

## XXV. COMMUNICATIONS BIOPHYSICS

### A. Signal Transmission in the Auditory System

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#### 1. BASIC AND CLINICAL STUDIES OF THE AUDITORY SYSTEM

National Institutes of Health (Grants 5 PO1 NS13126-02 and 5 KO4 NS00113-03)

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Members of the Research Laboratory of Electronics participate in basic and clinical studies of the auditory system conducted by the Eaton-Peabody Laboratory of Auditory Physiology. The Eaton-Peabody Laboratory, which is housed at the Massachusetts Eye and Ear Infirmary, also includes investigators from the Eye and Ear Infirmary, Harvard Medical School, and Massachusetts General Hospital, as well as from M. I. T. The goal of the Eaton-Peabody Laboratory is to investigate the physiological and anatomical bases of hearing and to apply results of fundamental research to clinical problems. Active areas of basic research include studies of sound transmission in the middle and inner ear, mechano-electric transduction in the inner ear, coding of sound stimuli into neural signals in normal and abnormal inner ears, processing of neural signals in the central nervous system, and the relation of gross population responses to the underlying cellular activity. Active areas of clinical research include the measurement of evoked electric response to sound for diagnostic purposes in patients with hearing or neurological pathology.

This work has been reported at meetings of the Acoustical Society of America,<sup>1-5</sup> and at other symposia.<sup>6, 7</sup> Journal papers have been accepted for publication.<sup>8-11</sup> One Master of Science thesis<sup>12</sup> and one Doctor of Philosophy thesis<sup>13</sup> have also been awarded this year to graduate students in the Research Laboratory of Electronics for their research in this area.

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## XXV. COMMUNICATIONS BIOPHYSICS

### B. Auditory Psychophysics

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### 1. INTENSITY PERCEPTION AND LOUDNESS

National Institutes of Health (Grant 2 RO1 NS11153-02A1)

National Science Foundation (Grant BNS77-16861)

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This research is oriented toward the creation of a coherent, quantitative, and unified theory of intensity perception and loudness, and involves the construction and integration of models of decision making, sensory processes, short-term memory, and perceptual context effects, as well as extensive psychophysical experimentation.<sup>1-10</sup> We expect the results to provide greater insight into basic phenomena of intensity perception and loudness, and to be of value in the study of equivalent problems involving other stimulus dimensions and subjective attributes and other senses. Also, we expect the results to be of use in the study of memory processes involving more complex stimuli or more complex tasks, and in various applications such as the evaluation of annoyance in noise pollution and the interpretation of abnormal intensity perception and loudness in subjects with hearing impairments.

During the past year, research has been conducted in five areas. First, we have extended our theoretical work on a perceptual-anchor model of context-coding designed to explain the resolution edge effect<sup>7</sup> and the effect of standards in identification.<sup>9</sup> This effort has been directed primarily toward deriving closed-form approximations to

exact formulations that cannot be expressed in closed form, and computing sets of curves to describe the dependence of the model's predictions on the various parameters of the model. The results of this effort are now being prepared for publication. Second, we have performed further experiments to evaluate our theoretical predictions<sup>8</sup> concerning the relation of discrimination to loudness matching. According to these predictions, two stimuli are matched in loudness when they divide their respective dynamic ranges proportionately in terms of number of just-noticeable differences in intensity. The experiments are designed to test these predictions for stimuli consisting of tones, noise, and tones partially masked by noise. The results of these experiments are now being analyzed. Third, we have initiated a new series of experiments to determine the effect of frequency-of-presentation and stimulus spacing on resolution in identification. In most of our past work, the frequency of presentation has been the same for all stimuli and the spacing has been uniform in dB. In the specific experiment now under way, we are examining how resolution is affected by increasing the frequency of presentation of the extreme stimuli or of a stimulus in the center of the stimulus range. Fourth, we have begun to explore how the dependence of intensity resolution on overall level<sup>6</sup> relates to physiological results on auditory nerve firing patterns. This work will make extensive use of data obtained at the Eaton-Peabody Laboratory of Auditory Physiology. Finally, we have started a new experimental program to determine whether the theoretical models and experimental techniques that we have developed to aid us in understanding intensity perception and loudness in normal-hearing subjects can be used to increase our understanding of the same topics in hearing-impaired subjects. All of these projects will be continued during the coming year.

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## 2. BINAURAL HEARING

National Institutes of Health (Grant 5 RO1 NS10916-03 and Fellowship 1 F32 NS05327)

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The primary objective of this research continues to be the development of a unified quantitative theory of binaural interaction that is applicable to a wide variety of binaural phenomena and is consistent with neurophysiological data on the auditory system.<sup>1-5</sup> A secondary objective is to apply our understanding of binaural interaction to the problems of the hearing-impaired. During the past year, significant progress has been made in a variety of areas.

In one project, we are examining more closely our assumption that the variability of the decision variable in binaural detection tasks with a noise masker can be ascribed primarily to the stochastic nature of the peripheral transduction from the acoustic stimulus to firing patterns on the auditory nerve and that the variability arising from the stochastic nature of the acoustic stimulus is negligible. So far, the results of this examination, which are based both on theoretical computations and experiments involving repeated noise bursts having fixed waveforms, are consistent with our assumption.

In a second project, we have explored further the ability to discriminate between interaural time delays and interaural amplitude differences. Earphone listening experiments were conducted in which the subject's task was to discriminate between two tones that were identical except for interaural parameters and were adjusted to have the same mean lateral position.<sup>6</sup> An inability to perform better than chance in this task for some combination of interaural parameters would imply that interaural time and interaural amplitude are completely tradable for this combination. These experiments differed from previous studies directed toward the same question in that acoustic monitoring was used to precisely control the stimulus conditions and that stimulus pairs with symmetric interaural differences were included. The results of these experiments indicate that

subjects who can focus their attention on aspects of the binaural image other than mean lateral position can perform well above chance for all ratios of interaural differences. Our results differ from those previously reported in the quantitative results obtained, the subjective reports of the listeners, and the dependence of the perceptions on training and listening technique. In general, these results support the idea that interaural time and intensity are not tradable (provided the subjects are given an ample amount of appropriate training) and have important implications for the further development of our theory.<sup>5</sup>

In a third project, concerned with binaural adaptation, a series of experiments was conducted to determine the effects that unbalanced interaural parameters have on lateralization judgments.<sup>7</sup> Two types of adaptation were considered: adaptation to interaural amplitude differences and adaptation to interaural time differences. In both cases, the amount of adaptation was measured by using a cancelling interaural time delay to move the binaural image to perceived center. Also, the amount of adaptation was measured over time (from onset of the adaptation period to the point at which the adaptation effect stabilized) so that time constants could be estimated. The results of these experiments indicate that substantial adaptation effects do indeed exist (changes by a factor of two in the time-intensity trading ratio are not uncommon), that the amount of adaptation is influenced by the initial position of the image, and that adaptation effects should be seriously considered in future work on lateralization.

In a fourth project, concerned with the binaural system's ability to extract envelope information, a series of experiments was conducted to investigate the binaural interaction of sinusoidally-amplitude-modulated-Gaussian-noise signals.<sup>8</sup> For conditions in which wideband noise carriers were interaurally incoherent, listeners were able to discriminate interaural differences in modulation phase or modulation rate for modulation rates less than approximately 400 Hz, presumably reflecting the listener's ability to utilize information from the temporal envelope of the stimuli at these modulation rates. The effects on performance of highpass and lowpass filtering of these stimuli implies that this envelope information can be mediated by either high-characteristic-frequency or low-characteristic-frequency neurons, but that interaural comparisons are made only between neurons with similar characteristic frequencies. For conditions in which the noise carriers are interaurally coherent, interpretation of the results is more difficult because of interactions associated with the fine structure of the waveforms.

In addition to the above projects, we have initiated two further projects: an investigation of lateralization "cue-reversal points" as a function of frequency<sup>4</sup> and an investigation of spatial resolution in impaired listeners. The latter project is being conducted in collaboration with the Eaton-Peabody Laboratory of Auditory Physiology. Work on most of these projects will be continued during the coming year.

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3. COMMUNICATION AIDS FOR THE HEARING-IMPAIRED,  
THE DEAF, AND THE DEAF-BLIND

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Edith E. Sturgis Foundation

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Edgar Villchur

The general goal of our research on aids is to develop aids that provide substantially improved speech communication for persons suffering from hearing loss or to understand the fundamental reasons why such aids cannot be developed. During the past year, our research in this area has focused on two main topics: matching speech to residual auditory function, and tactile communication of speech.

a. Matching Speech to Residual Auditory Function

Work on matching speech to residual auditory function continues to focus on multi-band amplitude compression for listeners with reduced dynamic range and on frequency

lowering for listeners with negligible hearing at high frequencies.

We have completed an initial study of the effects of multiband amplitude compression on speech intelligibility for persons with sensorineural losses.<sup>1</sup> Experiments were conducted on five listeners with sensorineural impairments and reduced dynamic ranges using 16-channel computer-controlled, amplitude-compression systems. Each subject was tested with two compression systems and, for reference purposes, four linear systems. One of the compression systems was chosen to restore normal equal-loudness contours; the other employed reduced high-frequency emphasis and reduced compression ratios. The four linear systems differed only in the frequency-gain characteristic (orthotelephonic plus three characteristics with high-frequency emphasis that were expected to produce better results than orthotelephonic). The six systems were compared on each of the five subjects using nonsense CVC monosyllables and sentence material spoken by male and female talkers and presented in quiet/anechoic and noisy/reverberant environments at the most comfortable level for each listener.

The principal results of these tests were: first, the linear systems with high-frequency emphasis produced substantially better performance than the orthotelephonic system, and second, neither of the two compression systems led to significantly better performance than the best linear system. In considering these results, it should be noted that (i) the long-term level of the speech material was held constant before processing, (ii) the subjects suffered from only moderate losses, and (iii) only two compression systems were tested. If we take account of the differences in the linear systems to which the compression systems were compared, these results are roughly consistent with those of Villchur<sup>2</sup> and of Barfod.<sup>3,4</sup>

Work on frequency lowering is directed toward evaluating a number of pitch-synchronous time-dilation processing techniques (including both lowering and warping<sup>5</sup>), as well as pitch-asynchronous techniques that have been studied by others. In initial studies we are employing listeners with normal hearing and using lowpass filtering and additive noise to simulate hearing loss. Three projects are now under way: (i) a study of the basic resolution for materials processed by frequency lowering, (ii) a study of the perception of frequency-lowered vowels, and (iii) a study of the perception of frequency-lowered consonants.

(i) Work on basic resolution is directed at exploring a wide variety of lowering schemes. By examining pairwise discriminations using test procedures which impose relatively little memory load, resolution can be studied without the need for extensive training with processed materials. We are testing schemes having different amounts of lowering and different degrees of warping. In addition, we are varying the amount of lowpass filtering for a given lowering-warping combination.

(ii) Work on the perception of frequency-lowered vowels has made use of a number of frequency-lowering schemes and has been concerned mainly with the performance of



relatively naive listeners on vowel identification tasks. These data will provide a baseline for studies involving extensive training and will also be used in interpreting results obtained by other investigators.

(iii) Work on the perception of frequency-lowered consonants has focused on the ability of listeners to learn (with extensive laboratory training) to recognize CV monosyllables processed by a specific pitch-synchronous lowering-warping scheme that alters high-frequency components to a greater extent than low-frequency components (and that appeared, on the basis of informal listening, to be more promising than some of the other schemes tested).

Substantial experimental work has been completed in each of these three project areas and the results are now being analyzed.

In conjunction with this research, we have also completed a comprehensive review of past work on matching speech to residual auditory function.<sup>6</sup> Work on both amplitude compression and frequency lowering will continue during the coming year.

#### b. Tactile Communication of Speech

The goal of this research is to increase our knowledge of the capabilities and limitations of various tactile display schemes for communicating speech signals. We are now involved in research with two types of display schemes: (i) spectral displays using the Optacon transducer system and (ii) articulatory displays using the Tadoma method (in which the "reader" monitors the articulatory features of speech directly by placing his hand on the talker's face).

(i) Current experiments with the spectral display have focused on discrimination and identification of consonants and vowels. In one experiment, in which frequency and amplitude information is displayed in the rows and columns of the Optacon, we are exploring subjects' abilities to identify a set of 12 consonants, recorded by four different speakers. In another experiment, we are exploring the discriminability of pairs of vowels using two different spectral displays: the frequency-amplitude displays used in the consonant study and a time-swept frequency display. Based on the results of these experiments, as well as further experiments involving other types of speech material and/or other spectral display schemes, we hope to determine the relative merits of a variety of spectral display schemes.

(ii) Experiments on the Tadoma method have been conducted both with a highly experienced Tadoma user<sup>7</sup> and with subjects with normal hearing and sight<sup>8</sup> (for whom deafness and blindness is simulated). Our recent work with the experienced Tadoma user has concentrated primarily on a study of vowel and consonant perception to determine the types of errors that are made and the perceptual cues that are used. Work with normal subjects has consisted of two projects: a study in which subjects were trained to recognize consonants and vowels; and a study in which subjects were trained

to understand connected speech through Tadoma. Preliminary results from the first study indicate that with several hundred hours of training, subjects are able to identify 24 consonants and 15 vowels with an accuracy comparable to that demonstrated by the experienced Tadoma user. In the study of the perception of connected speech through Tadoma, subjects began training with a small set of words that were first learned in isolation and then combined to form sentences. The number of words in the vocabulary was increased gradually over the training period to about 50 words. The data from this study are now being analyzed.

The direction and level of our future work on the tactile communication of speech will depend on the funds available for this research.

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#### 4. MUSICAL PITCH

National Institutes of Health (Grant 1 RO1 NS11680-01 and Fellowship 1 F32 NS05327)

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The overall objective of this research is to obtain a better understanding of the auditory processes that underlie the transformation of a complex sound into a sensation of musical pitch. In connection with this objective, two studies have been carried out.

In one study, concerned with the pitch of harmonic two-tone complexes, musical-

interval identification experiments were conducted using a pulse train for the first note (the reference) and a dichotically presented two-tone complex of nonsuccessive harmonic numbers ( $n$  and  $n+2$ ,  $n$  and  $n+3$ , or  $n$  and  $n+4$ ) for the second note (the target). The results of these experiments were compared with theoretical upper and lower bounds on performance predicted from a general template processing model.<sup>1</sup> The theoretical upper bound is formed by allowing a fundamental scan over the range of fundamental frequencies used in the stimulus set; the theoretical lower bound is formed by allowing an unrestricted fundamental scan. Generally speaking, the experimental data were found to be between these bounds, but, some notable exceptions were observed. For example, when the third and seventh harmonics of 200 Hz were used, performance fell significantly below the lower bound. A study of these results, as well as previous data<sup>2-4</sup> which demonstrate that information about a fundamental can be extracted from even one harmonic under the right conditions, suggested that for the present paradigm a sufficient condition for correct interval identification is that at least one of the two tones in the target complex bear an octave relationship to the target pitch (fundamental). This hypothesis was successfully tested by a control experiment in which only one of the two tones in the target complex was presented. In general, our results are consistent with the idea that a two-tone complex  $nf_0$  and  $(n+m)f_0$  evokes a pitch corresponding to the fundamental  $f_0$  (synthetic listening mode) and pitches corresponding to  $nf_0$  and  $(n+m)f_0$  (analytic listening mode), and that the strength of the former mode relative to the latter decreases with increasing  $m$ .

In a second study, we explored further the pitchlike quantities of the sinusoidally amplitude-modulated noise signals used in the interaural discrimination experiments described in Sec. XXV-2. The results of these interaural discrimination experiments provide indirect evidence that the pitchlike qualities of these stimuli are based on temporal information contained in the envelope of the modulated waveform. In particular, it was observed that the region of modulation rates in which listeners can discriminate interaural differences in the modulation phase (discrimination that is almost certainly based on temporal information) is very similar to the region of modulation rates in which listeners can identify musical intervals for these stimuli.<sup>5,6</sup> In a separate experiment designed to study the effect of interaural phase of the modulation waveform on the identification of musical intervals, it was found that performance was independent of whether the two ears were in phase (subjective image centered in the head) or out of phase (subjective image diffuse or lateralized in the two ears).

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5. MUSICAL ACOUSTICS

National Institutes of Health (Grant 1 RO1 NS11680-01)

Adrian J. M. Houtsma, Ernest J. Perevoski

The overall purpose of this program is to gain insight into the processes involved in the production and perception of music. Work during the past year has continued to focus on electronic pickup systems for the classical guitar and pitch tracking of recorded vocal music.

When an acoustically weak instrument such as the classical guitar is played in a large symphony hall, electronic amplification becomes a necessity. Furthermore, the conventional technique of amplifying a near-field microphone recording seems likely to produce a less than optimal representation of the far-field acoustic spectrum of the instrument. Thus, attempts were made to match the frequency response of a mechanically driven guitar body, measured through an acoustic microphone in the far field in a reverberant chamber, to a linear mix of signals obtained from contact microphones on the guitar body.<sup>1</sup> It was found that the closest match is obtained when the signal from an acoustic microphone in the sound hole is mixed with the integrated signal from a single accelerometer-type contact microphone placed on the bridge, the overall signal thus representing the sound pressure in the sound hole (principally the Helmholtz resonance of the body cavity) and the velocity of antinodes of the sound board (all higher characteristic modes). This "optimal" array was then compared with the conventional near-field microphone recording in a comparative listening test.<sup>1</sup> Listeners were exposed to various sounds from the guitar, such as mechanically driven white noise, pure tones, pulse trains, and string-driven open notes, fretted notes and chords, all recorded in the far field. Each sound was immediately followed by three "pickup versions" of that sound: one from a near-field acoustic microphone, a second from our "optimal array," and a third from another, less-than-optimal array. Listeners were asked to indicate which of the three versions was closest to the target (far-field) sound. The third array was never chosen, but in more than half the cases the near-field microphone

was chosen over the "optimal array." Presumably, this result reflects a significant discrepancy in the physical and subjective criteria used to match spectra.

Research on pitch tracking of recorded music has resulted in the construction of a "melograph" (based on a previous device<sup>2</sup>) which plots pitch vs time on a continuous strip chart. The melograph has an amplitude compressor to eliminate dynamic changes, a rectifying circuit to introduce energy at the fundamental in case there is no energy at the fundamental in the original signal, a bandpass filter tuned to the expected fundamental range, and a Schmit-trigger circuit. A second lowpass filter measures the dc value of the triggered pulse train, proportional to the pitch of the fundamental, and controls the vertical input of the strip chart. This system was found to handle a large variety of instrumental and vocal sounds, and, unlike most commercially available pitch-tracking devices, showed little sensitivity to timbre changes (e. g. , singing an /a/, /eI/, /i/, /o/, /u/ sound with a given pitch does not change the pitch reading).

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## XXV. COMMUNICATIONS BIOPHYSICS

### C. Transduction Mechanisms in Lateral Line and Vestibular Organs

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National Institutes of Health (Grant 2 ROI NS11080-04)

Lawrence S. Frishkopf, Charles M. Oman

Our broad goal is to understand the mechanisms of transduction in the receptor organs of the acoustico-lateralis system of vertebrates by studying the mechanical, electrical and synaptic events in hair cell organs, and their relation to nerve activity. During the past year we have: (i) completed an analysis of inner-ear fluid composition in representative vertebrate species;<sup>1</sup> (ii) completed a study of cupula motion in the semicircular canal of the skate;<sup>2</sup> and (iii) continued our efforts to identify the afferent transmitter substance in hair cells.

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#### 1. EVIDENCE OF THE PRESENCE OF MONOAMINE CONTAINING STRUCTURES IN HAIR CELLS

Lawrence S. Frishkopf, Richard D. Kunin

A number of recent studies provide evidence relating to the identity of the afferent transmitter substance in hair cells. Proposed candidates include glutamate and aspartate,<sup>1-3</sup> monoamines,<sup>4, 5</sup> and GABA.<sup>6</sup> Our results indicate that monoamine-containing structures are present in hair cells. Specifically, we have observed in the crista of the skate semicircular canal numerous small inclusions which fluoresce when the tissue is treated by a histochemical technique that demonstrates by fluorescence the presence of biogenic monoamines.<sup>7, 8</sup> We are attempting to localize and identify these inclusions, using techniques of fluorescence, phase, and electron microscopy. We have found that the inclusions are confined to the apical portion of the sensory epithelium, where hair cells are located; many are clearly within hair cells. It is not yet possible to say

whether they occur only in hair cells or may also be found in apical portions of supporting cells and nerve terminals. Earlier studies<sup>4,5</sup> have shown that drugs (reserpine, guanethidine, and FLA-63) that deplete monoamine stores cause significant alterations in synaptic bar and synaptic vesicle morphology in hair cells. The possibility is therefore suggested that the fluorescent inclusions that we have seen in hair cells may be synaptic bars. This interpretation is consistent with both the locations and sizes of the inclusions: like synaptic bars, they are found in hair cells, often close to the cell membrane, and most are less than 0.5  $\mu\text{m}$  in diameter.

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XXV. COMMUNICATIONS BIOPHYSICS

D. Biomedical Engineering

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Included under this heading are a variety of topics in biophysics, physiology, and medical engineering. Many of these are individual projects of students supported by training grants from the National Institutes of Health.