RLE **currents**

Volume 6, Number 2 • Spring 1993

The Research Laboratory of Electronics at the Massachusetts Institute of Technology

# Measuring the Dimensions of Sensory Communication at RLE


*Gathered around Senior Research Scientist Nathaniel I. Durlach (center at left) and Professor Louis D.B. Braida are staff members and students of RLE's Sensory Communication Group, some attired in the group's intriguing research devices. Sporadically clockwise: Visiting Scientist Yun Shao wears a pseudophone; Research Specialist Hong Z. Tan dons headphones; student Ross A. Yu is outfitted in a head-holding device and earphones; Research Specialist Lorraine A. Delhorne and graduate student Barbara Shinn-Cunningham sport headphones; Research Assistant Walter A. Aviles is masked by a pair of prism goggles; Administrative Secretary Eleanora M. Luongo minds the Tadoma synthetic face apparatus; the Knowles Electronic Manikin for Acoustic Research, called KEMAR, whose head is on loan to Boston University; Visiting Scientist Min Wei totes the Tactaid VII device; and Administrative Secretary Ann K. Dix is disguised by a head-mounted stereo image display. Discover more about sensory communication and these fascinating devices in this issue of* ***currents****.* (Photo by John F. Cook)

# Sensory Communication at RLE

It is only through our sensory systems that we can gather knowledge from the world around us. Our five senses—sight, smell, taste, touch, and hearing—convey the information we need to interpret and respond to stimuli of light, chemicals, mechanical pressure, and temperature. Simultaneously, we are able to distinguish between different colors, decide which flavors we like, and process speech, music, and environmental sounds. How can we respond so quickly to the endless flow of inputs from our environment? What can be learned by investigating our sensory mechanisms and their relationship to both physiological and psychological phenomena?

The field of *psychophysics* examines this relationship between physical stimuli in our environment and our psychological reactions or behavior to them. Although the physical events around us can be measured, they are perceived subjectively in a way that is difficult to measure. Research in this area has provided clues on how the mind works by examining how it processes physical stimuli from our environment. Psychophysical techniques have served as keys to unlocking the mysteries of human perceptual processes.

To begin to understand human behavior, we must know how sensory mechanisms are constructed and how they convey sensations. *Sensations* are the immediate and basic experiences caused by stimuli; our *perception* interprets these sensory experiences, giving them meaning and organization. The sensory and perceptual systems work together to accurately reflect our environment so the mind can comprehend the information it is processing. Basic research in this area focuses on the environmental factors that the sense organs respond to, and how these factors are detected and ultimately transmitted to the brain. This knowledge is the basis for examining an even more complex function called *cognition*, which involves the acquisition, storage, and retrieval of information. In the realm of basic research, RLE's Sensory Communication Group studies both the auditory and tactual senses, as well as auditory, visual, and sensory aids for individuals who are hearing impaired or deaf.

As technology advances, it becomes increasingly dependent on humans to perform more precise per-

*Professor Louis D.B. Braida shows a videotape of a teacher of the deaf demonstrating "Cued Speech." She provides gestures or "cues" with her hands while speaking normally in English. Studies in RLE's Sensory Communication Group have shown that a deaf person trained to interpret the cues while speechreading can understand spoken English at normal speaking rates. Current speech recognition technology may be capable of generating these cues from an acoustic speech signal.* (Photo by John F. Cook)


RLE **currents**

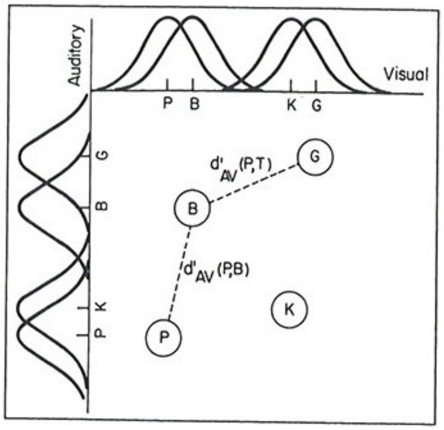
RLE ***currents*** is a biannual publication of the Research Laboratory of Electronics at the Massachusetts Institute of Technology.

Jonathan Allen . . . . . . . . . Editor-in-Chief
Joseph F. Connolly . . . . . Managing Editor
John F. Cook . . . . . . . . . . . . Photography
Everett Design . . . . . . . . . . . . . . . Design
Dorothy A. Fleischer . . . . . . . . Staff Writer and Editor
Barbara Passero . . . . . . . . . . . Production and Circulation
Henry J. Zimmermann . . . . . . . Advice and Perspective

The staff of ***currents*** would like to thank Professor Louis D. Braida and RLE's Sensory Communication Group for their contributions to this issue.

Inquiries may be addressed to **RLE *currents***, 36-412, Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307.

(ISSN 1040-2012)




*Speech reception is improved if a listener can integrate the cues derived from visible actions of the talker's face with cues derived from the acoustic signal. The process that integrates cues across sensory modalities is not well understood. Professor Louis D.B. Braida has developed a theoretical model (above) that describes auditory and visual cues when a speaker's voice can be heard and the face can be seen. This model has applications in intermodal integration, which is used to design improved hearing aids.*

ceptual discriminations. This dependency points to the need for applied sensory research. Humans and machines now work together in many situations where physical conditions may not be ideal. For example, pilots and astronauts must communicate their perceptual discriminations and judgments quickly and accurately to their instruments and equipment. This is the goal of the sensory scientists whose applied research seeks to determine the human ability to discriminate and interpret stimuli so that an individual's capabilities can be matched to the requirements of a task. In this area, a new research direction in RLE's Sensory Communication Group, the Virtual Environment and Teleoperator Research Consortium (VETREC), investigates human-machine communication for both virtual environments and teleoperator systems.

## Setting Limits for Detection and Discrimination

The electrical signals sent to the brain by auditory nerve fibers are not sounds in themselves, but are impulses that encode the sounds which elicit responses from various parts of the brain. A single sound can trigger physical reactions such as movement or speech, as well as emotions in the listener. But, any sound must reach a certain intensity level before it can be heard. All sense organs or receptors, such as the ear, have a minimal level of stimulation needed to activate a particular sensory system.

The smallest amount of stimulus energy needed to produce the weakest detectable sensation is known as the *absolute threshold*. The word absolute is somewhat misleading, since a threshold value is found by averaging a range of stimulus intensities. Because a sense organ's response may vary from moment to moment, a range of intensities is determined over which the stimulus' physical energy gradually moves from having no effect, to a partial effect, and finally to a full effect. The absolute threshold is the value at which the observer perceives the stimulus 50 percent of the time.

In contrast to the detection of stim-

*(continued on page 4)*

# Director's Message

Human communication occurs in many ways. We commonly think of language as the backbone of human communication and cognitive activity, but human sensory capability is also used for many other communication tasks, and the importance of these sensory pathways is rapidly increasing. In this issue of ***currents***, we examine the psychophysical studies of human sensory perception and how this knowledge is being exploited within RLE's Sensory Communication Group. Auditory, visual, and tactile sense modalities are being studied, and relationships are being derived between the objective attributes of stimuli and the nature of the subjective sensations that humans perceive. Basic psychophysical laws for these relationships have been discovered and are being used to design prosthetic aids and many other human-machine interfaces.

*Professor Jonathan Allen, Director Research Laboratory of Electronics*

An exciting facet of these discoveries is the phenomenon of *sensory plasticity* and how it enables information to be transmitted over several different sensory modalities. For example, although language is normally conveyed by speech to the auditory system, it can also be presented visually (as in lipreading) or by a variety of tactile means. In addition, increasing attention is being focused on *sensory integration* and how multiple sensory modalities cooperate to form an overall percept. These two phenomena are important in the design of *virtual environments*, where humans can use all of their sensory channels to interact with computers. Understanding how information can be communicated between humans and these computer-generated environments is now a major theme of research in the Sensory Communication Group. This knowledge is essential to the design of interfaces that seek to enhance the way in which humans and computers can communicate.

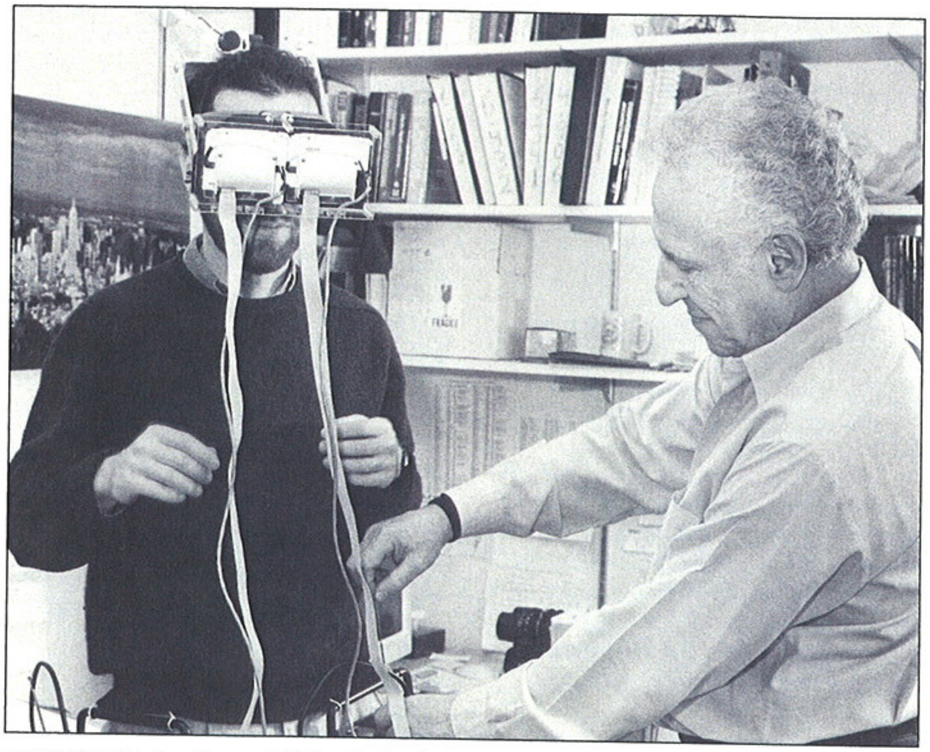
uli, discrimination studies examine how much a stimulus must change in order for the observer to perceive a *just noticeable difference*. The *differential threshold* measures this smallest detectable difference between two stimuli. Observers are asked to compare a standard stimulus with a comparison stimulus. From these experiments, a just noticeable difference is calculated for the stimulus.

The techniques used to determine absolute and differential thresholds are based largely on the combined psychophysical research of Ernst H. Weber, Gustav T. Fechner, and S. Smith Stevens. In 1829, German physiologist Ernst Weber noted that the greater the magnitude of a stimulus, the greater the change was required for a difference to be detected. Thus the difference threshold tends to be a constant fraction of the stimulus intensity. Although Weber's law was formulated for thresholds, German physicist and physiologist Gustav Fechner extended it to develop scales for measuring sensory experiences. In the mid-1800s, Fechner applied the first measurement techniques for subjective sensations of the human mind. He proposed that as stimulus intensity increases, so does the psychological response, but not proportionally. Instead, the magnitude of an observer's psychological response is directly related to the logarithm of the intensity of the stimulus. This logarithmic equation, known as the *Weber-Fechner law*, has been modified to examine the results from a wide variety of experiments. More recently, Harvard University psychophysicist S. Smith Stevens generalized Weber's and Fechner's findings and proposed the *power law*. It states that the magnitude of the psychological response grows in proportion to the physical intensity of the stimulus raised to a power ($n$). The nature of the judgements determines the value of $n$, which differs for each sensory modality.

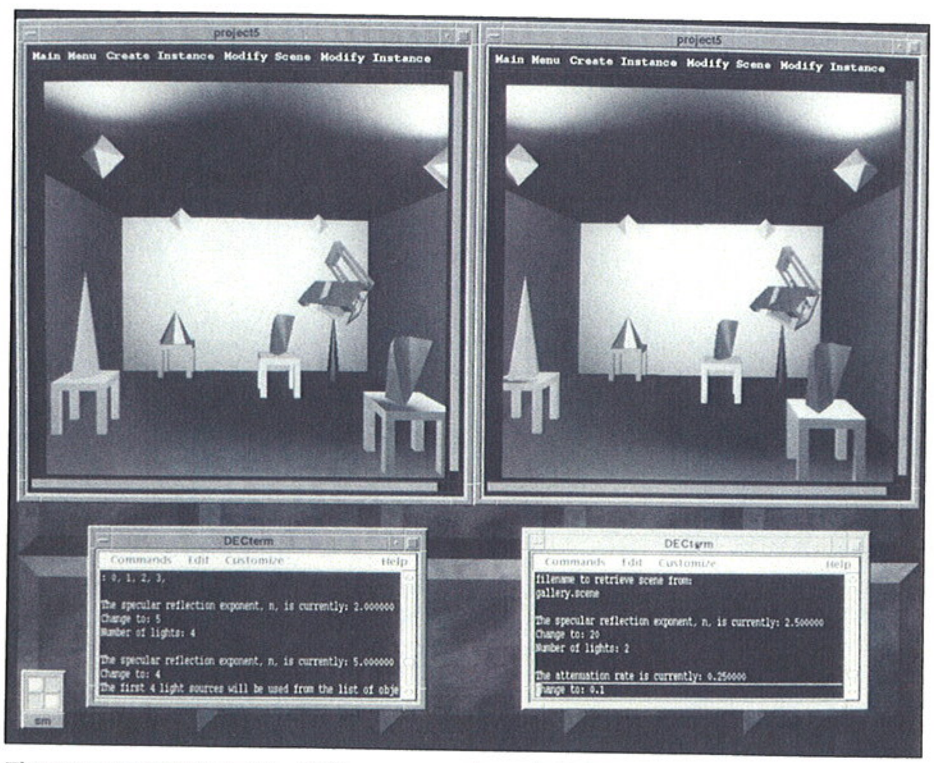
## Signal Detection Theory

The concept that a threshold must exist in order for a subject to determine whether or not a stimulus is present has been greatly disputed by many investigators. Classical methods in psychophysics do not consider the possibility that "no stimulus" is present, even though an observer might erroneously report that a stimulus was received. In 1954, W.P. Tanner, Jr., and John A. Swets proposed that a combination of statistical decision theory and signal theory used for communication systems and electronic signal-detecting devices might be adapted to build a model that closely approximates how people behave in detection situations. Signal detection theory (SDT) acknowledges that detection can vary in certain situations, taking into account people's sensitivity and decision-making strategies, as well as factors such as expectation and motivation. It provides a means of separating the factors related to criterion, motivation, and bias from factor related solely to sensory capabilities. SDT also recognizes noise in a system, specifically the noise or interference present in the background activity of the nervous system which can combine with meaningful sensory signals. Since noise varies randomly, the observer in a detection experiment must decide if the trial presents only noise or stimulus plus noise. Thresholds cannot be calcu-

*Principal Research Scientist Dr. William M. Rabinowitz and Postdoctoral Fellow Dr. Susan L. Goldman check on a prototype of a multiple microphone hearing array that is mounted along one arm of Susan's eyeglasses. Four miniature electret microphones are contained in the array, similar to the single microphones used in currently available hearing aids. The multimicrophone array provides a substantial improvement for hearing-impaired users when they are confronted by background noise and reverberation. Its enhanced spatial selectivity partially compensates for the benefits of binaural hearing which are degraded in the hearing impaired.* (Photo by John F. Cook)



*Assisted by Senior Research Scientist Nathaniel I. Durlach, Research Assistant Eric M. Foxlin (left) dons a head-mounted display (HMD) to view a stereo image in a virtual environment (see inset). As Mr. Foxlin moves his head, the mechanical head tracker transmits the new position to a computer that generates a new stereo image. (Photo by John F. Cook)*




*The HMD employs two color LCD screens and a wide field of view to display a stereo image. This computer-generated example shows views, from both the left and right eyes, of a room in a virtual environment.*

lated with SDT, and the classical psychophysical methods must still be used. However, SDT explores some of the problems associated with measuring thresholds when using these methods.

## Hearing And Sound

## Sensations in Sound: Detection and Discrimination

Sound is mechanical energy in the form of air vibrations produced by a moving or vibrating object. Sound waves are described by their physical dimensions of frequency and amplitude or intensity. Frequency is the number of cycles a sound wave can complete in one second, expressed in hertz (Hz), and is the physical dimension of what we perceive as pitch. Humans can hear tones in the frequency range of 20-20,000 Hz. Below 20 Hz, only a vibration or fluttering sensation can be detected. Above 20,000 Hz, a tickling sensation may be perceived. Although each frequency has its own threshold, tones are optimally detected in the 3,000-Hz range, and best discriminated at low frequencies of 2,500-3,000 Hz. Thus, the frequency range that requires minimal intensity for threshold detection is also the range with the smallest differential threshold. It has also been found that sounds in the 3,000-Hz range are generally perceived louder than sounds at other frequencies of the same intensity.

Subjectively, we perceive the frequency of a sound, or how high or low it appears to us, as pitch. Additional factors that influence how we perceive pitch include amplitude, previous sounds, and alertness of the observer. Loudness is a psychological dimension determined by amplitude or sound intensity, and intensity is the physical change in pressure created by sound waves. The relationship between the two is complex and not completely understood, since frequency plays a role in determining loudness. Intensity has been shown to influence pitch: as intensity increases, the pitch of high tones increases while pitch decreases for low tones. Discrimination of intensity is an important factor in localizing or determining the source of a sound. Frequency also has a greater influence on loudness at low levels of intensity and has a minimal effect on loudness at high

*(continued on page 6)*

levels of intensity. Thus, if tones are intense, they tend to sound equally as loud, regardless of their frequency. How much of a change must occur before a difference in frequency is detected? For frequencies up to 1,000 Hz, it has been determined that a difference of 3 Hz is needed to discriminate a change in sound frequency. For frequencies in the 1,000-10,000 Hz range, Weber's fraction is calculated. Intensity also influences one's ability to discriminate the smallest frequency change of a particular sound.

In order to obtain precise measurements, special facilities are used to test experimental subjects where the environment is totally without reflective sound. One type of testing facility is an *anechoic chamber,* which eliminates all sound reflections or echoes. In this environment, computers present a variety of sound stimuli to the listener, including pure and combination tones, complex sounds, beats, noise bursts or clicks, and masked tones. Using a combination of other phenomena such as sound-induced hearing loss or changing the sound's volume, density, and consonance or dissonance, the factors involved in the human perception of sound are explored.

# Higher Levels of Sound Perception

## Localizing Sound in Space

Sound localization is the identification of a sound source's direction and distance. Monaural or one-eared cues are mainly useful in determining the relative distance of a stimulus. Binaural cues, or the stimulation received by both ears, are important in determining the direction of a sound's source, since it must travel a different distance to each ear. This phenomenon leads to *interaural time difference*, which consists of an *onset time difference*, the time it takes for a sound to reach each ear, and a *phase difference*, when sound is diffracted around the head and different portions of the sound wave are presented to each ear. Sound also reaches each ear at different intensities and is sometimes affected by an *acoustic shadow* cast by the head. Other factors that influence sound localization include vision, head movement, the actual position of the sound source, and reverberation.

## Speech Perception

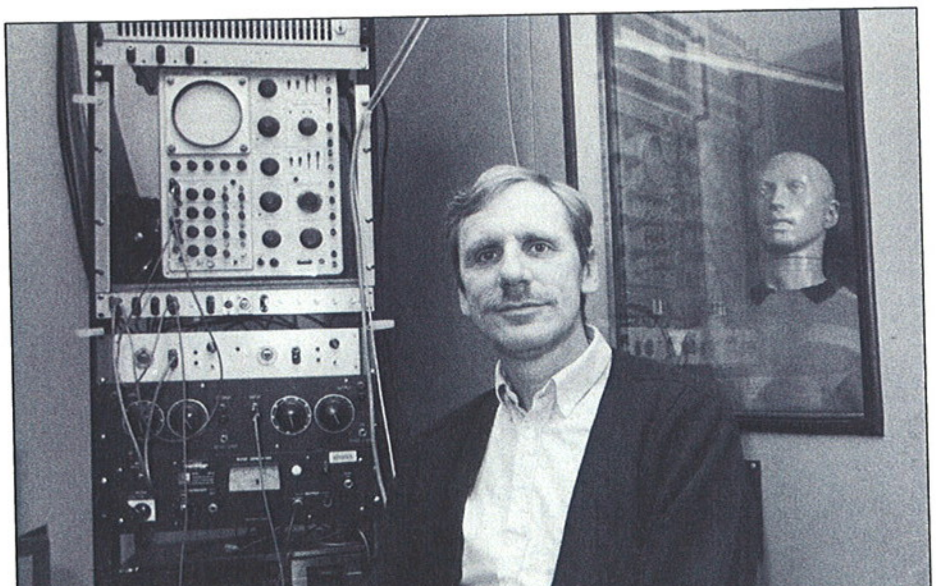
We are able to recognize speech successfully even though we typically experience conditions that distort it. Considering the vast size of our vocabularies and diverse speech patterns within a particular language, plus the fact that spoken words do not have audible boundaries, the phenomena of speech perception are truly astonishing. The intelligibility of speech can persist despite an infinite variety of pronunciations, speaking rates, and voice qualities, as well as environmental background noise, sound omissions, and speech distortions.

The process of speech recognition involves not only a sophisticated analysis of a continuous stream of sound patterns, but also the operation of a complex and integrative cognitive mechanism. Speech is not composed of pure or simple tones, and the human auditory system processes speech sounds differently from other auditory stimuli. Most speech sounds are a complex pattern of intensities and frequencies that occur over time. Although speech sounds are perceived symbolically, they are processed faster than any other auditory stimuli, possibly due to specialized perceptual processes.

# Hearing Impairments

Hearing impairment and deafness have many causes and their characteristics can vary from systematic sound distortions to a complete failure of the auditory system. The causes may involve congenital conditions, infection, the side-effects of drugs and chemicals, noise pollution, brain damage, or the normal effects of aging. Hearing impairments not only affect the ability to hear sounds at normal loudness, but also the quality of sound, because the perceptual relations between components of complex sounds have been altered. Music and environmental sounds may be muffled, distorted, and more importantly, speech can lose its intelligibility.

There are two classes of hearing loss. *Conduction* or *transmission deafness* affects the conductive structures in the outer and middle ears, where sound is normally amplified and sent to the



*Principal Research Scientist Dr. Patrick M. Zurek carries out studies of signal processing aimed at enhancing speech intelligibility for hearing aid users. In a soundproof room behind Dr. Zurek sits KEMAR, the Knowles Electronic Manikin for Acoustic Research. The equipment (at left) is used in conjunction with computers to modify the signals presented to KEMAR for testing experimental hearing aids.* (Photo by John F. Cook)

*Professor Richard M. Held wears a head tracking device as he prepares for an experiment on auditory localization. Professor Held investigates perception in the visual and auditory modalities with a special focus on the sensory transformations involved in virtual world technology.* (Photo by John F. Cook)

*cochlea*, which contains the essential organs of the inner ear. Sensitivity is reduced to all sounds. Surgery, drugs, and hearing aids may be helpful in alleviating some cases of conduction deafness. *Sensorineural deafness* affects the inner ear's sensory mechanisms, the fibers of the auditory nerve, and the auditory cortex of the brain. Hearing loss may be total or partial, affecting sounds heard at certain frequencies. Hearing aids that primarily amplify sound levels may not help individuals with this type of deafness.

Some hearing aids seek to restore sensitivity and clarity of sounds in both quiet and noisy environments, while keeping the amplification of higher intensity sounds at tolerable levels for the listener. The specific nature of an individual's hearing loss must be taken into account, as well as the nature of the acoustic environment in which the aid will be used and the characteristics of the hearing aid itself, such as ease of use. Underlying issues must be resolved, such as the best use of amplification and variable frequency response, the listener's ability to fuse binaural signals into a single sound, and sound localization. The influence of microcircuit technology has enabled investigators to achieve highly sophisticated signal filtering and signal manipulation in very small dimensions.

Hearing aids may provide only limited benefits to those with sensorineural hearing loss. If the inner ear mechanisms are functional, increased volume may enable hearing by causing the bones in the middle ear to vibrate more strongly and trigger more nerve impulses. If the inner ear and auditory nerve are impaired, amplification provided by the hearing aid may be of little help since the vibrations cannot be converted to meaningful sounds. The *cochlear implant*, a surgically implanted electrode array, has been developed to help restore hearing to people with sensorineural deafness. The implant acts as a substitute for damaged hair cells and other cochlear structures, bypassing the external and middle-ear pathways. An electrode stimulator excites the array, which generates electric fields close to the remaining active nerve fibers and stimulates the auditory nerve. The stimulator is a signal processing device that converts incoming acoustic signals into stimuli processed by the implant. When used in conjunction with lipreading, cochlear implants can provide substantial benefits to speech reception, enabling more reliable and comfortable communication.

## Turning Deaf Ears to Sensory Communication

Our sense of touch is quite similar to our sense of hearing. The auditory system uses specialized mechanical receptors (mechanoreceptors) to sense environmental disturbances in the air, while our sense of touch uses pressure-sensitive cells (also mechanoreceptors) distributed over the body's entire surface. Both hearing and touch transduce pressure and vibration, thus both of these sensory channels are capable of communicating speech.

The skin is our largest and most fragile sensory system. Several types of skin receptors are sensitive to specific stimuli, such as the mechanical distortion or deformation of the skin that happens when we come in contact with an object. The many types of skin receptors are all nerve endings that transmit information from the skin to higher processing levels. However, since there are no clear relationships between the specific types of skin receptors and the sensations that we experience, recorded responses to cutaneous stimuli are based on our subjective responses.

There are two classes of touch: *passive* and *active*. Passive touch refers to the cutaneous sensitivity that is felt as pressure, temperature, or pain when objects come in direct contact with the skin. The information detected by passive touch is called *tactile*. Tactile information describes the type of contact with the object (such as static, slipping, or vibrating) and certain properties of the object (such as texture). It is conveyed by the responses of several types of skin receptors within and around the object's contact region. Active touch is used to investigate objects and their properties and to interact with our environment. Active touch involves *tactual* information, both the skin's cutaneous sensations (tactile) as well as the body's *kinesthetic* sensitivity to spatial position and movement. Kinesthetic information is conveyed by sensory receptors in the muscles, tendons, and joint capsules, together with receptors in the skin around the joints.

*(continued on page 8)*

Probably the most well known and successful tactile aid is the Braille reading system for the blind. Several others systems and devices have been developed which have achieved varying degrees of success. An optical-to-tactual converter can enable a blind person to read the visual image of a printed alphabet character by converting it to a tactual image and transmitting it through the fingertip. Another tactile system uses small contact vibrators placed on the skin to transmit the alphabet. Each letter has its own unique duration, intensity, and contact vibration point. Another system uses an optical scanning device to convert printed material into vibrating touch stimulation. The *Tadoma method* of speech reception uses cutaneous stimulation to communicate speech to individuals who are both deaf and blind. By placing a hand on parts of the speaker's lips, face, and neck, the listener's hand receives not only vibrations, but also patterns of movement produced by the speaker's articulatory actions. Experienced Tadoma users have achieved almost normal levels of speech reception.

*Research Specialist Lorraine A. Delhorne (left) and Principal Research Scientist Dr. Charlotte M. Reed demonstrate the tactual reception of fingerspelling, a method used by deaf-blind individuals. Fingerspelling is being studied as part of a research program on natural methods of tactual communication. Tactual communication involves not only the skin's cutaneous receptors used in tactile communication, but also the kinesthetic elements and proprioceptors associated with the body's physical movement and spatial position.* (Photo by John F. Cook)

## Sensory Communication Research at RLE

The Sensory Communication Group conducts basic and applied research in a variety of areas related to the auditory and tactual senses: auditory, visual, and tactual aids for individuals who are hearing impaired or deaf; human-machine interfaces for teleoperator and virtual environment systems; the computer generation of virtual environments and the application of these systems to training. Although there is a strong emphasis on quantitative theoretical modeling, the group also conducts experimental work to test and guide the development of these models. Within the domain of psychophysics, the group's work is strongly influenced by communication theory. Unlike work by other groups on direct sensory scaling in which responses are taken at face value, the investigators in the Sensory Communication Group seek to examine the sensory system's underlying structures and limitations.

### Audition and Aids for the Hearing Impaired

The goal in developing hearing aids for people who suffer from sensorineural impairments is to improve speech communication. A large part of this work is focused on the design of improved signal processing schemes that will better match speech signals to the residual auditory function.

Several projects address the effects of speech articulation style and environmental disturbances and variability in speech segment production on speech reception in the hearing impaired. Previous studies have indicated that talkers can greatly improve speech reception by making an effort to speak clearly. The group is now determining which acoustical properties of clearly enunciated speech are responsible for its high intelligibility and is exploring the possibility of developing signal processing techniques aimed at these properties. Similarly, studies are underway to determine how background noise and reverberation interact with the loss of auditory sensitivity and resolution to degrade intelligibility as well as evaluations of the limitations on intelligibility related to intra- and inter-talker variations in speech segment production.

In connection with empirical studies, a computational model is being developed to predict the effects of various signal transformations in auditory abilities on speech intelligibility. The model is intended to have applications to both the acoustical and optical components of speech, and to visual and tactile displays that involve arbitrary recodings of speech.

Applied research to develop signal processing schemes for improved speech reception by the hearing impaired includes work on adaptive linear amplification techniques to combat environmental noise and acoustical feedback effects, and several forms of amplitude compression and frequency lowering to better fit the amplitude and frequency range of speech into an impaired listener's reduced auditory capability. Automatic speech recognition is also being studied for applications to the hearing impaired.

Since many hearing-impaired individuals rely heavily on speechreading in face-to-face communication (such as lipreading), several applied research projects are aimed at the development of hearing aids that may be effective speechreading supplements. The group has documented the empirical benefits obtained from various acoustic supplements and has shown that articulation theory accounts for the benefits to speechreading provided by partially intelligible acoustic speech. Modeling efforts are directed toward understanding how well acoustic and visual cues are integrated in various situations. The results suggest that automatic speech recognition systems may be accurate enough to generate auxiliary visual cues that can significantly enhance speech reception achieved by speechreading alone. Research is now focused on the development of recognizer output displays that can be integrated with speechreading and are resistant to recognizer errors.

*Visiting Scientist Yun Shao models the pseudophone, which has microphones installed in the extensions on the device's hat. The pseudophone acoustically rearranges auditory signals and helps investigators to study sensory motor adaptation. Assisting with the fitting are (from left) graduate student Barbara Shinn-Cunningham, Principal Research Scientist Dr. William M. Rabinowitz, and Visiting Scientist Min Wei. (Photo by John F. Cook)*

Cochlear implant research, performed in collaboration with the Massachusetts Eye and Ear Infirmary, addresses the condition of total deafness. Implant subjects have not only demonstrated the remarkable potential for these prosthetic devices, but they also present unique opportunities to explore the auditory code for sounds. The Sensory Communication Group has documented the speech reception performance of individuals with cochlear implants, interpreting performance limitations in terms of underlying aspects of speech signals and comparing performance among other prostheses for the deaf. Ongoing work includes studies of fundamental perceptual limitations that can help to predict speech reception from simple tests with nonspeech signals, with a major emphasis on the continuing design and evaluation of processing schemes that improve implant performance.

Other research on audition and hearing aids focuses on issues related to auditory spatial perception and the use of sensing systems to sample an acoustic field at several different locations. Much of this work is directed toward the role of binaural hearing in complex acoustical environments, where the perception of a target signal may be degraded by interfering signals and reverberation. In addition to empirical and theoretical efforts to characterize the performance of normal auditory systems, considerable attention is given to the inability of impaired listeners to function in complex acoustic environments, as well as to degradations in binaural processing associated with various types of hearing impairments. The long-term goal is to develop an integrated, quantitative theory of binaural interaction consistent with psychophysical and physiological data on normal and impaired auditory systems, and to apply these results to the diagnosis and treatment of hearing impairments.

Clinical experiments are conducted to compare normal and impaired auditory systems in performing such tasks as binaural masked detection, discrimination of interaural differences in time and amplitude, spatial localization, and contralateral masking. While theoretical models of binaural interaction have been successfully developed for normal listeners, the variability in impaired listener performance has made the development of theories for this population extremely difficult.

A second project is the development of *multimicrophone monaural hearing aids*. The processing used in this type of system is not only relevant to people with asymmetrical hearing impairments (for example, one ear with a mild hearing loss while the other ear is totally deaf), but also to people who use nonauditory devices such as cochlear implants or tactile aids. Ideally, a multimicrophone aid should enable the user to simultaneously focus on signals from a specific direction while monitoring and localizing signals from other directions. Key features of such a system are the angular resolution provided by the sensor array, simultaneous parallel processing for all directions, and direction coding. Although some psychophysical work has explored directional coding schemes, most of the work has focused on the development

*(continued on page 10)*

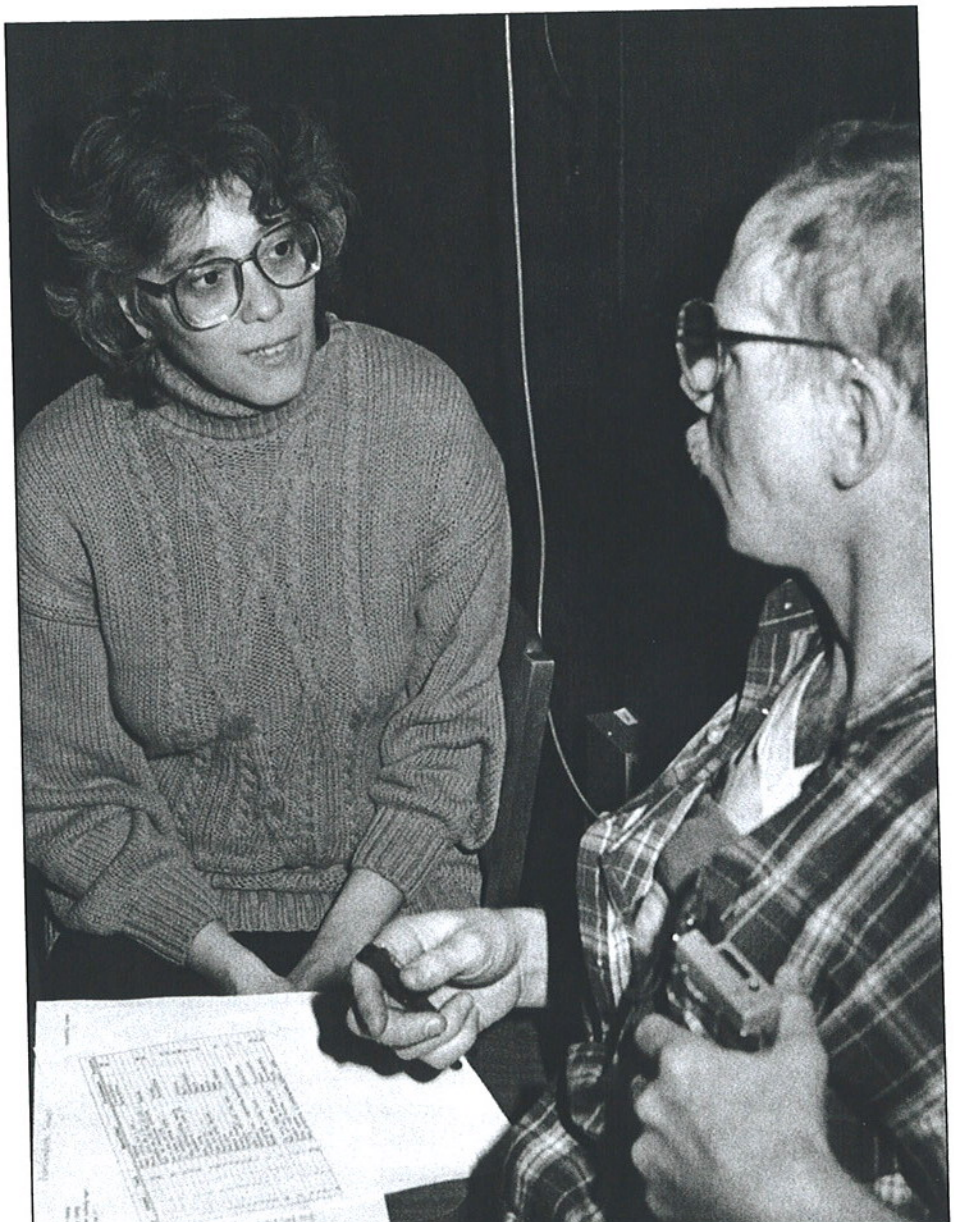
of microphone arrays and signal processing schemes to reduce interference from directions away from the target signal's source. The principal challenge is to eliminate the degrading effects on interference reduction caused by reverberation.

## Tactual Communication of Speech

The goal of this research is to develop tactual aids which can substitute for the hearing functions in speech communication for the deaf and deaf-blind, thus enabling them to achieve improved speech perception and production. This work is also aimed at increasing knowledge about the nature of speech communication, the capabilities of the tactual sense, design principles for the tactile displays, sensory substitution, and human plasticity.

Earlier research has demonstrated the effectiveness of various natural methods of tactual communication used by deaf-blind individuals. These include the Tadoma method of speech communication, the tactual reception of fingerspelling, and the tactual reception of sign language. In the Tadoma method, the deaf-blind person places a hand on the face and neck of the talker and monitors the mechanical actions that occur during speech. Although Tadoma use is confined to a small number of deaf-blind adults, research on this method has been important in demonstrating the adequacy of the tactual sense for speech communication. In the tactual reception of fingerspelling, the deaf-blind person places a hand loosely on the hand of the sender to feel the letter shapes of the American Manual Alphabet. The sender transmits a letter-by-letter representation of the words that would occur in spoken English. This method is used successfully by deaf-blind individuals who have acquired oral language skills before becoming both deaf and blind. In the tactual reception of sign language, the deaf-blind person places one or both hands in contact with the hand(s) of the sender to feel and interpret the signs associated with a given sign language (such as American Sign Language). This method is used by many deaf-blind individuals who have experienced deafness at a young age and exposure to sign language before the onset of blindness.

Studies of experienced deaf-blind users who use these methods not only indicate that good speech reception is possible through the tactual sense, but also that high levels of communication efficiency can be achieved without monitoring the articulatory speech processes and without exceptional tactual sensitivity. Common elements that appear to underscore the success of these different natural methods of tactual communication are a perceptually rich, multidimensional display that engages the hand's cutaneous and proprioceptive/kinesthetic senses, combined with strong motivation and training to communicate through the display. These results suggest that the limitations on speech reception with current artificial tactual aids are due primarily to inade-

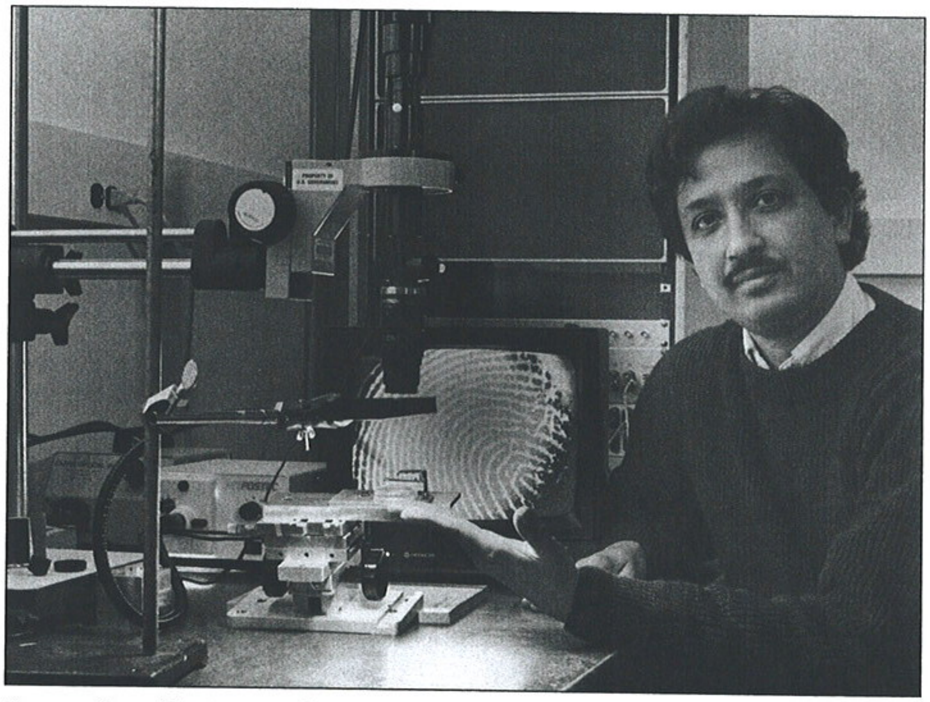


*Principal Research Scientist Dr. Charlotte M. Reed works with experimental subject Richard S. Skyer, Jr., to carry out field studies on the performance of deaf persons who use tactile devices. Mr. Skyer, who is deaf, wears the Tactaid VII, a tactile communication device that processes acoustic signals and presents them through the skin as vibrating patterns. The device provides information about environmental sounds as well as speech and is used in conjunction with lipreading for improved speech perception.* *(Photo by John F. Cook)* quacies in the aids' design or in the training received on how to use the aids. The Sensory Communication Group seeks to eliminate these inadequacies and achieve improved speech reception for individuals who use artificial tactile aids.

Basic studies of encoding and display schemes involve the development of methods to display acoustic signals to the tactual sense in order to improve the information-transfer rate. Displays to stimulate the hand's proprioceptive/kinesthetic and cutaneous sensory systems are being investigated. Ongoing projects include a study of manual joint-angle resolution, a study to define the range of amplitudes and frequencies that can be used to stimulate the tactual system, and experiments on the tactual/kinesthetic reception of Morse Code that may provide insight into the relationship between the ability to produce motor output sequences and the ability to learn these sequences as tactual/kinesthetic input sequences.

Research has been extended on artificial tactile devices to include systems designed to aid speechreading. One class of systems (called "acoustic") uses limited signal processing, no automated decision making, and continuous transformations from the acoustic domain to the tactual domain. Studies are underway to understand the performance characteristics for auditory and tactile presentation of low-bandwidth speech-envelope cues to supplement speechreading. The second class of systems (called "articulatory") uses substantial signal processing, automated decision making, and discontinuous transformations from the acoustic domain to the tactual domain. Work is aimed at the design of a speech-recognition system to remove ambiguity from lipread speech segments and the development of a tactual system to display information from a recognition device.

An evaluation of speech reception performance is underway using tactual aids that have been worn for long periods of time in the field. Subjects in this study are deaf adults who are highly motivated to use these multichannel, vibratory pattern devices. As they acquire practical training with their aids, the subjects also participate in periodic evaluations of their ability to receive various types of speech materials through lipreading alone, the tactual device alone, and lipreading combined with the tactual device. Investigators are comparing the performance of these tactual aids to the performance of other prostheses, including cochlear implants.



*By recording video images of contact regions and their corresponding forces, Principal Research Scientist Dr. Mandayam A. Srinivasan (above) and Research Assistant Jyh-Shing Chen investigate the mechanics involved in the contact between the human fingerpad and transparent test objects that differ in their mechanical properties. This data is used to infer mechanisms of tactile information processing by developing biomechanical models of the fingerpad to interpret the results of neurophysiological and psychophysical experiments performed with the same test objects. (Photo by John F. Cook)*

## Haptics

In addition to the tactile and kinesthetic subsystems, the *haptic system* also comprises the human motor system which enables the control of body postures and motions together with the forces of contact with objects. The haptic system helps us to identify and differentiate between various textured surfaces, recognize the shape of objects, and be aware of our surroundings. Haptics research in the Sensory Communication Group seeks to increase basic knowledge about manual sensing and manipulation, improve the clinical diagnosis and treatment of hand impairments, and contribute to the design and evaluation of artificial hands used in robotic systems. The group's multidisciplinary approach to haptics research employs biomechanics, neurophysiology, psychophysics, mathematical modeling, and robotics engineering. Investigators typically measure human capabilities in specified manual tasks that employ computer-controlled electromechanical devices, and determine the biomechanical and neural mechanisms that underlie performance. Research topics range from the tactile sensory information processing used in passive touch to the hand's full sensorimotor capabilities used in active touch.

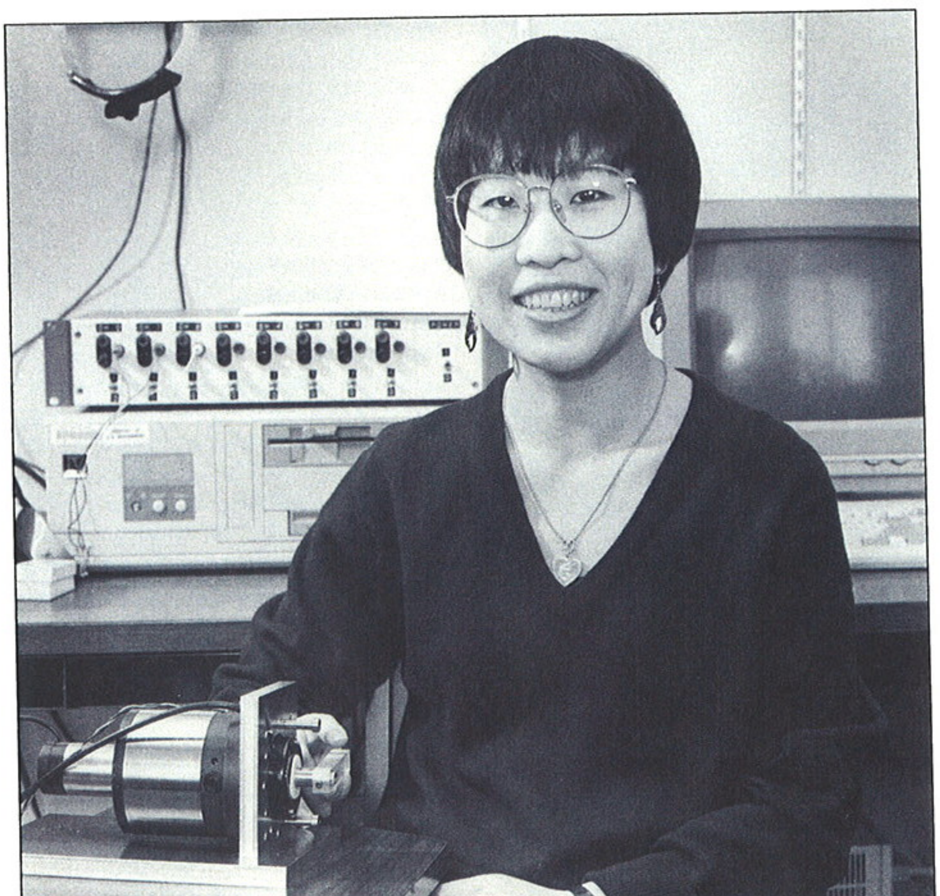
Whenever we touch an object, the source of all tactile information is the spatio-temporal distribution of loads on the skin at the contact's interface. The group's project in contact mechanics seeks to determine the growth and motion of contact regions due to force variations between the human fingerpad and selected transparent test objects whose microtexture, shape, or

*(continued on page 12)*

softness is varied in a controlled manner. A six-axis force sensor and a videomicroscopy system that consists of video zoom lenses attached to a high-resolution charge-coupled device camera have been designed for this purpose. Zoom lenses enable continuous variation of magnification, with a field of view that can cover the entire fingerpad or just a few fingerprint ridges. Experiments are being conducted to determine the relationship between contact force, contact area, and compliance of an object. The information from this project is used to test various biomechanical models developed by the group.

Although an empirical determination of mechanical strains in a mechanoreceptor is not currently possible, mechanistic models of the skin and subcutaneous tissues help to develop testable hypotheses about skin deformations and peripheral neural responses. These mechanistic models apply analytical and computational mechanics to the biomechanical aspects of touch, including the mechanics of contact, the transmission of mechanical signals through the skin, and their transduction into neural impulses by the mechanoreceptors.

As part of this work, two- and three-dimensional finite-element models of the fingertip have been developed, based on geometrical measurements of human and monkey fingertips obtained through the previously described videomicroscopy system. Simulations of the cutaneous mechanoreceptors that respond to various surface stimuli have been carried out, and hypotheses on peripheral neural coding have been proposed. In a related study that seeks to incorporate realistic material properties of the fingertip into these models, the *in vivo* compressibility of the human fingerpad was measured. Experiments are underway to determine the parameters that govern the fingerpad's mechanical behavior. Psychophysical and neurophysiological studies are also being carried out to determine how we sense (by touch alone) the microtextures, shapes, and softnesses of objects. Other projects consider the capability of human hands as well as robotic hands. Research on "reduced hands" focuses on degraded human hand performance associated with various hand constraints imposed by splints, gloves, thimbles, and local anesthesia. These studies seek to determine the potential capabilities of various artificial hands that might be incorporated in robotic systems.



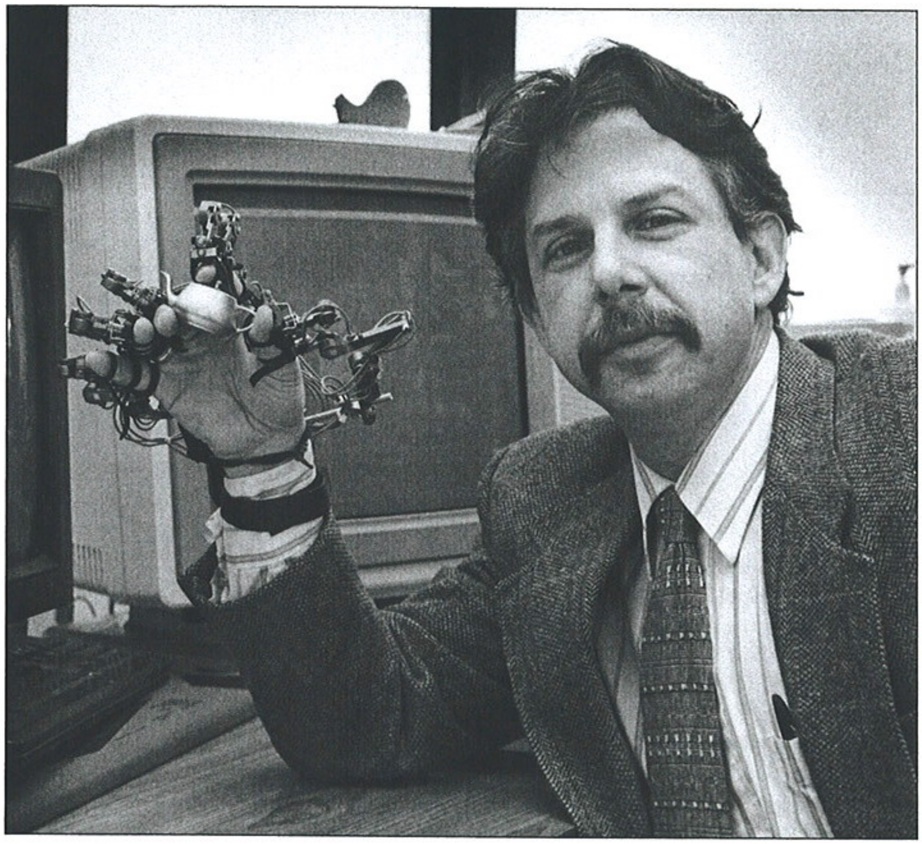
*Research Specialist Hong Z. Tan uses a finger mover with computer-controlled input to measure how people perceive finger joint positions and movements. This information will be used to develop a tactual interface that may lead to applications in speech communication for deaf and deaf-blind individuals.* (Photo by John F. Cook)

## Virtual Reality Comes to Its Senses at RLE

With wraparound three-dimensional views and sensors that track our movements, virtual environments and teleoperators systems take us into worlds that we have never experienced before. A teleoperator system consists of a human operator, a human-machine interface, and a remote device called a *telerobot*. The telerobot's mechanisms can sense signals in its environment which are communicated to a human operator. These signals are conveyed to the operator via displays that are part of a human-machine interface. The human operator's responses to the telerobot (usually motor responses) are detected by devices in the human-machine interface and transmitted back to the telerobot to control its behavior. Thus, in a teleoperator system, the human operator interacts in a real-world environment via an artificially transformed and mechanically extended sensorimotor system.

Virtual environments (also called artificial realities) are similar to teleoperators because they both involve a human operator and a human-machine interface. However, in a virtual environment, a computer replaces both the teleoperator's real-world environment and telerobot, and the human operator interacts with a computer-generated virtual world. In traditional simulation systems, the simulation itself is intimately tied to a physical situation. The simulation in a virtual environment is different because it is more intimately tied to the human operator by a general-purpose interface that matches the human sensory systems. In addition, a large set of algorithms generates a variety of virtual worlds. Since virtual environments are a flexible way to present a variety of controlled stimuli and to measure various human responses, they are ideal laboratories for research in experimental psychology.

The objective of a teleoperator system is to sense, navigate through, or operate upon the real environment. In contrast, the objective of a virtual environment system is to alter the human operator's state (by training or entertaining the operator) or alter the information environment (by modifying the computer's state). Generally, a virtual environment is capable of multimodalities (vision, audition, manual sensing, manipulation, and speech production) and can provide both interactive and adaptive environments. Virtual environments can generate supernormal situations not constrained by real-world limitations, such as the laws of physics. The basic alteration of properties and behaviors within the environment is made possible by reprogramming the software, not by rebuilding the entire system.



*Principal Research Scientist Dr. David Zeltzer wears an Exos Dexterous Hand Master (DHM) to measure finger positions in his study of human hand capabilities. The miniature teapot that he is holding is a three-dimensional physical object that was manufactured from a computational model. Using the DHM, he can "reach" into a computer world and seemingly "grasp" the models themselves. Dr. Zeltzer develops entire graphic systems that can simulate and display virtual environments with which human participants can interact. These environments have a variety of applications including design, visualization, and training.* (Photo by John F. Cook)

Human-targeted systems such as video games and flight simulators are already familiar devices to us. However, in the future, these systems will employ biofeedback methods in order to study human sensorimotor performance and behavior modification. Information-directed environments are expected to be capable of manipulating complex data structures for scientific visualization and theoretical modeling. More advanced systems may make it possible to design and build molecules for new drugs and materials atom-by-atom by observing their components in three dimensions and experiencing the force of interatomic fields. Teleconferencing in virtual environments, where participants can share auditory, visual, and tactual modalities, is also being considered. The fields of micromechanics and microelectronics also rely on this emerging technology, where integrated-circuit processing techniques will used to fabricate new devices and components for microsurgery, prosthetics, drug delivery, diagnostics, and solid-state sensors.

The Virtual Environment and Teleoperator Research Consortium (VETREC) is a new research direction within RLE's Sensory Communication Group. VETREC is led by members of the Sensory Communication Group with participating members from MIT's departments of Electrical Engineering and Computer Science, Mechanical Engineering, Brain and Cognitive Science, as well as the Artificial Intelligence Laboratory, the Media Laboratory, and various groups outside of MIT. Research on virtual environment and teleoperator systems in the Sensory Communication Group includes haptic interfaces, alterations in sensorimotor loops, the computer generation of virtual environments, and practical applications of virtual environment and teleoperator systems.

Haptic interfaces for human-machine interaction enable a human operator to sense and manipulate a real or virtual environment. The designers of these interfaces must not only provide high-quality feedback to the human operator for force, texture, and temperature, they must also enable the operator to manipulate real or virtual objects with precise dexterity. An ideal interface would consist of a glove or exoskeleton that could measure the position and posture of the hand and provide it with appropriate feedback. Most currently available interfaces are gloves or exoskeletons that measure the hand's position and posture, but they

*(continued on page 14)*

do not provide feedback; or systems such as joysticks that provide feedback on force, but use hardware that has fewer degrees of freedom than the human hand. Exoskeletons that provide feedback on force are still in the experimental stage.

Work on haptic interfaces is focused on the design, construction, and evaluation of various electromechanical control systems that will enable the operator to sense and control objects by means of task-dependent tool interfaces. Research is underway on a "tool-handle suite" that will facilitate the use of virtual environment and teleoperator systems for complex maintenance work, for example, to train workers or to perform the work remotely. Other laboratories around the country are using this "tool-handle" approach for surgical applications.

When a human "puts on" or "gets into" a virtual environment or teleoperator system, changes in human sensorimotor loops are likely to occur. For example, the relationship between a visual representation of your hand movement in a virtual environment display and the "felt" movement of your real hand in the human-machine interface is likely to be quite different from the hand movement that is normally seen and felt. Similarly, the relationship between auditory cues for sound localization relative to the orientation of your head and the proprioceptive/kinesthetic cues to orient your head relative to your body may be modified. Relationships such as these may be altered by distortions, time delays, or noise in the system. Although certain types of distortions may be introduced intentionally in order to improve performance, in most cases, these alterations result from inadequate technology and degraded performance. Knowledge about these alterations will enable system designers to predict their effects on the human operator's subjective state and objective performance. One project is studying the effects of distortions, time delays, and noise on manual task performance when a representation of the operator's hand is included in the visual display. A second project focuses on the operator's adaptation to altered perceptual cues in order to localize sound sources. These localized sound sources improve auditory spatial resolution by simulating the perceptual cues that could be obtained if the listener's head and ears were enlarged.

*Senior Research Scientist Nathaniel I. Durlach and graduate student Barbara Shinn-Cunningham test experimental facilities that will be used in studies of sensorimotor adaptation to altered auditory localization cues. In this set-up, Ms. Shinn-Cunningham is listening to a virtual loudspeaker whose location is identical to and moves with the location of her right hand.* (Photo by John F. Cook)

In the computer generation of virtual environments, one of the greatest challenges is to develop and incorporate the appropriate computational models for the behavior of autonomous, interactive agents. Work centers on the implementation of synthetic humans or virtual actors for virtual environments. In some cases, virtual actors may be guided so that their behavior is "slaved" to the behavior of a human participant in the virtual environment. In other cases, they may be required to be entirely autonomous, operating solely under the control of a computer program and capable of independent and adaptive behavior in interactions with objects, events, and other actors. Potentially, autonomous actors may augment or replace real human participants in the virtual environment by serving as a team member, an instructor, or a navigational guide. To be effective, such autonomous actors must be designed so that the human user can interact with them in real time through everyday language and gestures.

Work in this area attempts to model elementary motor skills, integrate these skills into a behavior repertoire for the actors, and develop a task-level, language-based software interface. Modeling is oriented toward routine motor actions that ordinarily do not require much conscious control, such as walking through cluttered environments or reaching and grasping objects. In addition to responding to the spoken or typed input of the human participant, such behavior requires the actor to be capable of generating appropriate motor goals and detailed motor actions. Current research involves the development of a reactive planner to adaptively control the autonomous actor, a behavior modeling system to construct motor skill modules, and a language-based, task-level interface to interpret spoken or textual input.

The Sensory Communication Group is now addressing applications of virtual environments and teleoperator systems for training, health care, and the understanding and manipulation of complex data structures. The group's main effort centers on the use of virtual environment technology in training, which includes the evaluation of evolving technologies and training procedures.

*by Dorothy A. Fleischer with Nathaniel I. Durlach*

# FACULTY PROFILE:

## Louis D.B. Braida

*New York native Professor Louis D.B. Braida (MSEE '65, PhD '69) came to MIT in 1964 from The Cooper Union (BEE '64). As a National Science Foundation Fellow in RLE's Communications Biophysics Group, his graduate research focused on hearing and auditory phenomena and communication theory. He worked closely with colleague Nathaniel I. Durlach as well as students in his field and was instrumental in developing a computer-based laboratory facility for auditory psychophysics.*

*In 1969, he was appointed to concurrent two-year terms as an Assistant Professor of Electrical Engineering and Vinton Hayes Postdoctoral Fellow in Electrical Engineering and received the department's Supervised Investor's Services Teaching Award for his contributions to teaching* Sensory Communication. *Professor Braida was Executive Officer for the Department of Electrical Engineering and Computer Science in 1971 and resumed full-time teaching and research in 1973. Promoted to associate professor in 1972 and full professor in 1981, he was named the first Henry Ellis Warren Professor of Electrical Engineering in 1982. His outside professional pursuits include serving on several committees and as an advisor to programs at the National Institutes for Health. He was Associate Editor of the* Journal of the Acoustical Society of America *from 1990-1992 and is a member of the Acoustical Society of America, the IEEE, Eta Kappa Nu, Sigma Xi, and Tau Beta Pi.*

*Professor Braida is internationally known for his research in the areas of intensity perception, the characterization of hearing impairments, and aids for the deaf. Using modern communication theory and computer-based techniques, his studies in auditory behavior transcend the sensory level of traditional psychoacoustics. He has quantitatively analyzed such issues as the functional attributes of short- and long-term auditory memory and its relationship to speech reception.*

*Professor Louis D.B. Braida*
*(Photo by John F. Cook)*

*His research style is characterized by a devotion to scholarship and creativity in his work. Since coming to MIT, he has been active in trying to improve student life and undergraduate education. He has also served on several committees such as the Equal Opportunity Committee, the Committee on Discipline, and the Committee on Graduate Admissions and Fellowships. He was also a faculty resident in Burton House from 1969 to 1972. In addition to his role as faculty member in RLE's Sensory Communication Group, he continues to teach undergraduate subjects in electronics, the structure and interpretation of computer programs, speech and hearing, and a project laboratory in psychoacoustics.*

**• *What sparked your interest in sensory communication?***

During my senior year at Cooper Union, our electronics professor took the class to the Albert Einstein Medical Center where electrical engineers were involved in biomedical research. This was something I had never even thought of before. I was already set to go to MIT for my graduate work, and when I told a former student of Professor Walter Rosenblith's about my interest in this field, he steered me in the direction of RLE. When I came to MIT in 1964, there wasn't much biomedical engineering activity, that didn't start until the '70s, but there was a lot of life sciences research. I was attracted to Walter's group, and at the suggestion of Larry Rabiner, I sought out Nat Durlach to supervise both my master's and doctoral theses.

**• *Did you have a mentor?***

Believe it or not, mentoring wasn't as central as the influence of the other graduate students Steve Burns, Ed Moxon, Jim Anderson, Paul Demko, and Adrian Houtsma. All of us were graduate students at roughly the same time, and much of our work was a start up activity in the late '60s. The graduate students had a lot to do with providing each other with guidance.

**• *When did you decide to teach?***

I had wanted to teach since high school. During my second year in graduate school, I volunteered as a teaching assistant for Walter Rosenblith's course in sensory communication. For the next three years, I was mainly responsible for the laboratory portion of the course. Certain topics in Walter's course were hard to discuss in a unified way. We would talk about *detection*—what is the weakest stimulus that an organism can detect and respond to; *discrimination*—how well does an organism tell the difference between two stimuli that it can detect; *identification*—how well can an organism recognize one of many stimuli; and *scaling*—how does an organism judge the magnitude of a stimulus. All of these topics were presented as if they were completely separate. Furthermore, we talked about them in different quantitative terms. In scaling, for example, we focused on the exponent of a power function to describe how loudness grew with intensity. Whereas in identification, we discussed how many bits of information are contained in an identification judgment. Even though an experiment might be done with the same sequence of stimuli, the results were analyzed differently, making it difficult to compare an identification experiment to a scaling experiment. There had to be some common aspects to those two experiments, and we tried to develop ways to look at *all* experiments so that we could identify the common elements. That was an important idea that came out of teaching Walter's course. The difficulty in teaching that subject also provided a focus for my doctoral thesis on intensity perception.

**• *What was the focus of research in RLE's Communications Biophysics Group during the 1960s?***

The group supported a wide range of activities, including research on the behavioral aspects of communication. That was really Nat's area. He was the first person in the group to systematize the study of human behavioral responses to sound. Up until then, that hadn't been a major behavioral focus of the group. There was also research on auditory neurophysiology, the vocal communication of frogs by Bob Capranica, and learning by Bob Hall. The physiological work eventually became housed at the Eaton-Peabody Laboratory. Some of the medical engineering work in the Harvard-MIT Division of Health Sciences and Technology under Roger Mark and Steve Burns also started in the group. Thanks to Nat, the Communications Biophysics Group became involved in human perception, and that evolved into the Sensory Communication Group.

**• *At what point did your work shift from the study of normal listeners to the hearing-impaired?***

Around 1972, people became interested in applying the results of fundamental research that had been going on. Much of this interest was due to the changing political scene and to some extent the students' disaffection with science. At that time, it was difficult to interest them in pure science questions. Another motivation was some of the existing theoretical work that had made reasonable predictions for certain types of hearing impairment. For example, in sensorineural hearing loss, the range of sound intensities that are both audible and comfortable diminishes, and the loudness grows more rapidly than it does in a normal ear. Our theories of intensity perception had predicted that, without considering the details of the hearing loss. Here was a possibility to apply a scientific theory to a phenomenon in hearing impairment. So, there were really two forces nudging us to change direction, the students' interests as well as some real opportunities to apply what we had done.

The major contribution of the Sensory Communication Group to the field of hearing has probably been the development and testing of quantitative models . . . But, we can't do modeling alone, the models must be tested experimentally.

**• *Your lab has been acclaimed as a world-class research environment. How did you become involved in engineering the computer-based instrumentation needed for your experiments?***

I'd been involved in the instrumentation aspects since I'd taught Walter's course. At that time, we did experiments by writing responses down on paper. That meant the amount of experimenting we could do in one laboratory session was limited. I worked on devices that could not only record responses automatically, but could also allow the students to listen to a wider range of conditions. Then, as computers became available, we began to develop computer-controlled systems where, instead of generating the stimuli in advance and tape-recording them, the entire experiment could be dynamically controlled in real time. For example, if we tried to measure the weakest sound that someone could hear, we would have the computer adjust the intensity of the sound when the subject behaved as though he or she couldn't hear it and lower the intensity when the subject's judgments indicated that the sound could be heard. Because of technological advances and because the kinds of experiments we want to do are constantly changing, we continue to develop the instrumentation. But many things that were done in the past with hardware are now done with software, and there's much less apparatus in the laboratory than there was fifteen years ago, although today it's much more capable.

**• *How would you describe the balance of theoretical and experimental research in your group?***

Although the balance differs from person to person and from project to project, almost all our research topics include both theoretical and experimental components. The major contribution of the Sensory Communication Group to the field of hearing has probably been the development and testing of quantitative models. These models include Nat Durlach's Equalization-Cancellation (EC) model of binaural hearing; the model that Steve Colburn and Nat worked on to extend the original EC model to physiological rather than acoustic inputs; Bill Siebert's models of intensity discrimination and frequency discrimination that are based on the neurophysiological representations of signals and trace the limits on discrimination to the stochastic nature of the neural responses to sound; and our group's modeling work in intensity perception. Although there have been other efforts to model these phenomena, I believe these models are distinctive, and there are no other groups where the modeling work is so characteristic.

There are other models that were first developed here, but they are not always associated with MIT because the developers are now at other institutions. Julius Goldstein, now at Washington University, developed a model of pitch perception. It was an optimum processor model that attempted to specify pitch by a best fit to the perceived spectrum, subject to certain stochastic limitations. Adrian Houtsma, now at Eindhoven University, developed a model for melody identification that was directed at understanding the missing fundamental phenomenon. Diek Duifhuis, now at Groningen University, developed a model of forward and backward masking that reflected the tuning properties of the inner ear.

Recently, Pat Zurek developed a model that tries to account for the usefulness of a second ear in real-world listening situations and is capable of accounting for most of the relevant data. Bill Rabinowitz is working to develop models that relate the ability of cochlear implant subjects to recognize words in sentences, based on their ability to recognize consonants in syllables. All of this mathematical modeling is one of our distinctive characteristics. But, we can't do modeling alone, the models must be tested experimentally.

***• How would you describe the broad range of your own research?***

At the moment, my efforts are concerned with developing and improving aids for the deaf. Most of our group has been involved in research aimed at improving people's communication abilities when they have lost some or all of their auditory function. This area has many fundamental questions that just don't have answers yet. For example, we don't know how much hearing one must have to experience satisfactory communication in everyday circumstances. If we knew the answers to such fundamental questions, designing better aids for the deaf would be much easier. Thus, to develop aids for the deaf, we must work on fundamental questions. Fortunately, our previous work in modeling, intensity perception, and other auditory phenomena is relevant to some of these questions.

Most of our group has been involved in research aimed at improving people's communication abilities when they have lost some or all of their auditory function. This area has many fundamental questions that just don't have answers yet.

I've recently become interested in developing aids for people who rely primarily on lipreading and who may have very little or no hearing left. If such aids are to be used, the question arises of how well the people will be able to integrate the speech outputs of the aids with visual images of a face that can convey the lipreading. This question hasn't been worked on extensively. For example, if we measure how well people can identify consonants by hearing and then measure how well they can identify consonants by vision, the question arises—how well should they be able to identify consonants when they have both hearing and vision available? As far as we can determine under typical experimental conditions, they combine the auditory and visual cues almost perfectly. It's possible that not all people do so well, and certainly we might expect that people who lost their hearing early in life to integrate poorly. It's also possible that people who use certain types of aids for the deaf do not integrate the cues provided by the aid with the cues provided by vision, even though normal-hearing people appear to integrate them well. I've been looking at that question quantitatively and have begun to think about how we could make aids that provide information to supplement lipreading and that could be integrated well with facial cues.

***• In this case, you'd be combining a variety of modalities.***

Yes, but the issues are the same within modalities. For example, in hearing, how well do we combine cues that we receive at low frequencies with the cues we receive at high frequencies? Most people haven't thought about this seriously. We know from psychoacoustic studies that we can't make comparisons across frequencies with perfection. So, the question of how well we can compare low-frequency speech cues with high-frequency speech cues is a quantitative one that can be addressed in experiments.

Another application occurs in cochlear implants. Most cochlear implants used today are multichannel. They contain several electrodes, and each electrode attempts to excite a different population of nerve fibers. If the electrodes stimulate different nerve populations without interfering with one another, then, knowing how well a subject does when a single electrode is stimulated, it should be possible to predict how well someone will do when two electrodes are stimulated. If we find that someone's performance is not up to that, then we begin to suspect the electrodes are interfering with each other. So, the same basic idea has many different applications. In a sense, this is basic research on integration across and within sensory systems. The fundamental models behind this idea are similar to those used in our work on intensity perception.

***• Your studies of intensity have been called definitive, going beyond the sensory level of traditional psychoacoustics to issues of memory, speech recognition, and sound localization. What is the nature of your work in this area?***

Intensity perception is a convenient problem domain to ask questions about detection, discrimination, identification, and scaling, because you can study all of them on the intensity variable. Also, people with normal hearing tend to have very similar detection, discrimination, identification, and scaling abilities. We can't say the same thing for pitch. Some people have an ear with perfect pitch, but intensity is not that way. Asking questions about intensity seemed like it would be fruitful, and although the topics we were teaching looked different, as I mentioned earlier, we had the feeling that there should be some common threads.

I think the major intellectual contribution in this area had to do with formalizing the experiments. That is, mechanisms have to be specified that allow us to determine in advance the limits of a person's ability to perform a certain task. For example, assuming the subject is motivated and trained, those mechanisms are usually a combination of sensory and memory mechanisms. In a given task, if we can specify which proportion of the limitation comes from the sensory mechanisms and which proportion comes from the memory mechanisms, we can then make measurements about hearing that are independent of the task performed.

The most important advance that has been made, although it's not completely understood by many people, is the concept of two memory mechanisms operating in parallel. We don't normally think about it, but one mechanism relates to what we might ordinarily call forgetting. That is, if you try to remember a sensation, your image of that sensation blurs as time goes on. Blurring is a diffusive process, similar to a *random walk*. You can prevent blurring by attaching a verbal label to the sensation—"That pie was very sweet," or, "That was an extremely loud sound." Obviously, these verbal labels are crude, but we tend not to forget them. If you compare two samples of pie and use crude labels like "very sweet," you won't be able to tell if there's a slight difference in the amount of sugar. In those cases, you'd taste one pie and shortly thereafter taste a second one, then compare the sensations before there was much blurring.

Quantitatively speaking, auditory blurring is a rapid phenomenon. After a couple of minutes, we have a minimal ability to specify how loud a sound was. After a day, the amount of blurring is so large, that you ought to be very surprised by the loudness of your alarm clock. There would be so much blurring that you could hardly tell whether the alarm was louder or softer than it was yesterday. The loudness of the alarm must be remembered by some code, something like fifty times louder than your breathing. That code is carried with you as it works from day to day. Our memory for physical events blurs rapidly, and we require crude ways to encode and represent loudness so that we can work with these events from hour to hour and day to day. This was a result of our work in the '70s.

It is interesting that these two ways to remember occur in parallel. This fact means that they can compensate for each other's limitations. When time is short, we compensate for our crude verbal label memory by our trace memory, which blurs with time. By using our verbal label memory, we compensate for the fact that after more than a couple of seconds the blurring is very severe. Because of it's obvious importance in communication, there's been a lot of study of verbal memory, but there hasn't been as much study of nonverbal memory. Some of the studies of nonverbal memory are not very illuminating today because they failed to consider the possibility that there could be two types of memory working together.

**• *Your studies have also applied signal processing techniques to hearing aids.***

These approaches are used to deal with what we might call abstractions of the hearing loss. People who lose their hearing tend to lose high-frequency before low-frequency hearing. It's not uniformly true, but it's usually the case when we consider aging. When we lose high-frequency hearing, we lose our ability to tell if certain elements, like the fricative sounds /f/ and /s/, are present in speech. Many people speculate this loss could be compensated by introducing audible, low-frequency sounds that code the high-frequency sounds. That was the basis of our work on frequency lowering.

The most important advance that has been made, although it's not completely understood by many people, is the concept of two memory mechanisms operating in parallel.

The difficulty in frequency lowering is the sounds introduced at low frequencies interfere somewhat with the sounds already present at low frequencies. The other problem is that people aren't prepared to interpret the high-frequency sounds when they are presented at low frequencies. This raises the issue of training when we try to evaluate a frequency-lowering hearing aid. So, the benefits derived from frequency lowering are not completely understood. We know that certain kinds of frequency lowering can be beneficial, but the amount of benefit that we've seen isn't enormous. We're still working on it because we know there's a benefit to be had, and we'd like to understand the cases where the benefit can be increased. The benefit is real, but it won't necessarily encourage many people who wear aids to use a frequency-lowering aid.

Amplitude compression is another approach that addresses the fact that when people lose their hearing, they tend to lose the ability to handle weak sounds, but there is no compensating ability to deal with intense sounds. Thus, the range of levels is reduced for people with sensorineural malfunctions. Amplitude compression is an engineering approach that shoe-horns the normal range of levels into a reduced range. Although the levels that fit into the reduced range of a hearing-impaired person is larger than the range that he or she would ordinarily hear, they may be unable to discriminate between levels within the reduced range. So, there are trade-offs. To the best of our understanding, the gains expected from multiband amplitude compression hearing aids are not likely to be much better than we could expect from a hearing aid with amplification and automatic volume control, which adjusts the aid's output to a reasonable level.

Frequency lowering and amplitude compression can be contrasted with the noise reduction processing that Pat Zurek and Bill Rabinowitz are now working on. This work is fundamentally a different kind of processing called *adaptive beamforming*, and the key is to use more than one microphone. All organisms that hear have more than one sensing organ; more than one ear. They use their multiplicity of sensors to process sounds which arrive differently from various spatial locations. Thus, they can determine the direction of a sound source, as well as focus in on one sound in the presence of others. The thought is that by using more than one microphone as an input to a hearing aid, we can do similar types of processing. Basically, adaptive beamforming tends to make a hearing aid's input unresponsive to a single noise source in a sound environment. So, if I talk to you as you sit face-to-face straight ahead of me, and there are microphones on my eyeglasses, as a noise source comes to me from another angle, the hearing aid would pay attention to you, but would not accept much input from the noise source at that other angle. If there was an additional noise source, and I had three microphones, I could then deal with that second noise source. The adaptive nature of beamforming indicates that we don't have to specify in advance where the noise sources come from.

The practical problem is that most acoustical environments don't direct sounds to our ears simply via one direction. There are echoes and reverberations from walls, and beamforming hearing aids don't operate well in reverberant environments. Furthermore, the aids are sensitive to small amounts of reverberation that we barely notice. The current idea is to make certain that a beamforming aid will perform well when there's minimal reverberation and, although it wouldn't help a great deal in a highly reverberant field, at least it won't degrade things. The idea is to design these aids so that their performance degrades gracefully as the amount of reverberation increases.

**• *At one time, the scientific community thought that channel capacity in the tactile sense was too limited. What suggested the use of tactile speech communication for the hearing impaired?***

If you walk down the Endless Corridor, you will see a photograph in the Norbert Wiener exhibit showing his hand on a set of vibrators in an attempt to transmit speech. Try as he might with this device called *Felix,* he was unable to interpret vibrations consistently as speech. His wasn't the only study which demonstrated that speech couldn't easily get through the skin. The weight of evidence convinced many scientists that the problem was the skin simply didn't have the capacity for speech. Unbeknownst to the people who drew that conclusion, there were people communicating speech via tactile sensations using the Tadoma method. The method was first used in Norway in the 1890s and introduced in the United States in the 1920s.

In the mid-'70s, we were interested in extending our work on hearing aids to other aids for the deaf, and the natural one to work on seemed to be a tactile substitution aid. Jacob Kerman at Queens College in New York had just reviewed work on tactile aids, and he generally found it pessimistic, except for one study conducted at MIT by Bob Mann. A master's student named Hansen wrote a thesis that took the Tadoma method seriously by making mechanical measurements of the face while people were talking. He looked at the tracings of the facial actions and concluded that one ought to be able to make the important distinctions. The tracings were sufficiently different so that he could tell them apart. Kerman commented favorably on Hansen's study, but no one had actually documented how well the Tadoma method worked. That's how we got interested in the topic.

Together with Mike Schultz and Susan Norton at Children's Hospital in Boston, Charlotte Reed, Nat Durlach, Bill Rabinowitz, and myself arranged to test one of these Tadoma subjects, Leonard Dowdy, who was deaf and blind. We were completely unsure of what to expect. We didn't know if we were dealing with a charlatan or someone with very limited abilities. We tested Mr. Dowdy blindfolded with masking noises in his ears, just to make sure he wasn't deceiving himself and us about how blind and deaf he was. It didn't matter since he really was both deaf and blind. We were truly amazed at how much speech reception he achieved through his skin. The effect of that study was quite large. First, it indicated the possibility of making a tactile aid for the deaf. Secondly, it changed the way people thought about speech and language. At the time, many people argued not only that the skin didn't have the capacity for speech, but also that the ear was intimately connected with the speech processing in the brain and with language reception. If people like Leonard Dowdy could understand speech through the skin, then the ear didn't have to be the only input. Unfortunately, precise conclusions about language acquisition through the tactile sense are difficult in Leonard's case because he had hearing for the first eighteen months of his life, and we don't know how much language he had acquired at time he went deaf. But there are other individuals who lost their hearing much earlier in life, at about six months, and must have acquired many language skills via tactile speech.

Within the next generation, our attitude toward deafness will change enormously. The majority of people who are now functionally deaf should be able to have essentially normal face-to-face communication with people who have normal hearing.

The users of the Tadoma method whom we have tested have a variety of histories, and they all do very well. It also seems from other experiments that their speech reception isn't based on superior sensory abilities, which means that we can make an aid. The issues involve knowing what to present with the aid and how to train people to use it. The fact that the method works means that the tactile sense is adequate. It doesn't tell us how to solve the problem. Existence proofs are important but they are incomplete, and they don't tell us how to get to our destination.

**• *How do you see your work as providing a direct benefit to society?***

Within the next generation, our attitude toward deafness will change enormously. The majority of people who are now functionally deaf should be able to have essentially normal face-to-face communication with people who have normal hearing.

There are several promising methods, such as cochlear implants, that are now being worked on. About one in five people who receive cochlear implants can achieve good levels of speech reception, and the fraction is more like four out of five people in face-to-face communication. In addition to cochlear implants, there is the possibility of providing people who have no residual auditory neurons with some sort of tactile aid. I'm sure that if research continues on that problem, the right kind of tactile aid will ultimately emerge. There is also the possibility of developing a visual aid to help a deaf person conduct face-to-face conversation. Recently, a *Science* magazine article addressed the regeneration of sensory cells. No one knows the limitations of that possibility at this point, but before long, they will be understood. One way or the other, whether it's the implant approach, tactile aid approach, visual aid approach, or the regeneration of sensory cells, we ought to make deafness not interfere with communication. Some of these methods are limited in that they all work best when the deaf person can see the person they are talking to. But, even if you're forced to communicate over a telephone, a Picturephone should be an option. I think that's an entirely reasonable goal that we can achieve within a generation, and it should have an impact on society.

Deafness has been a scourge to humanity throughout history. Deafness and blindness set aside part of our population and makes these people very different from the rest. Helen Keller, who was both deaf and blind, said that deafness was the more serious problem because it keeps you out of contact with other human beings. Communication is an important part of human life. The effects of deafness are very serious for children who are born deaf, because it interferes with their education, development, and communication. If we push on, there's every reason to think that the work at MIT will be influential in achieving the goal of eliminating deafness as a barrier to spoken communication.

### • *What are your thoughts on people who advocate deaf rights?*

It's important for the society to make all parts of modern life accessible for the deaf. That includes providing teletype service and access to municipal agencies so that the deaf can use the services they pay for—that's essential. They must not be discriminated against for being deaf. But it's also important to push on with the development of technologies that would permit those who are deaf to have access to the hearing world. Unfortunately, I do not think that the majority of the hearing population is likely to be convinced that it should learn how to communicate with the deaf. However, based on my observations of people who use cochlear implants, I think many deaf people would welcome the technology. Deaf people who previously had hearing for many years often don't assimilate into the deaf community. They remain connected to the hearing community, very thankful for the benefits provided by their cochlear implants.

The parents of a deaf child should also have access to a range of technologies they can use to help the child cope with deafness. One of those technologies is sign language, and they should understand its potential benefits, particularly how it relates to early access to education. Other technologies, such as cochlear implants, should also be considered. An important problem is how to perform studies that will enable the parents of a deaf child to know the possible benefits of a given technology. It's hard to do such experiments ethically, but inferences can be made from ongoing studies of adults and children who use cochlear implants.

### • *Are you excited about a current project that you're working on?*

A method of communication used by educators of the deaf, called *cued speech,* was developed at Gallaudet University by Orin Cornett during the '50s. Cued speech isn't sign language. The talker speaks normally while using hand cues to help the listener differentiate consonants and vowels that can't be told apart on the lips. The advantage to cued speech is that spoken English is used rather than sign language. Over the last few years, we've begun to study this system, and we've found that the deaf who know it are capable of receiving cued speech extremely well; it is an effective system. The limitation, just as with sign language, is that it requires the talker to generate cues for the listener. Of course, just as in sign language, the majority of the hearing population don't understand how to produce the cues.

I believe that speech recognition technology can be applied to the generation of the cues. Even today's speech recognizers would probably be good enough to make a workable automatic cuing system. The recognizer required for this system won't necessarily be satisfactory for other applications. It doesn't need to generate entire words, only parts of words that will enable the receiver to understand a message when used in conjunction with lipreading. The usual criteria aren't relevant in this application of a recognizer's performance. What does matter is that it's able to make certain distinctions and how well it makes other distinctions isn't as important because we can make those distinctions visually on the face. The system must also work quickly, because if it doesn't make decisions rapidly enough, a person won't be able to integrate the cues it produces with lipreading.

From a design perspective, I don't regard the recognition part of this system as a difficult problem since existing recognizers can be adapted and used. The problem is how do we present the recognizer's output to a deaf person in a way that he or she readily integrates it with lipreading and in a way that's fairly insensitive to errors made by the recognizer, because the recognizer will always make errors. It's a perceptual problem, and the engineering component is not the dominant part. We plan to do simulation studies in order to understand which displays are appropriate, how much delay is tolerable, how important it is to use foveal as opposed to peripheral vision, and other issues.

If we push on, there's every reason to think that the work at MIT will be influential in achieving the goal of eliminating deafness as a barrier to spoken communication.

### • *What has been the nature of your collaborations with Nat Durlach?*

We've worked together since the fall of 1964, when I was looking for a master's thesis. He supervised both my master's and doctoral theses, and we worked quite hard on the intensity perception series. We were involved in starting up the research on hearing aids, the studies of the Tadoma method, and investigating many issues related to hearing aid research. Recently, Nat has asked the question, "How much can you help someone who is having difficulty understanding speech if you change the way you talk?" That question sparked two doctoral theses on clear speech; speech that is more intelligible when the listener is hearing impaired or forced to listen to speech degraded by noise or reverberation. Nat continues to be interested and involved in my research, and I am interested in his research on virtual reality, but my interests are still firmly centered in aids for the deaf. For example, another project that I am starting involves the design of a visual artificial face—a sort of visual analog of the mechanical face that we developed to study the Tadoma method. I think it will be a valuable research tool for speechreading, which is an important topic in aids for the deaf. Of course, virtual environments won't be very interesting if there aren't virtual people to chat with.

An important characteristic of our effort is its breadth. Since many problems are common to all approaches, this allows us to be efficient and get insights from various areas.

**• *Do you see a place for virtual reality in developing aids for the deaf?***

Virtual reality is a large area, so it's hard to say if there isn't some connection. I haven't thought about the applications, but a convincing virtual face that you can't distinguish from a natural one on a television screen would have many applications both in virtual reality and in research on aids for the deaf.

**• *Do you collaborate with any other research groups in RLE?***

We do have interactions with Ken Stevens' Speech Communication Group. Seven years ago, when I was on sabbatical with Fred Jelinek's group at IBM, I was interested in applying their speech recognition system to inputs that weren't acoustic. These inputs were similar to the ones that Tadoma users might sense. Joe Perkell of Ken's group helped to prepare recordings of the material that Jelinek's group was recognizing. Surprisingly, Jelinek's recognizer performed as well as the Tadoma users, demonstrating again that the input is more than adequate for what we're doing. We have also cooperated with Al Oppenheim's Digital Signal Processing Group to develop and evaluate noise reduction techniques that might be used in hearing aids.

**• *Whom do you consider to be the leading contributors in developing aids for the deaf?***

The combined group of people from MIT and the Eye and Ear Infirmary is one of the largest in the world working in this area. But, it's not a closed field and there are unexpected and interesting results coming from many places. What's impressive about the MIT effort is that it's the only one that has components from all aspects on the problem of deafness. There are efforts in hearing aids, multiple microphone hearing aids, tactile aids for the deaf, and visual aids. The only area we're missing right now relates to the possibility of hair cell regeneration. An important characteristic of our effort is its breadth. Since many problems are common to all approaches, this allows us to be efficient and get insights from various areas. For example, we can get insights into the design of tactile aids from the study of cochlear implants.

**• *In terms of your research, what has been the biggest obstacle that you've had to overcome?***

For the field that I work in, I think that the complexity of the problem is the biggest obstacle. We're dealing with impaired auditory systems, and normally functioning auditory systems aren't completely understood. Impairments are often of a sort that each individual must be dealt with separately. You can't say that one deaf person is the same as another. Even when you have two people who should behave similarly by some objective measure, they often don't because they're different ages, or they've each had their hearing loss for different amounts of time.

The fact that many fundamental questions are still unanswered makes the work difficult. If we knew how the normal ear worked, or how speech was perceived, or what fundamental issues determined intelligible speech, our efforts would be vastly aided and much easier. Not everyone has the luxury, as many areas of engineering do, of having had the theoretical bases worked out a century ago, and simply working on the applications. Our work is much more like electrical engineering when the first transatlantic cable was laid. People didn't understand how signaling occurred over long cables; they learned that in the process of making the cable work. That's somewhat analogous to the development of aids for the deaf. In the process of developing improved aids, we expect to contribute to the understanding of auditory function.

So, the complexity of the problem is the obstacle, in addition to the fact that our fundamental knowledge is incomplete. When you have a complicated problem and lack the fundamental knowledge, then it's not as easy as you'd like to make great advances. That doesn't mean advances don't happen, they're just harder to realize.

**• *You once said that your primary long-term teaching interest at MIT is undergraduate education. What is your vision for undergraduate education at MIT?***

We have very capable students here at MIT. The real question is how does our teaching influence their education. One way of looking at it says that it has little influence, and, in fact, they learn almost entirely by themselves. I became convinced early on that the students learn a lot from one another. In a school where the undergraduates are of such a high caliber, you can turn to your roommate who might be taking the same course and learn a lot from what he or she has learned, even learning from their difficulties.

The longer I've been here, the more it seems that when we have a student who doesn't seem to be doing as well as the others, that doesn't mean the student is incapable. Often it means the student is interested in something else, or has family concerns, or is taking your course because he or she is forced to and would really rather take a different subject. In that sense, there may not be much we can do fundamentally to change education. It's important to keep our subjects up-to-date and motivating so the students can get on with their own education in an enthusiastic way.

> When you have a complicated problem and lack the fundamental knowledge, then it's not as easy as you'd like to make great advances. That doesn't mean advances don't happen, they're just harder to realize.

**• *What will be the impact of the new program in the Health Sciences and Technology Division?***

The aim of this new program is to train people broadly in auditory and speech science so they can do much more effective research. The program is important from both research and educational viewpoints. If it continues to be funded and if it can continue to attract seven to eight very strong students a year, not too far in the future, we'll have about forty students working at MIT and the clinical institutions around Boston as part of the program. In the long run, it will greatly help our research because one of the major problems in developing aids for the deaf is that few researchers are broadly trained. They may understand acoustics and signal processing, but they don't understand speech well. They can do certain things, but when it comes to determining whether a new hearing aid can work, they're at a disadvantage. If we try to involve people in a problem with a physiological component like cochlear implants, or with a perceptual component like hearing aids that are integrated with lipreading, we place severe demands on capably trained signal processing engineers.

A typical graduate of a speech and hearing program or of a psychology program in hearing also will not have the technical level of preparation that graduates of this new MIT program will have. Often, they don't understand acoustics, and they haven't had much clinical exposure. Even though the program we envision is large, it will not produce a large fraction of the speech and hearing scientists. But, it will produce influential graduates because of the breadth of their training. For example, few hearing scientists have spent any time training in a clinic because they're generally graduates of psychology programs. If they know anything about speech, it's perhaps from one course in speech. Whereas in this program, students will be required to take a course on the anatomy of speech, they'll learn the acoustics of speech production, and they'll take a solid graduate course in speech communication. They will be much better prepared to do research than many of the people who are being trained today as speech and hearing scientists.

**• *What do you consider to be your most significant achievement?***

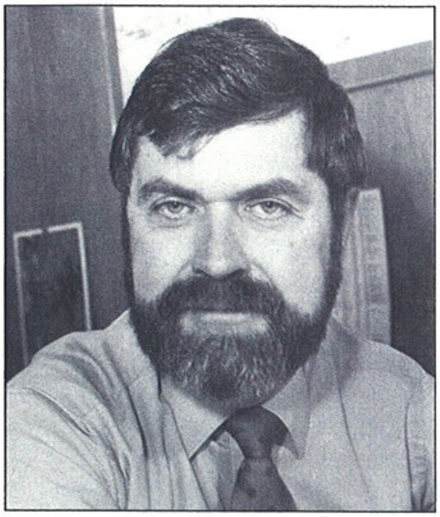
I tend to focus on the future. If I thought there was something in my past that I had to measure up to, I'm not sure that I'd be very successful at it. I think that for all of us who work on aids for the deaf the possibility of essentially eliminating the effects of deafness would be a real achievement. Unfortunately, it may not be the kind of thing that will strike the world like a lightning bolt. More likely, the number of deaf people who find it impossible or difficult to communicate with the hearing population will steadily decrease until the number is insignificant. I believe that will be a major achievement.

**• *What has been the most rewarding aspect of your career?***

Working with students and doing research are both rewarding. When you discover some unsuspected principle, that's just as rewarding in behavioral science as it is in physical science. When we began to develop models of audiovisual integration to predict how well hearing and vision are combined in speechreading, that was exciting. I was working with a postdoc who had done previous work on speechreading. He was excited by the fact that both hearing and vision seemed to combine in what he called a "super additive" fashion. In other words, 30 percent of the consonants were received correctly by hearing, and 50 percent by vision. But when he combined hearing and vision, he'd get 95 percent of the consonants right. He was extremely taken by this and got me interested in the problem. I said he shouldn't be surprised that the numbers are so good, what he should ask himself is how much should he *expect* the subjects to get. Should one be surprised that they're getting 95 percent correct, or that they're not getting 100 percent correct? I found that there hadn't been much work on this problem, so I did some mathematical modeling and made some predictions. The postdoc had all the data. Every day, I would show him the results of my calculations from the previous night, he would give me more data, and I would do the calculations on that. Finally, we had five or six sets of data to look at, and they were spectacularly accurate. That was very exciting. It's the kind of thing that can keep you going twenty hours a day. It was very rewarding in an intellectual sense, and just as exciting as it was when I was a graduate student.

> I think that for all of us who work on aids for the deaf the possibility of essentially eliminating the effects of deafness would be a real achievement. Unfortunately, it may not be the kind of thing that will strike the world like a lightning bolt.

# circuit breakers

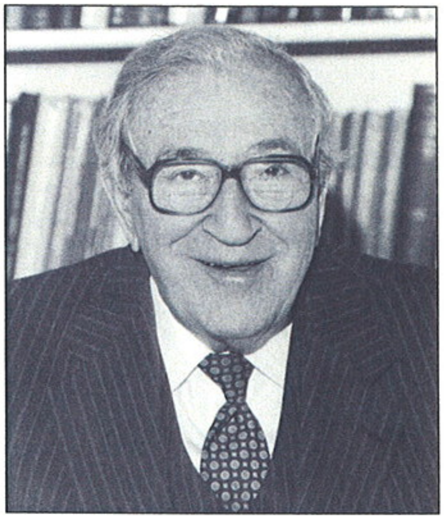


***Dr. Arthur B. Baggeroer*** (SM/EE '65, ScD '68), Ford Professor of Engineering and Professor of Electrical and Ocean Engineering, received the Ocean Engineering Society's 1992 Distinguished Technical Achievement Award. Professor Baggeroer was recognized for his applications of advanced signal processing methods to underwater acoustics and geophysics. As an investigator in RLE's Digital Signal Processing Group, he has served as chief scientist at six field experiment stations in the Arctic marginal ice zone where large aperture arrays are used to gather seismic data. This information is applied to measurements of long-range propagation, reverberation, ambient noise, and tectonics in the Arctic. *(Photo by John F. Cook)*

***Dr. Jacqueline N. Hewitt***

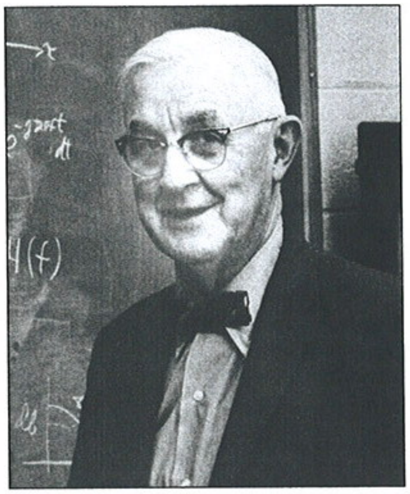
***Dr. Jacqueline N. Hewitt*** (PhD '86), Assistant Professor of Physics and Class of 1948 Career Development Professor, was awarded the Henry G. Booker Prize from the International Union of Radio Science (URSI). The award is presented to an outstanding American scientist who is younger than 35 years old and who works within the disciplines represented by URSI. Dr. Hewitt was cited for her research on gravitational lenses conducted in RLE's Radio Astronomy Group. The Booker Prize will be presented at the union's XXIV General Assembly, held August 25-September 2, 1993, in Kyoto, Japan. An assistant professor of physics at MIT since 1989, Dr. Hewitt was also recently appointed Class of 1948 Career Development Professor for a three-year term. *(Photo by John F. Cook)*

***Dr. David H. Staelin*** (BS '60, MS '61, ScD '65), Assistant Director of Lincoln Laboratory and Cecil H. Green Professor of Electrical Engineering, was awarded the IEEE Signal Processing Society's 1992 Senior Award in the image and multidimensional signal processing area. Dr. Staelin was cited for his paper, "The LOT: Transform Coding without Blocking Effects," coauthored with former doctoral student Henrique S. Malvar (PhD '86). The paper appeared in the April 1989 issue of *IEEE Transactions on Acoustics, Speech, and Signal Processing*. The award was presented on April 29, 1993, during the IEEE International Conference on Acoustics, Speech, and Signal Processing, held in Minneapolis, Minnesota. Professor Staelin has been affiliated with RLE's Radio Astronomy Group since 1959 and has conducted research in electromagnetic systems and signal processing, remote sensing, radio and optical astronomy, video image processing, and manufacturing. *(Photo by John F. Cook)*



Award ceremonies were held in Washington, DC, on April 26, 1993, as the National Academy of Sciences presented its highest honor to ***Institute Professor Jerome B. Wiesner***. Dr. Wiesner received the academy's Public Welfare Medal for his devoted and successful efforts in science policy, education, and nuclear disarmament and world peace. The award was established in 1914 to honor distinguished contribution in the application of science to the public welfare. Over the years, Dr. Wiesner's record of service has included tenures as RLE Director, MIT President, and presidential science advisor to Presidents Kennedy and Johnson. *(Photo by John F. Cook)*

# IN MEMORIAM

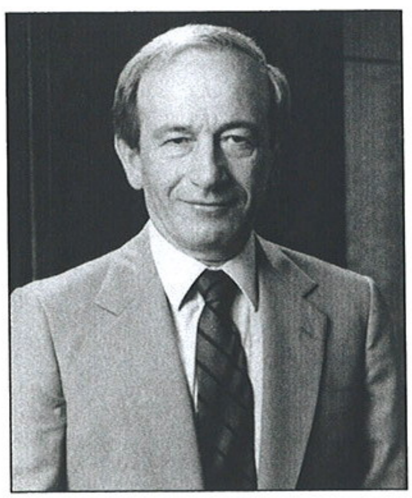


*Professor Emeritus Truman S. Gray* (SM '28, ScD '30), 86, died November 7, 1992, at Mt. Auburn Hospital in Cambridge, Massachusetts. He had suffered a heart attack several days earlier at his home in Lexington. Born in Indiana, Dr. Gray was raised in Austin, Texas, where he attended the University of Texas and received a bachelor's degree in engineering in 1926, and another in physics in 1927. He came to MIT as a research assistant, and under the supervision of Vannevar Bush, completed his doctoral dissertation on the design of an analog numerical integration machine. Dr. Gray joined MIT's Electrical Engineering Department faculty as an assistant professor in 1935 and was promoted to associate professor in 1942, and to full professor in 1960. Dr. Gray also served as head of the department's graduate office and as a faculty counselor to the department's cooperative education program. He retired from the faculty in 1971.

Although Dr. Gray did not have an official title at RLE, he is noted as an early contributor and guiding faculty member in establishing the laboratory in 1946. His work involved the study of stabilized oscillator problems, which was documented in one of the laboratory's earliest reports. In 1947, he took a two-year leave of absence from MIT to consult on reactor development at Brookhaven National Laboratory.

A pioneer in the field of electronic instrumentation, measurement, and control, Dr. Gray is well known for his graduate-level course *Electronic Instrumentation and Control*, which he initiated in 1934 and continued to teach after his retirement. He was author of the book, *Applied Electronics: A First Course in Electronics, Electron Tubes, and Associated Circuits*, published in 1943. A music aficionado, Dr. Gray enjoyed playing the clarinet and was a founding member of the Tabor Hill Dixieland Jazz Band. He was still active in the band at the time of his death. Dr. Gray was also an amateur silversmith, glassblower, and jewelry craftsman.

A resident of Lexington for 57 years, Dr. Gray is survived by his wife of 60 years, Isabel Crockford Gray; a sister, Margaret Shepherd of Texas; and two nieces. *(Photo courtesy MIT Museum)*



*Dr. Solomon J. Buchsbaum* (PhD '57), 63, died March 8, 1993, in a Morristown, New Jersey hospital after suffering from multiple myeloma. Dr. Buchsbaum, a noted physicist at AT&T Bell Laboratories, was senior vice president of technology systems at the time of his death. Dr. Buchsbaum was born in Stryj, Poland. Although his parents died in the Holocaust, he and his sister escaped and eventually moved to Canada. After graduating from McGill University (BS '52, MSc '53), he came to MIT in 1953 as a Moyse Fellow. In 1954, he joined RLE as a teaching assistant and doctoral student under Professors Sanborn Brown and William P. Allis in the Plasma Physics Group. He was an IBM Fellow from 1955-1957 and became a member of RLE's research staff in 1957. Professor Emeritus Allis remembers, "Sol was unquestionably my brightest and best graduate student. Repeatedly, when I tried to interpret some experimental result, he would give an obviously better interpretation without implying that mine was foolish."

In 1958, Dr. Buchsbaum left MIT to begin a 35-year career with Bell Labs in Murray Hill, New Jersey. As a member of the technical staff, he rose to department head in 1961. He was a consultant for RLE from 1961-1963, working with Professor David J. Rose in the area of nuclear engineering. In 1963, he coauthored the book *Waves in Anisotropic Plasmas* with MIT Professors William P. Allis and Abraham Bers. Dr. Buchsbaum became director of Bell Lab's Electronics Research Laboratory in 1965. From 1968-1971, he served as vice president of research at Sandia National Laboratory, and returned to Bell Labs in 1971 as executive director of the Research Communications Principles Division. He became senior vice president of technology systems in 1979. A holder of eight patents, Dr. Buchsbaum's work is well known in the areas of plasma physics, gaseous electronics, and plasmas in solids.

Dr. Buchsbaum was active on many government agency committees and advisory boards, including the President's Science Advisory

*(continued on page 25)*

# alumni notes

***Lee W. Casperson*** (SB '66) sent us his comments on the ***currents*** issue on plasma physics. He reminds us that it was not only Oliver Heaviside who realized that long-distance radio communications could benefit from using the reflective layer of the Earth's upper atmosphere. In fact, Harvard faculty member Arthur Kennelly suggested it several months before Heaviside. Although Kennelly is not widely remembered today, he made important contributions to circuit theory, mathematics, and electroacoustics. Professor Casperson is on the electrical engineering faculty at Portland State University and recalls his undergraduate thesis days in RLE with Professor John C. Ingraham.

***Charles L. Seitz*** (SB '65, SM '67, PhD '71), Professor of Computer Science at the California Institute of Technology, enjoyed the article "Lights Out for Last LINC," which appeared in the last issue. Professor Seitz was able to put us in touch with LINC's designer, Wesley A. Clark (EE '55), who is now living in New York City.

---

### IN MEMORIAM
*(continued)*

Committee and the White House Science Council. He also served on the boards of MIT, Stanford, Rand Corporation, Draper Laboratory, and the Argonne and Sandia national laboratories. Dr. Buchsbaum received the National Medal of Science from President Reagan, as well as many awards from the IEEE and National Academy of Engineering, and several medals from defense and energy agencies. A senior member of the IEEE, he served as associate editor to three physics journals and chairman of the plasma division of the American Physical Society.

Dr. Buchsbaum is survived by his wife, Phyllis Isenman Buchsbaum of Westfield, New Jersey; a daughter, Rachel J. Buchsbaum of Winchester, Massachusetts; two sons, David J. Buchsbaum of Atlanta, Georgia, and Adam L. Buchsbaum of Princeton, New Jersey; a sister, Dorothy Steinbach of Glen Rock, New Jersey; and three grandchildren. *(Photo courtesy of AT&T Bell Laboratories)*

## RLE Collegium

The RLE Collegium was established in 1987 to promote innovative relationships between the laboratory and business organizations through research projects and special partnerships. Its goal is to increase interaction and communication between RLE researchers and outside professionals in electronics and related fields. Collegium members have the opportunity to develop close affiliations with the laboratory's faculty, research staff, and students, and can quickly access emerging results and scientific directions. This kind of professional interaction provides RLE Collegium members with the most up-to-date technical information, often in areas not fully addressed by business and industry.

Collegium benefits include access to a wide range of RLE publications, personalized seminars and laboratory visits, and other opportunities for technology transfer. RLE also hosts visiting scientists from collegium companies. Individual research projects and special partnerships may develop with mutual technical interests and the appropriate external sponsorship.

The RLE Collegium membership fee is $20,000 annually. Members of MIT's Industrial Liaison Program can elect to transfer 25% of their ILP membership fee to the RLE Collegium. Collegium fees will encourage new research initiatives within RLE.

RLE welcomes inquiries regarding the laboratory's research. To request an RLE ***Progress Report,*** an RLE ***Collegium Prospectus,*** or for more information on other RLE publications, please contact:

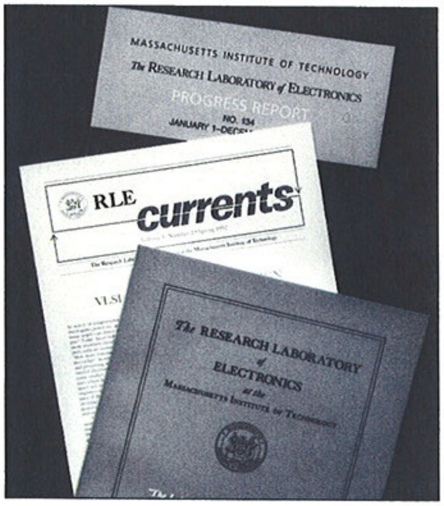
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139-4307
Collegium: (617) 253-2509/2510
Publications: (617) 253-2566
Fax: (617) 258-7864

## Publications

RLE has recently published the following technical reports:

***Synchronized Chaotic Circuits and Systems for Communications***, by Kevin Cuomo and Alan V. Oppenheim. RLE TR No. 575. November 1992. 59 pp. $11.00.

***Ab-initio Condensed Matter Calculations on the QCD Teraflops Computer***, by T.A. Arias, B.E. Larson, M. Galvan, and J. Joannopoulos. RLE TR No. 576. February 1993. 17 pp. $11.00.




***Inorganic X-ray Mask Technology for Quantum-Effect Devices***, by William Chu. RLE TR No. 577. April 1993. 123 pp. Price to be announced.

***Physics and Fabrication of Quasi-One-Dimensional Conductors***, by Reza A. Ghanbari. RLE TR No. 578. April 1993. 134 pp. Price to be announced.

In addition, ***RLE Progress Report No. 135***, which covers the period January through December 1992, provides extensive information about the research objectives and projects of RLE's research groups. It also lists faculty, staff, and students who participated in each research project, in addition to current RLE personnel, and identifies funding sources. The ***Progress Report*** is available at no charge.

# History of Sensory Communication at RLE

## 1950

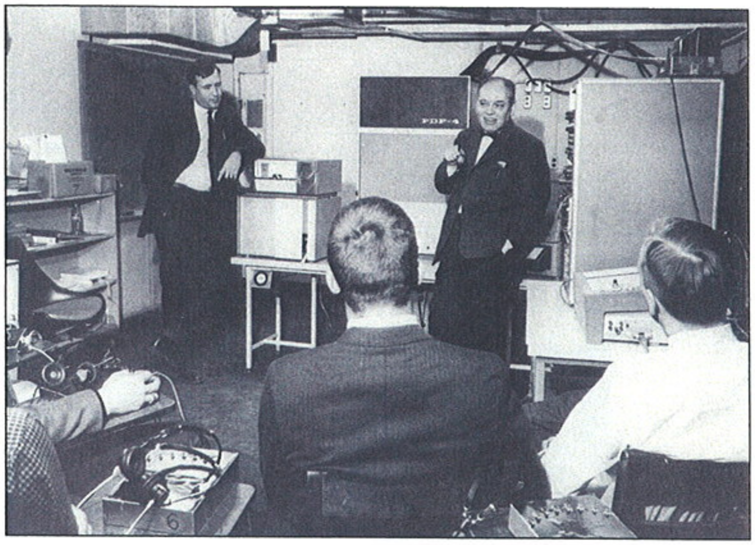
*Dr. Norbert Wiener conducts experiments to convert speech signals into a sequence of tactilely perceptible patterns that a deaf person might learn to understand. The original experimental device, called "Felix," used several band-pass filters to subdivide the range of the spoken voice. To assign successive band limits, each band approximately represented an equal amount of energy when averaged over speech. Initially, five channels were used with the outputs arranged to control the amplitude of five small vibrators, upon which the fingers of one hand rested.* (Photo by Alfred Eisenstaedt)

## 1953

*Technical Assistant Joanne J. English of the MIT Acoustics Laboratory and Professor Walter A. Rosenblith conduct a series of experiments in the anechoic chamber, a shielded, echo-free room that eliminates mechanical vibrations as well as acoustical and electronic interference. Professor Rosenblith came to MIT in 1951 from Harvard's Psycho-Acoustic Laboratory and was a key figure in the development of RLE's Communications Biophysics Group.* (Photo by Phokion Karas)

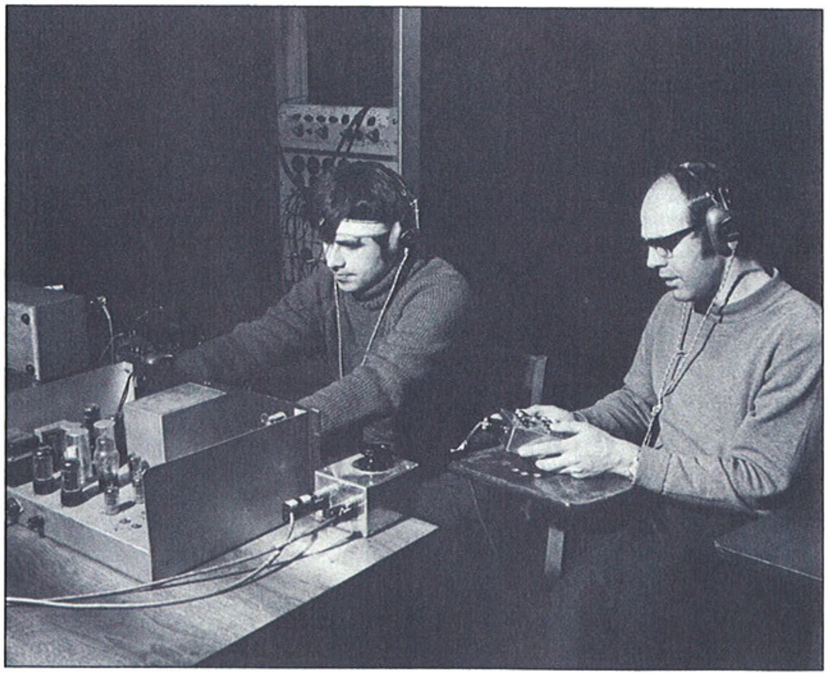
## 1955

*Research staff members Lamar Washington, Jr. (left) and Dr. Clifford M. Witcher developed the experimental Vocatac device for RLE's Sensory Aids Project. The device was based on earlier research by Dr. Norbert Wiener to convert speech signals into tactile patterns.* (Photo by Benjamin Diver)




## mid-'60s

*Professors William M. Siebert (left) and Walter A. Rosenblith demonstrate the first real-time computer used in a classroom experiment. Acoustic stimuli were generated by the computer to experimental subjects who would respond. The computer then displayed the reaction time data immediately. Response devices were built by Research Assistant Steven K. Burns, and the computer's interface was developed by Research Assistant Richard J. Clayton.* (Photo by Phokion Karas)

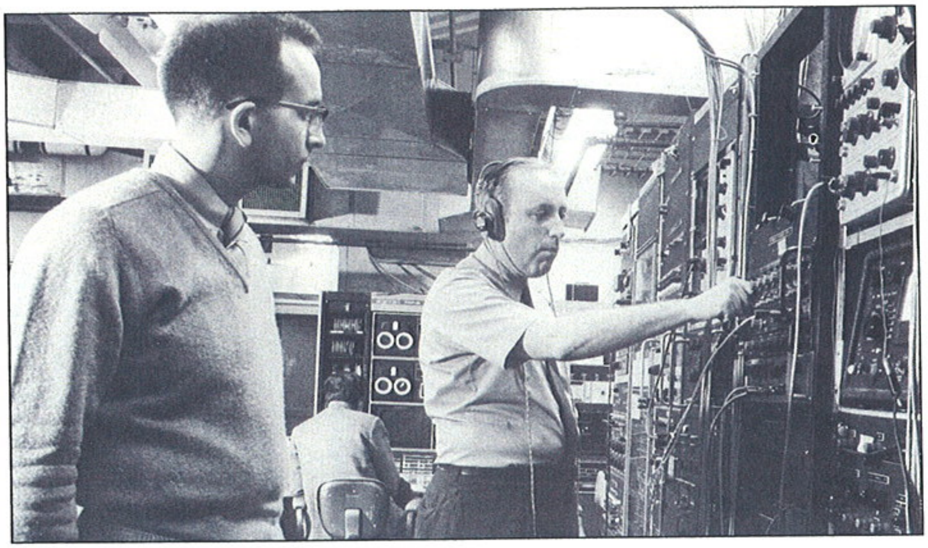


## 1971

*Graduate student Paul Demko, Jr. (left) and Research Associate Andrianus J. Houtsma use auditory stimulus generators in a phase shifter-lateralization experiment.* (Photo by John F. Cook)

## 1971

*Professor Louis D. Braida (left) and research staff member William F. Kelley test a controlled frequency oscillator used in pitch discrimination experiments.* (Photo by John F. Cook)



## 1980

*Two experienced Tadoma method users who are deaf and blind (Leonard Dowdy on the left and Raymond Boduch on the right) communicate with each other and Principal Research Scientist Nathaniel I. Durlach (center), who is hearing and sighted. In this method, speech is received by placing a hand on the face of the talker and monitoring the mechanical actions associated with the speech production process. The study of this tactile communication method was used to determine its effectiveness in speech reception.* (Photo by Hansi Durlach)

## 1981

*Professor Louis D. Braida and graduate student Diane K. Bustamante examine the dynamic characteristics of a multichannel compression system being evaluated for use in hearing aids.* (Photo courtesy MIT Department of Electrical Engineering and Computer Science)

## 1985

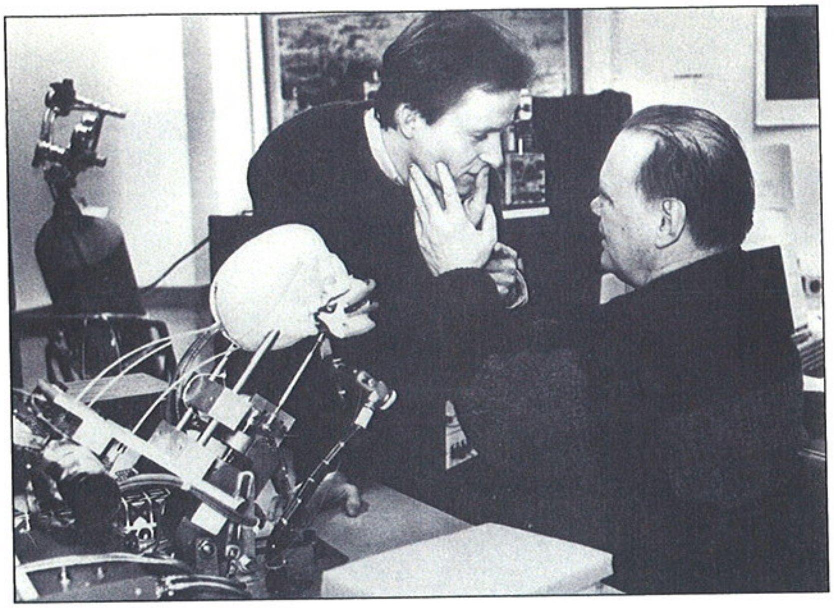
*Research Scientist Lorraine A. Delhorne carries out a length discrimination experiment that is designed to select the smallest increment. This was among the first experiments performed by RLE's Auditory Psychophysics Group (now the Sensory Communication Group) involving the manual resolution of the properties of objects.* *(Photo by John F. Cook)*

## 1989

*When used in conjunction with lipreading, cochlear implants provide substantial benefits to speech reception, enabling more reliable and comfortable communication. Principal Research Scientist Dr. William M. Rabinowitz works with Research Specialist Lorraine A. Delhorne of RLE's Sensory Communication Group to examine audiovisual stimuli used in patient evaluations. The sentence under examination, "How many of your brothers still live at home?," is part of a corpus available on laser video disc. This technology allows computer-controlled, high-speed access to high-quality audiovisual events.* *(Photo by John F. Cook)*

## 1986

*Gathered in RLE's anechoic chamber are Professor H. Steven Colburn (seated) with (from left) Research Assistant Patrick M. Peterson, Research Specialist Harry L. Norris, Research Scientist Dr. Patrick M. Zurek, and Visiting Scientist Dr. Janet D. Koehnke.* *(Photo by John F. Cook)*



## 1989

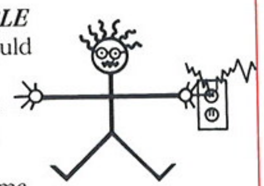
*Graduate student Douglas R. Henderson (left) works with Leonard Dowdy. Mr. Dowdy, who is deaf and blind, successfully uses the Tadoma system of tactile speech reception. The equipment (at left) is a synthetic Tadoma system, which employs a computer-driven artificial face to simulate the mechanical actions that occur during speech production.* *(Photo by Donna M. Coveney)*


## 1989

*Research Scientist Dr. Xiao Dong Pang experiments with the prototype of Cyberface and the remote presence head.* *(Photo by John F. Cook)*

## SHORT CIRCUITS

The staff of ***RLE currents*** would like to note the following correction to the fall 1992 issue on plasma physics:



The 1971 photo caption on page 22 mistakenly identified Richard J. Hale as D. Bruce Montgomery. Hale is currently on the research staff at MIT's Plasma Fusion Center, and Montgomery is Associate Director of the center. Thanks to Lawrence G. Rubin, Division Head at the Francis Bitter National Magnet Laboratory, who checked the error and correctly identified Richard Hale.

# From a Biophysicist Who Came to Supper
## (a chronological rather than a logical tale)

*by Walter A. Rosenblith*

*Professor Rosenblith's comments are from his essay of the same title, which originally appeared in the commemorative booklet* **RLE: 1946+20**, *published in 1966.*

A relatively young man with a background in communications engineering and classical physics joined the Harvard Psycho-Acoustic Laboratory in 1947 to work on hearing. Soon thereafter he attended a Norbert Wiener colloquium on information and entropy. In July 1948, Wiener invited him to the postwar supper club, also known as the seminar on scientific method. . . . Two speech conferences later, in 1951, he joined MIT's Department of Electrical Engineering. A polysyllabic professorial label—Communications Biophysics—was coined at that time to indicate that electrical engineering no longer stopped at the terminals of man-made equipment.

He started by teaching electric circuits under [Ernst] Guillemin and was a staff member in both the Acoustics Lab and RLE. [Jerry] Wiesner encouraged him to form a group to study sensory communication in organisms with the aid of up-to-date electronics and Wienerian analytical techniques. A special facility for animal (electrophysiological) and human (electrophysiological and psychophysical) experiments were built. From the very beginning the use of computing equipment and mathematical model-making in the analysis of neuroelectric data characterized much of the group's work. The first two special-purpose computers built were a time-gated amplitude quantizer and an analog correlator; the latter was a modification of a design by E. Colin Cherry, then a visitor to RLE from Imperial College.

The construction of the correlator in 1954 cemented a long-lasting and fruitful collaboration with Mollie Brazier's group at the Massachusetts General Hospital. (Several years ago this correlator was moved to Brazier's old lab at MGH; there its continues to do yeoman's service for John Barlow, who stayed on when Mollie Brazier moved to UCLA's Brain Research Institute.) A meaningful and quantitative description of the human electroencephalogram (EEG) was the common purpose. Both groups were powerfully spurred on by Norbert Wiener's interest, curiosity, and hopes. For years he would come to Building 20 several times a week to inspect EEG correlograms, to instruct and to share his ideas, and sometimes even his fears and dreams. He clearly lacked the patience of participating in actual experiments and expressed occasionally some doubts regarding the wisdom of investing so much time in experimentation.

Students started to join the Communications Biophysics group: most of them were EEs, but there were some young physicists and even mathematicians. By the mid-50s, the group was regularly attracting postdoctoral and even senior postdoctoral visitors; they came for a year or two to acquire what they considered to be promising techniques. Most—though by no means all—of these visitors came from and returned to departments of Psychology and Physiology where they were experimenting on sensory systems; one who fortunately stayed on and became an RLE staff member was Nelson Kiang, a PhD in Biopsychology from the University of Chicago.

Through the good offices of students and young colleagues, advanced development groups in other MIT laboratories—such as Lincoln Laboratory and the Electronic Systems Laboratory—became interested in challenging instrumentation problems. This cooperation led to the design and construction in 1957-58 of the ARC-1, the Average Response Computer, by Wes Clark and his Lincoln and Communications Biophysics associates. This digital special-purpose computer was fast enough, thanks to its transistor circuitry, to process and display "on-line" averaged responses evoked by sensory stimuli. Even more than the various uses of the analog correlator, the ARC-1 and certain demonstration programs written for the Lincoln-developed TX-0 and TX-2 computers contributed substantially to the development of a new style in neurophysiological experimentation. The MIT 1959 summer program, "Quantitative Approaches to the Study of Neuroelectric Activity," was symbolic of a stage in this development. It was for this occasion that the Communications Biophysics group prepared the monograph entitled *Processing Neuroelectric Data*.

The foregoing account suffers of course from a highly personalized kind of tunnel vision, and the activities sketched above represent only a fraction of RLE's involvement with the life sciences. But if communications biophysics must in no way be taken as *pars pro toto*, it represents nevertheless, in both research and education, a sample point in a metaphorical hyperspace in which the physical sciences, the associated varieties of contemporary engineering, and the life sciences increasingly encroach upon one another.

Since the early 1950s, the Neurophysiology group—McCulloch, Pitts, Lettvin, Wall, and others—had worked on a large variety of important biological problems. The group's cybernetic concerns led them to go about their experimenting and theorizing in an unorthodox and highly imaginative manner. They

*(continued on page 32)*

# From a Biophysicist Who Came to Supper

*(continued from page 31)*

thereby contributed much to the RLE pool of exciting ideas, and in particular influenced the thinking of those interested in artificial intelligence.

During this same period numerous groups and approaches emerged that contained ingredients labeled "engineering" and "living systems" in varying proportions. Inside RLE activity in the area of sensory prostheses had continued ever since the Wiener-Wiesner-David project Felix. A few years after Cliff Witcher's untimely death, Sam Mason developed an interest in this area. His engineering background of circuits, flow graphs, and signal analysis formulated problems in a new way, and his enthusiasm attracted many students. Before too long Mason's group coalesced with groups around Bill Schreiber (interested in picture processing) and Murray Eden, who worked on recognition of biologically significant patterns. Today the combined group goes under the name of Cognitive Information Processing: their major current project, a reading machine for the blind, is symbolic of an entirely new cognitive technology. Another merger brought together the Acoustics Laboratory group on speech communication led by Ken Stevens with the linguistically oriented Speech Analysis group under Halle. . . .

What precedes emphasizes the pervasive nature of the interaction of engineering and the organism. The non-narrow way in which electronics was defined in RLE's original terms of reference accommodated itself to the emergence of the communication sciences. The subtitle of *Cybernetics*, "Control and Communication in the Animal and the Machine," remains perhaps to this day the most concise definition of the communication sciences. This definition is symmetrical with respect to living and nonliving aspects of organized complexity.

*Institute Professor Emeritus Walter A. Rosenblith* *(Photo by John F. Cook)*

Biologically speaking the level of systems considered is not that of the cell or its subsystems but rather that of the whole organism and its functional, symbol-manipulating subsystems. Without becoming either too philosophical or too historical, the foregoing perhaps make plausible why molecular biologists were less attracted to RLE than their more systems-oriented brethren.

Ten years after its formation the Communications Biophysics group had changed considerably in character. Graduate students who had done their doctoral theses in the laboratory had been appointed to the EE faculty (Moise Goldstein and Bill Peake were the first two); they thereby started a kind of renewal process that is more than mere intellectual iteration. Bill Siebert with his rich experience in random processes and radar systems had joined, thereby strengthening the group immeasurably in the area of applied mathematics. Today's research style not only encompasses new techniques but undeniably shows signs of having been tempered in the educational process. This type of coupling between research and education keeps both, shall we say, more honest.

Another event of historical importance for the future of the Communications Biophysics group had also taken place in the late 1950s: a group of distinguished Boston otologists approached the Institute for assistance in developing a long-range program of basic research in hearing at the Massachusetts Eye and Ear Infirmary. The two institutions agreed to cooperate: the proposal they submitted in common to the National Institutes of Health resulted in the establishment and construction of the Eaton Peabody Laboratory of Auditory Physiology located at the Infirmary. The program which has now been underway for almost a decade provides a successful demonstration of how medical, biological, and engineering purposes can be served when men like Nelson Kiang and Bill Peake are given an opportunity to work in a medical setting while retaining ties with colleagues, students, and facilities at RLE.

One further strong personal impression of the author's fifteen years in RLE: not only is RLE multidisciplinary, it is also highly cosmopolitan. Visitors from all parts of the world arrive for periods of hours to years. Those who have difficulty mastering spoken English come here to study the abstractions of transformational grammar. Some whose homeland lacks a good electric power grid participate in microelectrode experiments that require the programming of highly sophisticated computers. But such is the international character of science: not something to be trotted out for gala occasions, such as a symposium on sensory communication, but a venture in day-by-day multinational cooperation.