Psychological and Physiological Acoustics

Introduction

The scope of the Psychological and Physiological Acoustics Technical Committee of the Acoustical Society of America includes "the investigation and the dissemination of information about psychological and physiological responses of man and animals to acoustic stimuli." This statement encompasses the essence of the study of hearing the study of what we hear and how we hear it. The ensuing research, scholarship, and educational efforts bridge many disciplines associated with the hearing sense. Moreover, the Psychological and Physiological Acoustics Technical Committee is not isolated within the Acoustical Society of America; there is cross-fertilization between a number of sub areas, including Animal Bioacoustics, Architectural Acoustics, Noise, and Speech Communication.

To provide an overview of the history of the important technical, theoretical, and even practical aspects of the study of the psychology and physiology of hearing is a daunting, if not impossible, task. In their reviews, Professors Ira J. Hirsh and Murray B. Sachs provided well researched, and at times charming, historical reviews of the research questions, the theoretical approaches, and the progress researchers have made answering fundamental questions about how we hear. Concordant with research published in the Journal of the Acoustical Society of America through the past seventy-five years, the current reviews emphasize basic questions concerning auditory perceptions and the anatomy and physiology of the peripheral auditory system. Both chapters also look to recent advances; one needs only to consider recent research concerning hearing loss and deafness in order to appreciate the import of the foundational work successfully completed during the past seventy-five years. Also of note are the descriptions of the how changes in electronic technology, and now biotechnology, have impacted on the evolution of hearing research. In his chapter, Dr. Hirsh (who gratefully acknowledges the editorial help of Neal Viemeister and Dennis MacFadden) organizes the history of psychological acoustics by linking together research on fundamental questions concerning auditory perception what is absolute sensitivity for most human listeners, how well can listeners determine the location of a sound source, etc. Dr. Sachs, on the other hand, organizes his chapter on physiological acoustics by starting with a current model of the peripheral auditory system, and then describing the variety of work that has led to our current understandings. As the chair of the Psychological and Physiological Acoustics Technical Committee,

I extend a heartfelt thank you to Drs. Hirsh and Sachs for their efforts, and the resulting chapters.

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Psychoacoustics and The Acoustical Society Of America

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What follows is a bird's-eye view of psychoacoustics, with chief emphasis on the relation between that field and the 75 years of this Acoustical Society of America. The limitations of a single viewer of all the research that could be included are enormous. I can describe matters that seem to this bird major steps along the way. For many of these matters the reader will be referred to secondary sources where the subject is summarized well. Areas of research of great interest to others may not be well represented here.

In 1929, this Society was founded, and the first *Journal of the Acoustical Society of America* (JASA) was published. In fact, the first few volumes of "acoustics" was largely about "hearing," a subject matter that is now of principal concern to only one or two of many Technical Committees within the Society.

This Society's first President, Harvey Fletcher, also had a regular day job at the Bell Telephone Laboratories (BTL). He assembled a remarkable group of scientists and engineers whose names are well known for fundamental papers on auditory capacities in the 1920s and 1930s. The goal, the design of the best telephone system that could

be produced, was based in part on characteristics of listeners. The principal features concerned the minimum acoustic energy for hearing at different frequencies, the magnitude of the smallest change in frequency and in intensity that was noticeable, and the masking effects of one sound on another. An early summary of this aspect of psychoacoustics, along with much about speech and speech perception, appeared in Harvey Fletcher's *Speech and Hearing* (1929).

I mention Fletcher first, in part because of his great contributions and that of his group, and in part because of the context of this "acoustical society." In this chapter we are concerned with "psychological acoustics," the psychological aspect of acoustics, or more simply "psychoacoustics." If we flip the coin, then we could as well refer to the "acoustic" or "auditory" aspect of psychology, represented in laboratories and books of experimental psychology, especially in chapters on "hearing." Such early work is found in Helmholtz's *Lehre von den Tonempfundingen* (1863). By that year, we also had the beginnings of psychophysical methods from G.T. Fechner, and sensitivity to differences from E.H.Weber. Robert Woodworth's *Experimental Psychology* (1938) contains, in its chapter on hearing, a great summary of what was known. More detailed information on both psychological and physiological acoustics was published in the same year (1938) in *Hearing* by S.S. Stevens and H. Davis, a classic for students in psychology, acoustics, and, more recently, audiology.

Auditory Sensitivity - Absolute and Differential

Absolute threshold

How much acoustic energy must be delivered to the ear for a listener to respond that he heard something? Does that energy depend on the frequency of a tonal signal? Such questions were important, not only for the designers of telephones, but also for describing a capacity of human listeners and the assessment of hearing loss, or degree of hearing impairment. Sivian and White (1933) published their results in JASA. That early work was followed by hearing surveys and reports from other laboratories. Licklider (1951) put several different results together and eventually there were agreements across national borders, principally through the International Organization for Standardization (ISO).

The availability of these measures of thresholds for tones of different frequencies permitted an increase of serious measures of hearing loss. Eventually international standards, contributed largely by members of this Society and its Committee on Standards, were agreed.

Differential sensitivity for intensity and frequency

Given that a sound is heard, what do we know about differences between different sounds? The reports of Shower and Biddulph, in 1931, followed the earlier report of Knudsen (1923) on the smallest noticeable difference or change in frequency. Just-noticeable differences (JNDs) for intensity were reported by Riesz in 1928.

These early reports on both absolute and differential sensitivity, as well subsequent reports covering a large corpus, are well summarized in Green (1988).

Masking

Discriminating between two tones of different frequency or of different intensity is not far from discriminating between a noise and that same noise with a tone in it. Thus masking can be regarded as another example of discrimination.

The classic paper on the masking of tones by tones was by Wegel and Lane (1924), who showed that low-frequency tones can mask higher-frequency tones better than the higher on the lower. There were also clear dependencies on frequency, and also peculiar discontinuities in the functions, presumably due to beats near the coincident tones (the masked and masker). The wrinkles were ironed out by Egan and Hake (1950), who used a narrow band of noise instead of the masking tone. Here the masking functions were simpler.

In 1940, Fletcher proposed that when a white noise masked a pure tone, only a narrow band of noise around that tone was effecting [sic] the masking. He suggested further that this "critical band" at any frequency was that band whose total energy was equal to that of the tone being masked. But a "critical band" was used by Zwicker, Flottorp and Stevens to describe loudness integration as bands were enlarged. Many authors favored use of "critical ratio" as a term better associated with the masking experiments.

Binaural masking

Somewhat more complicated was the masking of tones or speech by noise delivered to both ears. One had to take into account the phase or time relations between signals and noises at the two ears (Hirsh, 1948). The effects were robust and challenged simple notions of masking at the periphery only. (Yost and Trahiotis have had copied or reprinted a large number of relevant articles in "The MLD: A collection of seminal papers.")

Psychological Attributes of Sounds

Most listeners can describe the degree of loudness or of high or low pitch in common parlance. The earliest goal of the new psychophysics (1850) was to establish a relation between the psychological aspect of subjective dimensions and the pertinent aspect of the physical (in this case the acoustic) stimulus.

Decades of studies with listeners' estimations of the loudness of sounds, fractionation and matching proce-

dures, have yielded solid relations between loudness and intensity, pitch and frequency and applied scales like "perceived noisiness" (Miller, 1974). Indeed, these procedures have been extended to other sensory domains like vision and touch (see Stevens, 1951).

Pitch and frequency analysis have been the key to emphasize the association with a biological mechanism, like "place" along the cochlea or among nerve fibers. (See especially, Moore, 1993.)

Method and Theory

Signal detection

Psychophysical procedures, formalized by Fechner in 1860, and with newer varieties, were used by psychologists, engineers and physicians to explore the sensory characteristics of humans. In general those classical procedures yielded results on sensitivity that contained information not only about sensitivity but also about factors related to listener's criteria in listening tasks. Then, about 100 years later, application was made from the theory of signal detectability (TSD) to psychophysical investigations in which one could separate detectability from other aspects of decision-making. Reviews of much of the work as applied to auditory psychophysics can be found in Green and Swets (1966), and in Tanner and Sorkin (1972). TSD has been important in psychophysical theory, not only in sensory science, but also in more general decision tasks. We learned, or were reminded, that a listener brings to the task of discrimination a variety of factors other than those associated with a barrier or assumed "threshold" in the auditory mechanism itself—expectations, degree of attention, costs and rewards.

Auditory processing

Throughout the 75 years of the ASA, and before, scientists have sought to know how the hearing system does what it does. There have been explanatory theories or models based primarily on biological mechanisms. These have been alluded in Murray Sachs' companion chapter on Physiological Acoustics in this monograph. Other schemes have been rational, often mathematical, systems that may be purely formal, or explanatory through a physical, often electronic, model. If we can describe such a system that behaves in the same way, as do listeners, then we have a theoretical model in physical terms.

Temporal processing

For some time in this history, the stimulus dimensions studied concerned the spectrum: intensity, frequency, bandwidths, etc. It has been clear, however, that the acoustical message in any sound must also describe how the message evolves in time. The oscillogram gives a spatial display of long-time and short-time temporal changes. The former is a major aspect of speech and musical sounds. The latter describe the fine temporal grain within brief signals. A fine summary of theories concerning such time varying changes is given by Viemeister and Plack (1993). Identification of longer signals and signal sequences is treated by Hirsh (1988).

Auditory perception

Psychoacoustics has sometimes been characterized as the esoteric aspects of auditory processing, especially cochlear mechanisms, the details of psychophysical procedures, the relevance for theories of auditory processing. It has not, until recently, been closely associated with the auditory perception of speech, of natural sounds, or of music.

The limitation of the stimulus properties to be studied was really a limitation of the instruments available at any given time. Sound-level meters, wave analyzers, and filters served well the steady state. But music had a time pattern, often laid out in a space on a score. Speech sounds were displayed in Fletcher's 1929 book by oscillograms, and were later rescued by the sound spectrograph. Now we could think about temporal grain and the minimum interval between two sounds, and about order in which elements in an auditory display followed each other (Hirsh, 1959, 1974; Bregman, 1990). These were some of the now available dimensions to expand the repertoire of studied sound patterns.

Auditory perception of space

The localization of sound sources in a listener's environment is one of the oldest subjects in psychoacoustic research. Studies in the late 19th century had already established that the judgment of the laterality of a sound source was related to differences in intensity or in time of arrival of the sounds at the two ears. A summary of experiments of these dependencies is given by Wightman and Kistler (1993). In addition, there are other contributions of the particular individual distributions of the sound pressure at the eardrum from sounds emanating from different azimuths (Shaw, 1965; Wightman and Kistler, 1993). Human listeners show a remarkable ability to focus on the earliest of a series of reflections in a room—the precedence effect. An early synthesis with earphones was reported by Wallach, Newman and Rosenzweig (1949) and clarified many of the limits.

Perception of speech

Fletcher's group at the Bell Labs explored auditory psychophysics to assist in predicting the intelligibility of speech through different telephone systems. How to validate the relation? In characteristic manner, that group created a variety of syllables, words, and sentences to be used in listening tests, where the most frequent measure was 'percentage correct.' Much of that early work was

summarized in Fletcher's 1929 book and was extended by Egan at Harvard's Psychoacoustic Laboratory, by the group at Northwestern University, and by Hirsh at Central Institute for the Deaf.

The relevance of measures of sensitivity to differences in pure-tone frequency or in intensity for predicting speech intelligibility was not clear then, and is really not very clear now. But of course the basic levels of intensity and bandwidths of a transmission system were clear and were useful in telephone and radio communication. In fact, those two principal dimensions form the basis of an Articulation Index for just such predictions of new designs (French and Steinberg, 1947) and later was applied to hearing-aid design and selection.

A scheme that relates speech perception to the frequencies and intensities in a transmission system is important in designing such systems. But as a theory of sound-to-speech, the spectrum is not sufficient. Students of speech perception are going beyond characteristics of the spectrum and even the temporal features of syllables to aspects of the ensemble of words and still larger units, and include aspects of the listener's language history. Perhaps such characteristics go beyond acoustics, but they are coming to occupy readers and speakers at ASA meetings and publications.

Applications

Noise

One theme that runs throughout the history of this Society is noise—an interest for several of our Technical Committees. The simple physical definition of noise is its non-regular repetition, its random character. The subjective annoyance aspect of noise was treated by Laird in Vol.1 of JASA. As it grew to affect working environments, schoolrooms, communities around airports and highways, annoyance was studied, calculated in various schemes—especially during the last 50 years.

The many-faceted problems around noise were a great fit for this Society. The problems required the talents of physicists, noise-control and machine-design engineers, psychologists, audiologists, otolaryngologists, and land-use planners. Technical symposia and Society committees were at work, in parallel with efforts in, for example, the National Research Council (NRC) that profited from the model of this Society in bringing these specialties together in the Committee on Hearing and Bioacoustics and Biomechanics (CHABA) under the NRC, along with our own Standards Office. In this enterprise, Edgar Shaw, Henning von Gierke, William Galloway, Karl Kryter, Ken Eldred and many others provided the breadth that was necessary to bring measurements, psychological scales, community surveys and principles of noise reduction together.

Studies that related spectrum, level, intermittency and other predictors of masking played an important role in estimating how much interference with speech communication could result from ambient noise. In addition, a serious health problem was the loss of hearing from exposure to high levels and durations of noise, particularly important in noisy workplaces. The attendant literature is huge. A concise summary of these various effects of noise is the report by Miller (1974). It was not just our literature, but also our societal responsibilities that came to the fore—in our own standards program, in our participation in international standards and cooperation with other societies and governmental agencies. These efforts showed the strength of having an Acoustical Society that involved various specialties from physics and engineering, from biology and psychology, and from medical and legal points of view. Agencies within our government as well as from other countries have followed similar patterns.

Retrospective

During the 75 years of ASA's existence, psychoacoustics has evolved from studies of sensory capacities to bridge parallel development in physiology and in communication theory within this hospitable Society, which accommodated varieties of specialties. The development of theory in several lines has enhanced our ability to understand and explore complex perceptual and artistic domains.

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The History of Physiological Acoustics

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When Neal Viemeister asked me to give a lecture on the history of physiological acoustics, I was reminded of a time when I was playing ball with my sons and their friends. One of the kids picked up my Stan Musial mitt and asked innocently "who is Stan Musial?" The question went right through me. Who wouldn't know about my childhood hero! Recently a graduate student in our lab had the temerity to ask, "who is Jerzy Rose?" That question struck even deeper, for I had only idolized Stan the Man from afar, but I had known Jerzy "up close and personal." The crowning blow came when a postdoc in our department told me he had thought that Nelson Kiang was my first student! Of course nearly the inverse was true—I was one of Nelson's early students. I realized that we were failing to pass on the rich historical perspective of our field to the next scientific generation, and so with some trepidation I accepted the invitation to give the lecture.

The first two papers that I could find in JASA that might be called "physiological acoustics" appeared in Volume 2 in 1930 and in more or less direct ways they portend the future of the field. A paper by Smith and Laird (Smith and Laird 1930) on effects of noise on stomach contractions could be considered an early precursor of the rapidly growing literature on cross-modality interactions in the system (Kanold and Young 2001). Firestone's analysis of interaural acoustic differences for tones in the same volume (Firestone 1930) gives rise to an enormous literature on this topic. The next paper was an invited talk by Hallowell Davis at the 1934 Meeting of the Society

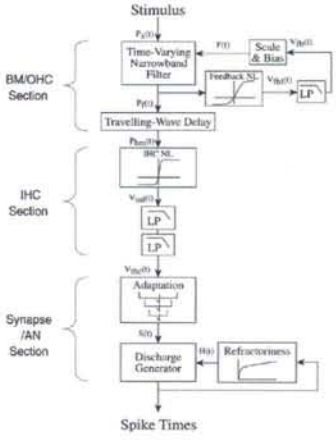

Figure 1. Model of stimulus processing in the peripheral auditory system. From (Carney 1993).