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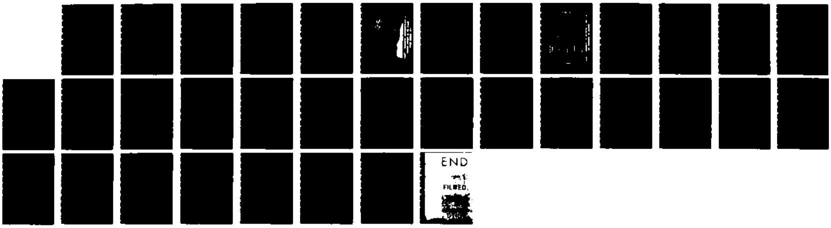

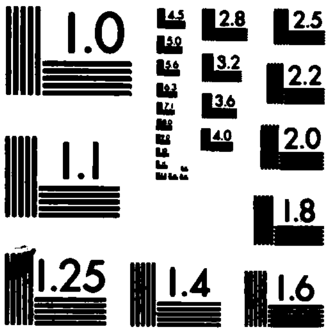

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PERCEPTION OF ACOUSTIC TRANSIENTS: FINAL REPORT

James H. Howard, Jr.

ONR CONTRACT NUMBER N00014-79-C-0550

Technical Report ONR-84-24

Human Performance Laboratory
The Catholic University of America

January, 1984

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

~~The findings of~~ research carried out under contract N00014-79-C-0550 ~~between the Office~~ of Naval Research, Engineering Psychology Programs ~~and The Catholic~~ University Human Performance Laboratory are summarized. This ~~The~~ research investigated the role of knowledge-based or top-down processing in the perception of non-linguistic, transient signals. The experiments addressed issues in transient-pattern classification, target

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observation, attentional focusing, auditory induction, and computer-based performance aids. The theoretical significance and naval relevance of the research is considered.

Introduction

Human listeners possess a remarkable ability to make sense out of multiple and diverse arrays of acoustic information. At any particular instant the complex acoustic waveform arriving at the ear will likely contain information about a variety of individual sound sources as well as background noise. Despite this, the experienced listener perceives sounds from each of the separate sources individually (e.g., the dog barking, a Bach cantata, the telephone ringing) rather than as a nonsensical hodgepodge.

This impressive human pattern-recognition ability has been exploited in a number of Navy applications which involve acoustic signal processing. In both passive-sonar and ship-silencing operations complex acoustic data are analyzed for their tactical significance. In passive sonar, sounds from the underwater environment are recorded on hydrophones, processed, and presented on both visual and acoustic displays. Both long-duration steady state and brief-duration transient signals arise from a variety of sources as illustrated in Figure 1. The task of the sonar operator in this context is to distinguish the sources of radiated noise from each other as well as from the background of ambient and platform-generated noise. Ultimately, the identity (friend or foe?) and intention (threat?) of these noise sources must be determined. The ability of experienced sonar technicians to make these decisions is legendary. In ship silencing the objective is to reduce the radiated noise produced by a ship not simply in intensity but in detectability/classifiability. Unwanted sources of noise must be identified and eliminated to reduce the vulnerability of the vessel to early detection by

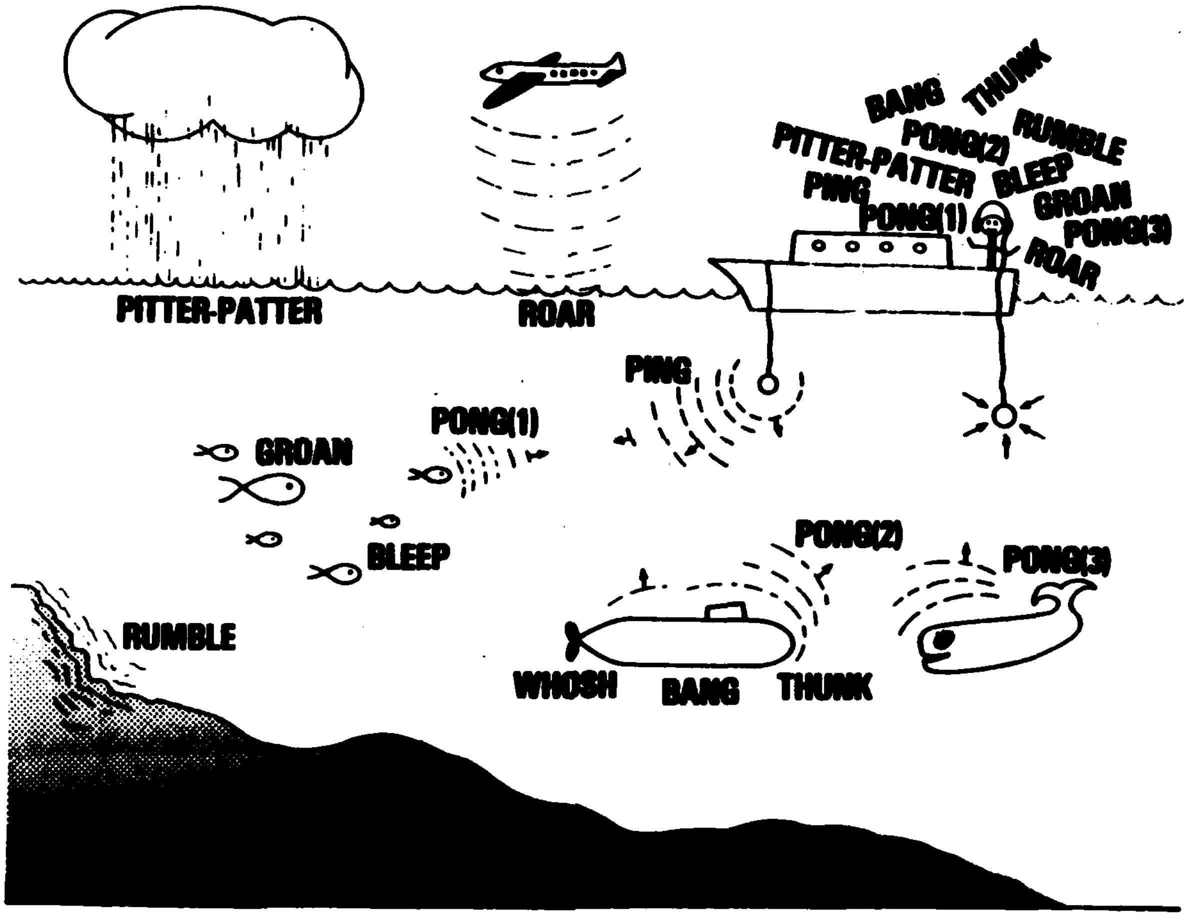

FIGURE 1. SCHEMATIC REPRESENTATION OF VARIOUS SOUNDS IN THE OCEAN (FROM BISSON, 1981)

enemy sonar. The sonar and the ship-silencing problems represent opposite sides of the same perceptual coin. On the passive-sonar side one searches for cues to facilitate detection and classification whereas on the ship-silencing side such cues are eliminated to make detection and classification difficult.

Despite the significance of the auditory recognition problem, surprisingly little research has investigated how human listeners perceive complex nonspeech sounds. The present report summarizes a series of experiments which examined these processes.

Background and Theory

Historically, most psychoacoustic research has focused on the ability of listeners to detect isolated pure tones of relatively brief duration. Although this research has led to significant advances in our understanding of energy detection mechanisms in the peripheral auditory system, it has contributed little to our understanding of how human listeners process complex environmental sounds. The primary difficulty of this approach for complex sounds is that it necessarily focuses on specific signal parameters and disregards any external knowledge which the listener may bring to the task. In the contextually-rich acoustic world of meaningful environmental sounds, listeners do not ignore their experience, but rely on what they know to identify sound patterns. For example, an experienced sonar technician knows a great deal about the sounds likely to occur, and this knowledge plays a major role in determining what is heard. Historically, too little attention has been paid to these important "knowledge sources" and their role in auditory perception.

In contrast to the traditional approach, our research program was based on the assumption that both bottom-up or data-driven and top-down or knowledge-driven processes are important in the perception of complex nonspeech sounds. Bottom-up processing is based exclusively on the information available in the acoustic waveform. Specific cues or features are present which suggest a particular category or source event. In contrast, top-down processing occurs when the perceiver uses prior knowledge to generate expectancies of what is likely to occur. This information is not available in the signal itself, but is applied by the perceiver in interpretation. Figure 2 illustrates bottom-up and top-down processing as it was thought to occur for underwater sounds. Several levels of interpretation were proposed which ranged from low-level spectral parameters to high-level multi-ship configurations. Bottom-up processing proceeds up through the interpretation hierarchy (i.e., certain parameters imply particular harmonics which imply source events, etc.), whereas top-down processing proceeds from higher to lower levels (i.e., the expectation that a particular ship was present suggests that particular sources and harmonics exist).

The most convincing evidence that human auditory perception involves both bottom-up and top-down processing was found in the speech perception literature. Logically, the "raw data" or specific sounds in continuous speech are not sufficient to account for language understanding since the "raw" input is neither complete nor unambiguous. Rather, the listener relies on prior knowledge of the proper orderings (syntax) and the meaning (semantics) of the

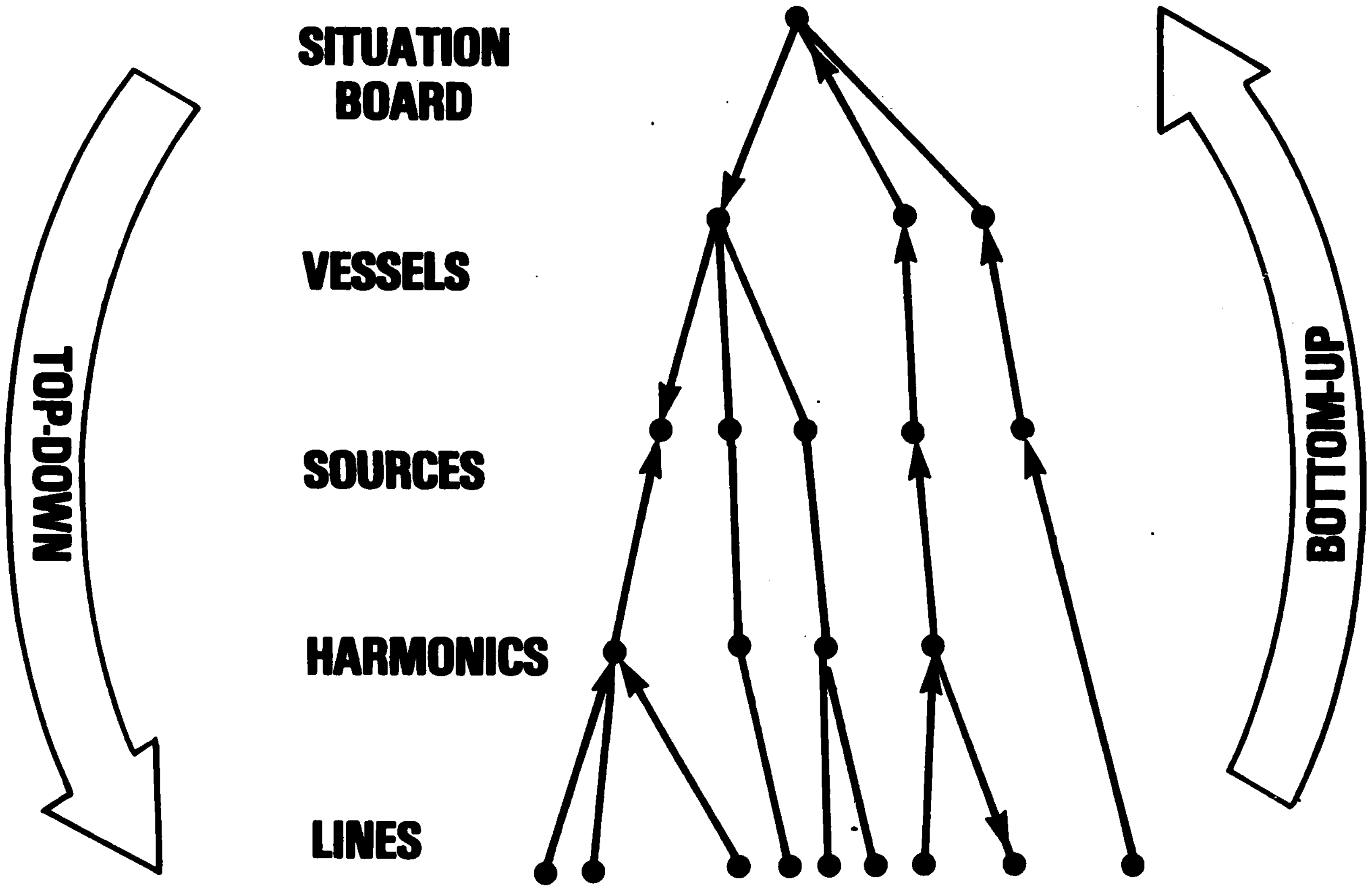

FIGURE 2. HIERARCHY OF INTERPRETATION LEVELS FOR UNDERWATER SOUNDS

words in the utterance. Those elements that can be interpreted unambiguously provide constraints to facilitate the interpretation of other elements. It is common for people to "hear" missing words or to "correct" mispronounced words when they occur in continuous speech. Many recent studies have demonstrated that listeners use a number of knowledge sources in speech perception ranging from fairly specific item-to-item syntactic constraints to global semantic considerations such as the theme or title of a story. Two speech scientists, Ronald Cole and Jola Jakimik, have recently concluded that "it is not only what we hear that tells us what we know; what we know tells us what we hear" (Cole & Jakimik, 1978). The results of a number of our recent experiments have led us to conclude that much the same thing occurs in the perception of certain complex nonspeech sounds.

In the present project we focused on the perception of a large class of nonsteady-state sounds produced by relatively brief-duration mechanical events such as hatch closings or pump operations. Events of this type generate acoustic transients. The human ability to perceive these sounds is of particular interest since current automatic signal-processing devices have limited utility for classification of transients, and brief-duration signals are not easily depicted on visual displays.

Our research demonstrated that top-down processes are especially significant for the perception of most acoustic transients. Such signals are often too brief for listeners to make an extensive analysis of their perceptual features, and acoustic transients frequently occur in temporal successions that form more complex transient patterns. Since these patterns mirror the physical events which produced them, the order of transient components within a pattern is not arbitrary, but reflects the temporal structure of the generating events. Although the temporal structure in patterns of this sort is clearly less rigid and well specified than the syntax of language, a consistent temporal structure exists. Our research indicated that listeners make use of prior knowledge of this structure when processing patterns of complex environmental transients.

Transient Pattern Classification

We conducted a number of experiments to investigate the role of both knowledge of temporal structure (i.e., syntactic knowledge) and knowledge of the source events (i.e., semantic knowledge) in two-alternative (target/nontarget) classification of transient patterns (Pubs. 1, 2, 4, 9, 12). Our findings have shown that both knowledge sources can play an important role in the classification of such patterns.

One experiment was designed to demonstrate that listeners use syntactic information to facilitate the classification of nonspeech transient patterns. Listeners were required to classify sequences of brief-duration pure tones as either "target" or "non-target" patterns. For one group the target patterns were determined by a simple finite-state rule system or grammar. In contrast, another group received target patterns which were randomly determined but matched to the structured targets in length. Consequently, the target set for the first, structured group, had a coherence of temporal order which was lacking in the target set for the second, unstructured group. The results showed that listeners used syntactic pattern structure to their advantage in classifying simple, tonal transient patterns. Listeners who categorized the syntactically-structured target set performed substantially better than those who categorized the unstructured set.

Two other experiments were similar to this, but listeners classified patterns of meaningful, brief-duration, complex environmental sounds such as pipe clangs, steam hiss, and other steam- and water-related noise bursts rather than tones. Semantic knowledge about those events was provided to some listeners in the form of explicit thematic descriptions of the pattern components. Our results revealed that this semantic knowledge led to improved classification performance for interpretable, temporally-structured patterns. However, it was surprising to find that the same semantic knowledge impaired performance when dealing with temporally-unstructured patterns. It was conjectured that in classifying ambiguous or unstructured sounds, dependence on prior knowledge of natural pattern structure led to a greater number of false classifications. Knowledge of temporal structure and knowledge of the source events interacted in an important way to influence classification performance. Individuals relied on their knowledge of the sounds that were likely to occur was well as on the specific perceptual features in the acoustic signals.

Since the effects of pattern meaningfulness can depend on the listener's ability to make sense out of individual pattern components, an additional three-phase experiment was conducted to assess listeners' ability to recognize and to identify isolated environmental sounds (Pubs. 7, 11, 13). The first phase involved free identification of ten short-duration recordings of real-world events. The second phase required free identification of five multi-element sequences composed of a subset of the ten acoustic transients. These sequences were meaningful and represented sounds produced by opening and/or closing water or steam valves. The third phase involved a forced-choice identification of the ten transients using a checklist of descriptors. The results showed that whereas some types of sounds were identified easily by most listeners, others were confused and rarely identified correctly. For example, several metallic sounds were often confused semantically even though they were quite distinct perceptually. The identification of patterns depended on both the salience of the individual sounds in the pattern and the semantic relationships among the sounds.

To summarize, we have demonstrated that many complex sound patterns have both syntactic (temporal) and semantic (contextual) structure which is determined by the sequence of source events which produced them. In interpreting such patterns, human listeners relied on their knowledge of these factors as well as on the perceptual cues available in the sound itself. Although most theorists agree that this occurs in the perception of speech, the role of these factors in the classification of nonlinguistic acoustic patterns had not been demonstrated previously. Our findings have shown that these factors can play an important role in even relatively simple classification tasks.

Target Observation

The pattern classification experiments described in the preceding section demonstrated that listeners use their knowledge of temporal structure to classify patterns of transient events. This raised the question of how the underlying structure was initially acquired or learned by listeners. Three additional experiments investigated how individuals learn to classify sequentially-structured patterns of complex environmental sounds (Pubs. 3, 10). In the first of these experiments listeners classified either auditory patterns or their visually-presented symbolic analogs as targets or nontargets. Some individuals received "observation" trials on which they simply heard (saw) examples of the target patterns prior to classification. The observation trials were shown to be effective for target acquisition, and positive transfer occurred between symbolic observation and subsequent auditory pattern classification. The results of the two follow-up experiments suggested further that listeners acquired a global attentional strategy during the observations and that the generalizability of observational learning was limited when structurally ambiguous patterns were used. Post-experimental tests suggested that individuals implicitly learned something about the composition rules used to produce the target patterns rather than simple paired-associate responses. These findings provided some insights into the abstraction processes which enabled listeners to construct an internal representation of the temporal or sequential structure of nonlinguistic transient patterns.

Attentional Focusing

The preceding experiments established that top-down processes play an important role in the perceptual processing of acoustic transients. This has two important implications. First, top-down processing may lead to improved performance when it helps the individual focus attention on a particular pattern component. Such attentional focusing can lead to an enhanced ability to resolve individual elements from multi-component acoustic patterns. Second, top-down processing may impair performance whenever it leads the listener to "hear" pattern elements which are not physically present in the acoustic signature. Although such auditory induction is helpful in interpreting highly-redundant signals such as speech, misinterpretation can occur when listeners must detect individual components in noisy underwater sound patterns.

An important issue addressed in the attentional focusing experiments was the ability of listeners to use the earlier pattern components as cues to listen selectively for later elements. We carried out a series of experiments in which listeners were presented with twelve-element tonal patterns at a low signal-to-noise ratio (Pubs. 5, 14, 15). Two presentations of a pattern occurred on each of a series of trials. One presentation of the pattern was complete whereas the other was missing the eleventh (primary) tone. The listeners judged which of two consecutive presentations of the pattern had the eleventh element missing and which was complete. On 20% of the test trials, the eleventh component of the complete pattern was replaced with one of four "probe" tones.

Our findings indicated that listeners were more sensitive to the primary tone than to the probe tones. This suggested that as listeners acquired experience with the patterns, they used the earlier components as cues to predict the later elements. This resulted in a selective increase in sensitivity to the expected component with a contrasting inability to hear unexpected elements (i.e., the low-probability probes). Furthermore, this sensitivity changed moment-to-moment as a function of the attentional cues provided by earlier pattern components.

These results suggested that the early components serve two distinct cue functions: (1) an "informational" function that provides information regarding which primary tone was likely to occur on a given trial, and (2) a "frequency" function that automatically directs listening to an appropriate frequency range and narrows or "fine tunes" the listening band. The informational function was demonstrated since "off-pattern" primaries (i.e., high-probability test signals at a frequency which differed from that of the early components) as well as "on-pattern" primaries (i.e., high-probability test signals at a frequency consistent with that of the early components) were detected more reliably than the low-probability probes. The frequency function of the pattern cues was demonstrated since a greater sensitivity advantage was observed for the on-pattern primaries than for the off-pattern primaries. Specifically, when the early pattern components provided a consistent informational cue but inappropriate frequency cue for the test signal, degraded listening performance was obtained.

Auditory Induction

In another series of experiments we examined the second implication of top-down processing described in the preceding section--auditory induction. Auditory induction occurs when sufficient contextual cues exist for listeners to perceive or "induce" implied signals which are not physically present (Pubs. 6, 16). In an auditory detection context induction leads to impaired performance when listeners report hearing targets which are not actually present.

In three experiments, listeners were asked to detect signals embedded in noise bursts which were preceded and followed by an acoustic context designed to be either consistent or inconsistent with the to-be-detected signal. The signals were 200 ms pure tones of constant, rising, or falling frequency. The contextual flanking tones which preceded and followed the noise burst were either continuous or discontinuous in frequency with the to-be-detected target tone. For example, a signal of rising frequency would be "in-context" with low frequency preceding and high frequency following flanker tones. On the other hand, the same rising frequency signal would be "out-of-context" with high frequency preceding and low frequency following flankers.

The results of the first two experiments showed that detection of in-context signals was associated with an increased false-alarm rate and lowered sensitivity relative to out-of-context signals. In the third experiment the signal and the contextual flanking tones were presented to different ears to eliminate the possibility that peripheral masking contributed to this result. The same pattern of selective contextual impairment of detection performance was obtained.

Overall, the results indicated that auditory induction occurs with discrete target signals. In other words, the contextual tones were perceived as continuing through the noise bursts and this illusion degraded detection performance. However, the effect occurred only when the target signal was consistent with its acoustic context. Sufficient top-down processing occurred for listeners to "hear" the in-context signals even when they were not actually present.

Performance Aids

A question of practical significance concerns the design of interactive operator performance aids based on our understanding of how people process acoustic transients. The most recent experiment carried out on this project investigated this issue (Pubs. 8, 17). Specifically, the experiment explored how the interface design of a computerized database system influenced the use of that system by novice (non-technical) users. Alternative displays or performance aids were constructed to provide different "conceptual models" of the system. Training with a conceptual model affected the user's "mental model" of the system, that is, their knowledge or understanding of it. This, in turn, led to substantial differences in performance when the display was used as an aid in classification.

Listeners learned to search a two-dimensional database (sounds varying in pitch and loudness) with one of two conceptual models of the system (analogical or abstract). These models involved different graphical representations of the database which were presented on a video display. After training, listeners were tested on both the two-dimensional and an extended three-dimensional database (sounds varying in pitch, loudness, and duration), using a neutral, verbal display with no graphical component.

The findings indicated that the performance aids provided the users with an initial mental representation of the database system. Users with the analog graphical aid performed better on the two-dimensional database, whereas users with the abstract graphical aid performed better with three-dimensional database. These results indicate that incorporating conceptual models as performance aids in interface design influences novices' performance with a simple perceptual database system.

Conclusions and Implications

Theoretical Significance. It is clear from this research that human listeners depend heavily on their knowledge of the acoustic environment in both classifying and detecting complex nonlinguistic signals. These knowledge sources include syntactic knowledge of the temporal structure or orderings of sounds as well as semantic knowledge about the source events likely to have produced them. As demonstrated on this project, the implications of this top-down processing can be significant for the classification of acoustic transient patterns or isolated meaningful sounds as well as for the detection of contextually-embedded targets. Without considering the external knowledge which listeners bring into an auditory perception task, the processes involved in interpreting complex meaningful environmental sounds cannot be understood.

An important implication of this conclusion is that traditional, bottom-up-oriented approaches to psychoacoustics will not lead to an understanding of how contextually-embedded or meaningful nonlinguistic signals are perceived. As in the case of speech, the information present in the signal itself is insufficient to account for what is heard. For example, in our attentional focusing experiments, the signal context was more important in determining signal audibility than was the signal intensity, and in our auditory induction studies, listeners heard contextually-plausible signals which were not actually present. The most productive strategy for investigating the perception of these sounds is (1) to identify the information or knowledge-sources actually used by listeners in detection or classification, and (2) to determine the relative importance of both top-down and bottom-up processes for various task and signal conditions. The studies carried out on this project have demonstrated the effectiveness of this approach.

Naval Relevance. We live in an age of technology—an age of ever-increasing automation. A natural question to pose in this context is "why study basic human perceptual capabilities when the human is likely to be automated out of the system?" After all, intelligent, knowledge-based computers are reliable, adaptable systems which are especially well-suited to tedious surveillance and monitoring tasks. In our view, the answer to this pragmatic question lies in recognizing the value of basic human research to the automation development effort. Few current pattern recognition systems are fully automated. Rather, most incorporate some combination of human operator and expert system in an interactive environment. An optimized system will achieve a division of labor which is best suited to the capabilities of both the human and the computer system.

Basic perceptual research can contribute to this in two ways. First, once the processes which underlie the human's listening capability are understood, preprocessing performance aids can be developed to facilitate the operator's task. Second, in most cases the very design of expert systems depends in some way on understanding how a human performs the task. For example, H. Penny Nii and Edward Feigenbaum of Stanford University have developed an intelligent, knowledge-based expert system called HASP (SU/X in its earlier versions), for use in machine-aided interpretation of data from an extensive underwater surveillance system (Nii & Feigenbaum, 1978; 1982). The system is based on the HEARSAY-II speech understanding system (Erman, Hayes-Roth, Lesser, & Reddy, 1980), and is designed to identify and track multiple-ship targets by monitoring spectral data over time--much as a sonar analyst monitors a sonogram display. Nii and Feigenbaum have argued convincingly that traditional statistical signal processing methods are ineffective in this complex environment; what is critical is that the system have a knowledge base or level-of-expertise similar to that of the experienced human technician. Given this expertise, the HASP system can use some of the rules or heuristics employed by experienced analysts in data interpretation. As in other expert systems, the knowledge base for this system was developed through an extensive analysis of the procedures followed by expert human technicians. HASP has achieved impressive success with large amounts of real data at poor signal-to-noise ratios. In its current implementation, the raw data input to the system--equivalent to sonogram lines and line parameters--are encoded by human operators for input to HASP. A somewhat more complex, but similar expert system for acoustic signal processing has been developed by Maksym and his colleagues (Maksym, Bonner, Dent, & Hemphill, 1983). Basic research such as that described in this report will be of use in developing fully- or partially- automated systems for sonar analysis.

Research Apprentice Program. We participated in the Minority High Schooler Research Apprentice Program throughout the four-years of this project. Four individuals, all students at Archbishop Carroll High School adjacent to the Catholic University campus, were employed on the project. The students assisted in a variety of laboratory tasks, but focused primarily on computer programming projects since they all had interests in this area. The students were selected on the basis of interviews after a preliminary screening by the school's guidance director. The major criteria used for selection included a strong interest in science, good academic achievement, and a high level of motivation. The students adapted well to the laboratory environment and they got along well with our undergraduate and graduate students and with other staff. All four students continued their education with an undergraduate concentration in computer science at major universities. Vincent Harrison and Joseph Jennifer are both Juniors at the University of Virginia, Earl Mitchell is a Freshman at The Massachusetts Institute of Technology, and Patrick Outlaw is a Freshman at Howard University.

Directions for Future Research

A number of areas for future research were indicated by our findings. First, several direct extensions of the studies reported here would be of value. For example, our attentional focusing experiments revealed that both informational and frequency cues were significant in selective listening, however, the relative importance of these two types of cues was not determined. We have pilot data which indicate that informational cues are ineffective without supplementary information. Similarly, the conditions which determine the strength of induced, "phantom" signals should be explored.

Second, an issue of primary importance concerns the ability of listeners to segment complex acoustic signatures into separate, interpretable sound sources. Bregman has referred to this as auditory stream segregation or streaming (Bregman, 1978). Many recent studies have looked at auditory streaming in simple rhythmic- or in complex musical-patterns, but the segmentation of complex environmental sounds has not been addressed. The experiments carried out on this project provide a good foundation for investigating auditory stream segregation for complex patterns of this type.

Third, although the present project addressed issues primarily of relevance to passive sonar, a range of similar issues should be explored for active sonar. In active sonar, a brief pulse is reflected off of an object to determine its properties by analyzing the reflected signature. Pilot studies in our laboratory indicated that under some conditions, human listeners can learn a great deal about unknown objects by listening to pulsed signatures of this sort. A more thorough understanding of when and how this occurs would be of both theoretical and practical value.

Acknowledgments

The author thanks all of the individuals listed in Appendix B for their important contribution to this research with special thanks to Jim Ballas, Kevin Bennett, and Janet McLeod for their long association with the project and their significant contribution. I am especially grateful to John O'Hare, the scientific monitor for the project, for his encouragement, sharp and relevant criticism, and continued interest in the research.

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Note: references cited as "Pub" in the text are in Appendix A.

Appendix A: List of Publications

1. Howard, J.H., Jr., & Ballas, J.A. (1980). Syntactic and semantic factors in the classification of nonspeech transient patterns. *Perception & Psychophysics*, *28*, 431-439.
2. Ballas, J.A., & Howard, J.H., Jr. (1980). Preliminary research on perceiving patterns of underwater acoustic transients. *Proceedings of the Human Factors Society 24th Annual Meeting*, (Pp. 292-296). Santa Monica, CA: The Human Factors Society.
3. Howard, J.H., Jr., & Ballas, J.A. (1982). Acquisition of acoustic pattern categories by exemplar observation. *Organizational Behavior and Human Performance*, *30*, 157-173.
4. Howard, J.H., Jr., & O'Hare, J.J. (in press). Human classification of complex sounds. *Naval Research Reviews*.
5. Howard, J.H., Jr., O'Toole, A.J., Parasuraman, R., & Bennett, K.B. (in press). Pattern-directed attention in uncertain frequency detection. *Perception & Psychophysics*.

Manuscripts Under Review and In Preparation

6. Bennett, K.B., Parasuraman, R., Howard, J.H., Jr., & O'Toole, A.J. Auditory induction of discrete tones in signal detection tasks.
7. Ballas, J.A. & Howard, J.H., Jr. Interpreting the language of environmental sounds.
8. Bennett, K.B. (in preparation). *The effect of display design on the user's mental model of a perceptual database system*. Unpublished doctoral dissertation, The Catholic University of America, Washington, D.C.

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9. Howard, J.H., Jr., & Ballas, J.A. (1981). Sequential structure and context in the classification of nonspeech transient patterns. *JSAS Catalog of Selected Documents in Psychology*, *11*, Ms. 2188. (also Technical Report ONR-80-14; ADA 087649)

10. Howard, J.H., Jr., & Ballas, J.A. (1982). Event observation in the acquisition of acoustic transient patterns. *JSAS Catalog of Selected Documents in Psychology*, *12*, Ms. 2464. (also Technical Report ONR-81-16; ADA 110522)

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16. Bennett, K.B., Parasuraman, R., Howard, J.H., Jr., & O'Toole, A.J. (1983). Auditory induction of discrete tones in signal detection tasks (Technical Report ONR-83-23; ADA 135502). Washington, D.C.: The Catholic University Human Performance Laboratory.

Papers

17. Bennett, K.B., Howard, J.H., Jr., & Parasuraman, R. (1984). Interface design and "mental models" of a perceptual database system. To be presented at the Mid-Central Ergonomics/Human Factors Conference, April 12-13, 1984.

Appendix B: List of Project Personnel

	Active on Contract	Current Affiliation
Principal Investigator		
James H. Howard, Jr.	8/79 - 12/83	CUA
Research Associates		
James A. Ballas	10/79 - 7/82	Georgetown U.
Raja Parasuraman	8/82 - 6/83	CUA
Administrative Staff		
Lawrence McFarland	10/79 - 7/80	-
Janet McLeod	5/81 - 11/83	CUA
Graduate Research Assistants		
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Gayle Wisdom	1/83 - 7/83	CUA
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