. Each point represents a single stimulus. For clarity only the 24 exemplars are shown. Different symbols are used for each of the eight stimulus categories. Each symbol appears three times in each plot to represent the three exemplars from each category.

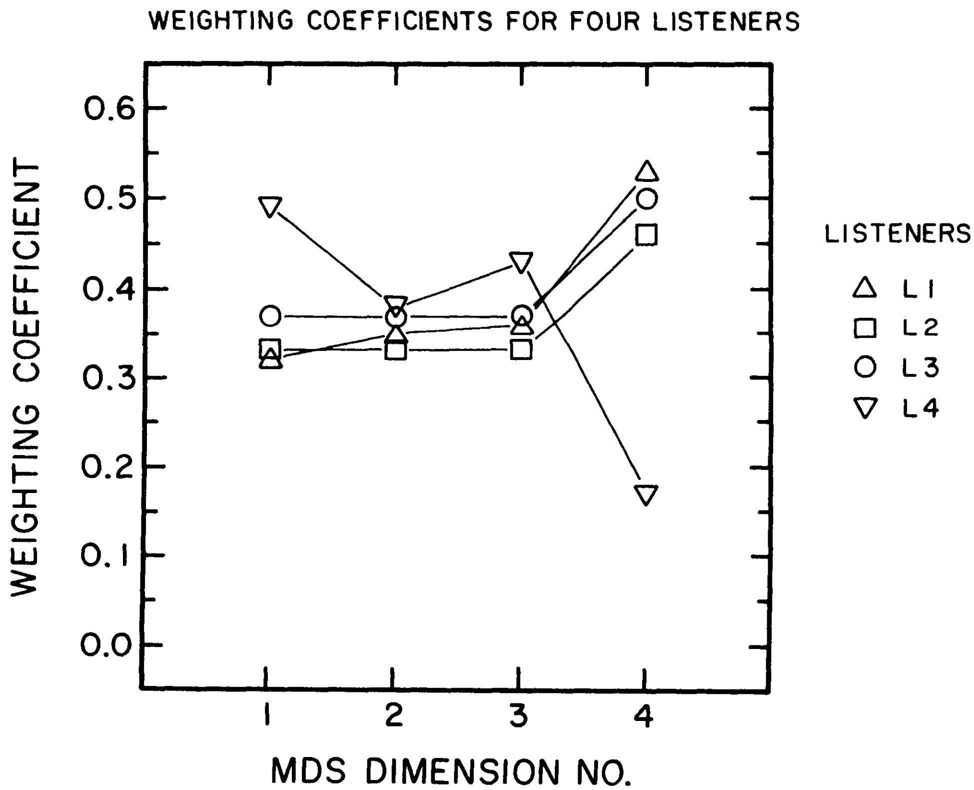

Figure 2. Dimensional weighting coefficients for the classification of the original signals. The different symbols represent the four listeners.

Examination of how stimuli varied along the individual dimensions suggested perceptual correlates for each of the four dimensions (the first attribute corresponds to a positive value on the given dimension): Dimension 1 - heavy vs. light, Dimension 2 - rough vs. nonrough, Dimension 3 - extended vs. compact in duration, Dimension 4 - soft vs. hard.

Figure 2 shows the dimension weights for individual listeners for the original signals. L1, L2, and L3 have similar weightings, but L4 gives a much lower weight to Dimension 4. L4's lower performance can be attributed to an insensitivity to this dimension. Figure 3 shows the dimension weights for L1 for each of the five conditions. Again, Dimension 4 shows the greatest differences, with greatly reduced weight in the modulated tone condition and almost no weight in the modulated tonal-complex and the modulated-noise conditions. In addition, Dimension 3 receives less weight in the modulated tonal-complex and modulated-noise conditions. These decreases in weights can be interpreted as a reduction or masking of the cues underlying these dimensions. This reduced sensitivity to Dimensions 3 and 4 is compensated for by a relatively greater weight given Dimensions 1 and 2. These results are consistent with the conclusion that the cues lost in the modulated-tonal-complex and modulated-noise conditions are in addition to those lost in the envelope and modulated-tone conditions.

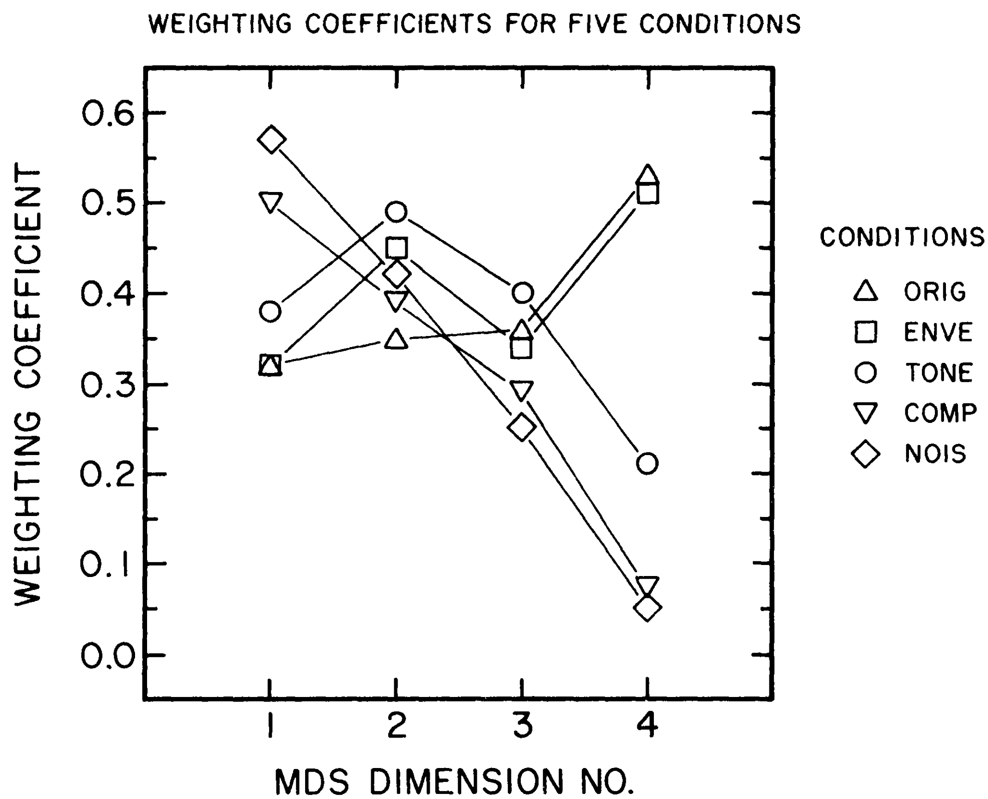

Figure 3. Dimensional weighting coefficients for L1. The different symbols represent the five stimulus conditions.

DISCUSSION

Although the number of listeners and conditions tested in this current study are limited, the results serve to demonstrate that envelope features may have a very significant role for aural classification of brief nonspeech sounds. As indicated by performance in the envelope and modulated-tone conditions, sufficient information exists in the envelope to classify these brief nonspeech sounds very well. It would seem that the very low modulation rates, less than 80 Hz, are not critical because listeners could classify signals in the envelope condition where frequencies less than 80 Hz are relatively inaudible. However, low modulation rates may still be very important after including auditory processing effects. The auditory system may be insensitive to modulation rates of 800 and 820 Hz, but easily hear the 20 Hz intermodulation which exists between them. Thus, low frequency modulation that is not present as a discrete component may be carried by high frequency modulation rates.

The poorer performance in the modulated tonal-complex and modulated broadband-noise conditions is likely due to interaction of sidebands from nearby carrier frequencies. For low modulation rates, perhaps less than 50 Hz, these interactions would probably not interfere much with the coherent modulation of the carrier frequencies. For larger modulation rates, the sidebands will be distributed widely, producing complex sets of intermodulations at modulation rates that are lower than the coherent modulation. The effects of critical band filtering and limited temporal resolution would provide greater emphasis to the intermodulations than the coherent modulation, resulting in a significantly different modulation pattern than in the original signal. These interactions would also reduce the modulation depth of the envelope and make its lower-frequency components less discernable. Whether the poorer performance with these broadband carriers is due to the loss of the higher modulation rates or simply the masking of the lower modulation rates remains to be determined.

The SINDSCAL analysis provided four dimensions with perceptual correlates that are potentially related to sound source properties, such as hardness or weight. Gibson (1979) suggested that perceptual information is organized according to its specification of object properties. The current results are consistent with Gibson's theory. Warren and Verbrugge (1984) and Richards and Ullman (1988) also suggest that temporal features can provide information about object properties. A psychoacoustic theory of classification would specify the acoustic features by which object properties are auditorily determined. Results with the modulated carriers are first steps towards identifying acoustic correlates in that the presence of Dimension 3 and 4 cues are significantly reduced. Apparently the sideband interactions with broadband carriers affected the cues underlying Dimension 3 and 4 but not those cues underlying Dimensions 1 & 2.

In summary, four dimensions have been identified for aural classification of a set of brief underwater signals. Various methods of presenting envelope information aurally suggest that the envelope contains important features for aural classification of these signals. Listeners were insensitive to some of these features under certain modulated-carrier conditions, but an acoustic analysis of the important envelope features and modulation rates will require further data and reference to auditory models of modulation sensitivity.

ACKNOWLEDGMENTS

This research was supported by the Perceptual Sciences Program of the Office of Naval Research. I thank Dr. Tom Santoro and Lee Shapiro for writing signal-editing and experimental programs; Sue Carpenter for collecting the data and assisting with the data analysis; and Drs. Jerry Tobias and Paul Weathersby for comments on drafts of the manuscript.

DISCLAIMER

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Life Sciences Directorate
Bldg. 410
Bolling AFB, DC 20332-6448

Dr. Ronald J. Tusa
Johns Hopkins University
Neurology Department
34th & Charles Place
Baltimore, MD 21218

Dr. Harold P. Van Cott
Committee on Human Factors
NAS-National Res. Council
2101 Constitution Ave, N.W.
Washington, DC 20418

Dr. Charles S. Weaver
MAXIM Technologies, Inc.
3000 Patrick Henry Drive
Santa Clara, CA 95054

Dr. John Weisz
Technical Director
US Army Human Engineering
Laboratory
Aberdeen P. G., MD 21005

Dr. Milton A. Whitcomb
NAS-National Res. Council
CHABA
2101 Constitution Ave., N.W.
Washington, DC 20418

Prof. Christopher D. Wickens
Department of Psychology
University of Illinois
Champaign, IL 61801

Dr. Wayne Zachary
CHI Systems, Inc.
Gwynedd Plaza III
Bethlehem Pike
Spring House, PA 19477

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION: Unclassified	1b RESTRICTIVE MARKINGS: N. A.
2a SECURITY CLASSIFICATION AUTHORITY: N. A.	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE: N. A.	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NSMRL Report No.	5 MONITORING ORGANIZATION REPORT NUMBER(S): Same
6a NAME OF PERFORMING ORGANIZATION: Naval Submarine Medical Research Laboratory; 6b OFFICE SYMBOL (If applicable):	7a NAME OF MONITORING ORGANIZATION: Office of Naval Research
6c ADDRESS (City, State, and ZIP Code): Naval Submarine Base- New London, Box 900, Groton, CT 06349-5900	7b ADDRESS (City, State, and ZIP Code): 800 N. Quincy Street, Arlington, VA 22217-5000
8a NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research; 8b OFFICE SYMBOL (If applicable): Code 1142PS	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N00014-88-WR24003
8c ADDRESS (City, State, and ZIP Code): 800 N. Quincy Street, Arlington, VA 22217-5000	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61153N 42	RR 04209	RR0420901	R&T4424207

11 TITLE (Include Security Classification)

(U) Contributions of envelope information to classification of brief sounds

12 PERSONAL AUTHOR(S)
Thomas E. Hanna

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Technical	FROM 87/04/01 TO 90/09/30	1990 December 10	16

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Auditory perception; Aural classification; Envelope features; Sonar signals

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Listeners were trained to classify a set of sounds into eight categories. Classification was almost as good in subsequent tasks where listeners classified signal envelopes or signals created by modulating a tone with the signal envelopes. Classification of signals created by modulating a tonal-complex or broadband noise was markedly worse, probably due to interaction of sidebands from nearby carrier frequencies. These results suggest the importance of envelope cues for aural classification. Further investigation of envelope features and aural sensitivity to these features would further our understanding of aural classification of brief complex sounds.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: John J. O'Hare	22b TELEPHONE (Include Area Code): (202) 696-4502; 22c OFFICE SYMBOL: Code 1142PS