Psychoacoustics: A Brief Historical Overview

William A. Yost

Postal:
Speech and Hearing Science
Arizona State University
PO Box 870102
Tempe, Arizona 85287
USA

Email:
william.yost@asu.edu

From Pythagoras to Helmholtz to Fletcher to Green and Swets, a centuries-long historical overview of psychoacoustics.

Figure 1. *Gustav Fechner (1801-1887), "Father of Psychophysics."*

What is psychoacoustics?[1] Psychoacoustics is the psychophysical study of acoustics. OK, psychophysics is the study of the relationship between sensory perception (psychology) and physical variables (physics), e.g., how does perceived loudness (perception) relate to sound pressure level (physical variable)? "Psychophysics" was coined by Gustav Fechner (**Figure 1**) in his book *Elemente der Psychophysik* (1860; *Elements of Psychophysics*).[2] Fechner's treatise covered at least three topics: psychophysical methods, psychophysical relationships, and panpsychism (the notion that the mind is a universal aspect of all things and, as such, panpsychism rejects the Cartesian dualism of mind and body).

Today psychoacoustics is usually broadly described as auditory perception or just hearing, although the latter term also includes the biological aspects of hearing (physiological acoustics). Psychoacoustics includes research involving humans and nonhuman animals, but this review just covers human psychoacoustics. Within the Acoustical Society of America (ASA), the largest Technical Committee is Physiological and Psychological Acoustics (P&P), and Psychological Acoustics is psychoacoustics.

[1] *Trying to summarize the history of psychoacoustics in about 5,000 words is a challenge. I had to make difficult decisions about what to cover and omit. My history stops around 1990. I do not cover in any depth speech, music, animal bioacoustics, physiological acoustics, and architectural acoustic topics because these may be future* Acoustics Today *historical overviews. I focus on aspects of pitch perception and sound source localization because these topics have a very long history of study. I briefly cover other topics, but many had to be omitted. The overview will be "English-centric," at least after the 1920s. I am fluent only in English, so my knowledge of psychoacoustics is dominated by what I have heard and read, and* Acoustics Today *is a magazine of the ASA and* JASA *is the scientific journal of the ASA. I believe it is fair to say that the majority of the articles written on psychoacoustics from 1929 (ASA's founding) to the end of the 20th century appeared in English in* JASA. *I have attempted to recognize key scholars who did not always publish in English, but I am sure that I have not done a good job of covering non-English psychoacoustic contributions.*

[2] *See Internet Archive BookReader:* https://www.google.com/#q=Elemente+der+Psychophysik+.

Table 1: ASA Psychoacoustician Award Winners and Presidents

Gold Medal		Silver Medal		Helmholtz-Rayleigh Interdisciplinary Silver		ASA Presidents	
Harvey Fletcher	1957	Lloyd A. Jeffress	1977	W. Dixon Ward	1991	Harvey C. Fletcher	1929
Ira J. Hirsh	1992	Eberhard Zwicker	1987	Jens P. Blauert	1999	J. C. R. Licklider	1958
David M. Green	1994	David M. Green	1990	William M. Hartmann	2001	Ira J. Hirsh	1967
Brian C. J. Moore	2014	Nathaniel I. Durlach	1994			Karl D. Kryter	1972
		Neal F. Viemeister	2001			David M. Green	1981
		Brian C. J. Moore	2002			W. Dixon Ward	1988
		H. Steven Colburn	2004			William M. Hartmann	2001
		William A. Yost	2006			William A. Yost	2005
						Judy R. Dubno	2014

Although a defining aspect of Fechner's psychophysics was relating perception to physics, attempts to find the physical bases for perception predate Fechner by centuries. The early Greeks, such as Pythagoras, sought physical/mathematical explanations for many aspects of music. The Greeks did not have a name (e.g., psychoacoustics) for their studies, but they were engaged in psychoacoustics just as much as Fechner and others before and after him.

I divide the history of psychoacoustics into several periods: Psychoacoustics Before the 19th Century, the Realm of Helmholtz, Bell Laboratories, the Theory of Signal Detection, the Study of Complex Sound, and Auditory Scene Analysis (Yost, 2014; **Table 1**). I have relied on the classic perception history text by E. G. Boring (1942) and R. B. Lindsay's article on the history of acoustics (1966).

Psychoacoustics Before the 19th Century

As already mentioned, Pythagoras and fellow scholars were fascinated by music. Greek musical instruments were simple-stringed (e.g., lyre), tubed (e.g., flute), and percussion (e.g., tympanum) instruments. Greek scholars tried to understand the physical/mathematical bases of musical scales, consonance, and dissonance produced by these instruments.

Aristotle (around 350 BC) was the first to suggest that sound is carried by air movement. But Leonardo De Vinci (around 1500) was likely the first to realize that such movement was probably in the form of waves. Galileo Galilei, 100 years later, scraped a chisel across a brass plate, producing a screechy pitch. Galileo calculated that the spacing of the grooves caused by the chisel was related to the perceived pitch of the screech. However, it wasn't until the 17th century that the relationship between vibratory frequency and pitch was confirmed. Robert Hooke (1635-1703) made a wheel with small teeth sticking out from the edge at equal intervals. As the wheel rotated on an axle and the teeth pressed on a card, a sound was produced when the card vibrated. The pitch of the sound rose as the wheel's rotational speed increased. A century and a half later, Felix Savart (1791-1841) refined the wheel to study human hearing (**Figure 2**).[3]

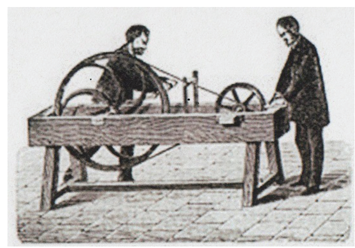


Figure 2. *An illustration of a Savart wheel. An earlier version was used by Hooke to study sound frequency and pitch.*

By the 18th century, the main method for creating sound for the study of pitch was the tuning fork, invented by John Shore in 1711. Shore (1662-1752) was an accomplished trumpeter and lutenist, and he is reported to have said at the beginning of a concert that he did not have a pitch "pipe," a common means to tune instruments, but he did possess a pitch "fork." Other forms of resonators, sirens, tubes, and strings were used to study sound until the use of electrical devices and the vacuum tube (invented about 1910) came into existence.

The early scholars had their humorous observations as well. For example, Leonardo Da Vinci wrote "an average human looks without seeing, listens without hearing, touches without feeling, eats without tasting, moves without physical awareness, inhales without awareness of odor or fragrance, and talks without thinking."

Realm of Helmholtz (1800s-Early 1900s)

Hermann von Helmholtz was a commanding, if not the leading, scientist of the 19th century. His book (1863/1954) *On the Sensations of Tone as a Physiological Basis for the Theory of Music* was the major reference for hearing and musical

[3] Wave-Action in Nature. *(1873).The Popular Science Monthly, Volume III, 7–8.*

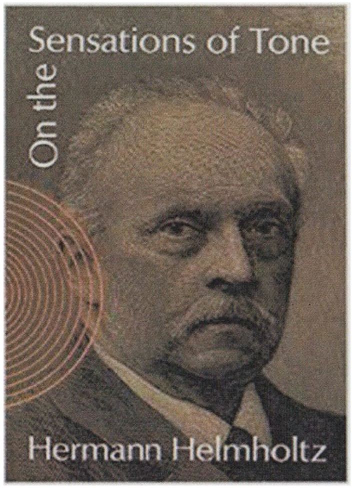


Figure 3. *Hermann von Helmholtz (1821-1894) and his book On the Sensation of Tones.*

perception for many decades (**Figure 3**). With the publication of Fechner's and Helmholtz's books, the study of hearing turned from one of observations based on a scientist's perceptions to a more systematic collection of psychop physical data, often stated in terms of acoustical variables, in somewhat well-controlled experiments.

Many studies of hearing occurred in the 18th century, and two areas of interest, pitch and sound source localization, have had a lasting impact on psychoacoustics. Helmholtz was influenced by Georg Simon Ohm's (1789-1854) "acoustic law" that stated that the ear performs a limited Fourier analysis by determining the sinusoidal components of complex sound. Ohm is perhaps better known for his work on electricity and for whom the unit of resistance is named. Fourier (1768-1830), a French physicist/mathematician working earlier in the 19th century, established a theorem regarding complex fluctuations of heat over time. Fourier's theorem can be applied to sound pressure varying as a function of time. Helmholtz used Fourier's theorems to describe a resonance theory of frequency analysis performed by the inner ear as the basis of pitch and argued that the resonance place with the greatest magnitude would be a determining factor in pitch perception. Because his inner ear resonators were more sharply tuned at low frequencies, low frequencies were likely to be a dominant factor in pitch perception.

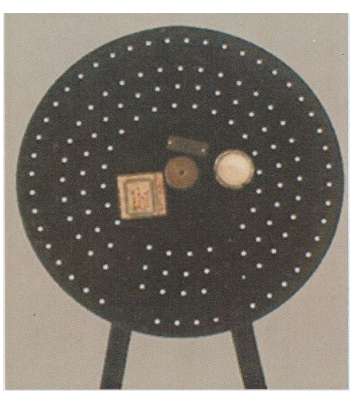


Figure 4. *Seebeck's siren.*

In 1844, August Seebeck (1805-1849) constructed a siren (**Figure 4**) through which air passed as the siren rotated (see Turner, 1977). The siren produced a pitch based on a series of harmonic tones, each an integer multiple of a fundamental tone the frequency of which was the value of the perceived pitch. However, Seebeck's siren was constructed so that the fundamental frequency was not physically present, only the harmonics. The pitch of this "missing fundamental" sound appeared to be the same as when the fundamental was present. This implied that the fundamental of a harmonic sound does not have to be physically present for the pitch to be perceived as that of the fundamental. This was at odds with Ohm's acoustic law as interpreted by Helmholtz. Helmholtz cited several reasons why Seebeck's missing fundamental pitch was an "artifact," and it was many years before the missing fundamental stimulus was cited as a serious challenge to Helmholtz's spectral/resonance theory of pitch perception. Decades later, Schouten (1940) formulated his "residue theory," which suggested that the missing fundamental pitch was based on the temporal amplitude envelope of the missing fundamental stimulus that would exist in a high-frequency region after the sound was transformed by inner ear filtering processes. Helmholtz's spectral approach to explaining pitch perception and Schouten's temporal approach characterize today's debate as to the probable auditory mechanisms accounting for pitch perception (Yost, 2009).

Perceptual scientists in the 19th century observed that the source of a sound could be spatially located based entirely on sound despite the fact that sound has no spatial properties. So how could sound provide information about spatial location? Lord Rayleigh (James William Strutt, 3rd Baron Rayleigh, 1842-1919, Nobel Prize in Physics 1904) and others reasoned and observed that a sound presented to one side of the head would be more intense at the ear nearest the sound than at the far ear, especially because the head would block the sound from reaching the far ear (the head forms an acoustic shadow). This would produce an interaural level difference (in the horizontal or azimuth plane), which would increase as a sound source was moved from in front toward one ear or the other. Thus, Rayleigh (1876) proposed his "binaural ratio" explanation for sound source localization.

Rayleigh was aware that others (e.g., Silvanus Thompson, 1878) used tuning forks delivering sounds of different frequencies to each ear to suggest that the interaural phase might also provide a cue for sound source localization. When one calculates the interaural time difference (ITD) associated with the perceptible interaural phase difference, the ITD is often less than one millisecond. Rayleigh and others felt that a difference this small could not be detected by the auditory system and, besides, Helmholtz had shown that the "ear was phase insensitive." Thus, interaural phase (time)

> **Today psychoacoustics is usually broadly described as auditory perception or just hearing, although the latter term also includes biological aspects of hearing.**

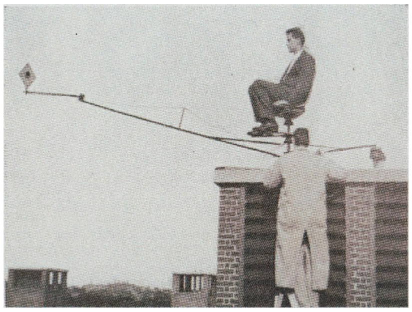


Figure 5. Stevens and Newman on the roof (to avoid sound reflections) of James Hall at Harvard University conducting their sound source localization experiment (Stevens and Newman, 1936). [Photograph from American Journal of Psychology 48:2 (April 1936): pp. 297-306. Copyright 1936 by the Board of Trustees of the University of Illinois. Used with permission from the University of Illinois Press.]

differences were rarely considered as a cue for sound source localization until Rayleigh (1907) reevaluated the cues that might be used for sound source localization. Rayleigh argued that the interaural level difference (ILD) was a possible cue at high frequencies where the ILDs would be large due to the head shadow, and an interaural time (phase) difference could be a cue at low frequencies. This "duplex theory of sound source localization" was further validated by others including Stevens and Newman (1936) in their experiment on the roof of James Hall at Harvard (**Figure 5**). See Jens Blauert's (1997; **Table 1**) often-cited book *Spatial Hearing* for a detailed review of spatial hearing.

Although it was clear for centuries that sound had magnitude (loudness) in addition to pitch, it was not easy to accurately manipulate and control sound magnitude. One could change the length of a tube or string, alter the characteristics of a tuning fork, and vary the density of spikes on a wheel or holes of a siren to change the frequency (pitch). But there was no easy way to vary sound magnitude. So studies on audibility, perceived sound level differences, loudness, and masking were not studied, not because of a lack of interest in these topics but because of a lack of means to accurately vary the sound level. With electroacoustic devices, studies involving sound level proliferated in 1920s and 1930s, especially at Bell Laboratories.

Bell Laboratories (1920-1960)

Bell Laboratories was truly a unique institution both in business and in science (Gertner, 2013). Bell Laboratories (formally founded in 1925) was the "research branch" of the original version of the American Telephone & Telegraph (AT&T) company that was consolidated with Western Electric (the manufacturing arm of AT&T), forming a government-supported monopoly for the US telephone system. Bell Laboratories was first established in New York City but moved to a new, specially designed space in Murray Hill, NJ, in 1941. Harvey Fletcher,[4] a modest son of a Utah farmer (**Figure 6; Table 1**), worked at Western Electric and then Bell Laboratories from 1917 to 1949 and was at one time director of acoustical research and then physical research. In addition to his pioneering roles in the ASA, Fletcher is also well known for his laborious efforts in the Nobel Prize-winning experiment measuring the electron charge carried by a single atom (awarded to Robert Millikan in 1923). As director of acoustical research (see Allen, 1996), Fletcher oversaw a litany of psychoacoustic research achievements unmatched in the history of the field,[5] which included measurements of auditory thresholds (leading to the modern-day audiogram, the gold standard for evaluating hearing loss), intensity discrimination, frequency discrimination, tone-on-tone masking, tone-in-noise masking, the critical band, the phon scale of loudness, and the articulation index. Two of the more important psychoacoustic contributions of the Bell Laboratories years are the critical-band and equal-loudness contours.

Figure 6. Harvey Fletcher (1884-1981), former Director of Physical Acoustics at Bell Laboratories and first President of the Acoustical Society of America.

Fletcher originally conceived of critical bands in terms of both loudness and masking (Allen, 1996). The critical band is a frequency region that is "critical" for masking and/or loudness summation (the masking definition is used most

[4] *See http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/fletcher-harvey.pdf.*

[5] *In addition to Jont Allen's article (1996), see* Study of Speech and Hearing at Bell Telephone Laboratories, *ASA-CD, ASA-DS-02, ASA-Online Book Store. Produced by Christine Rankovic and Jont Allen.*

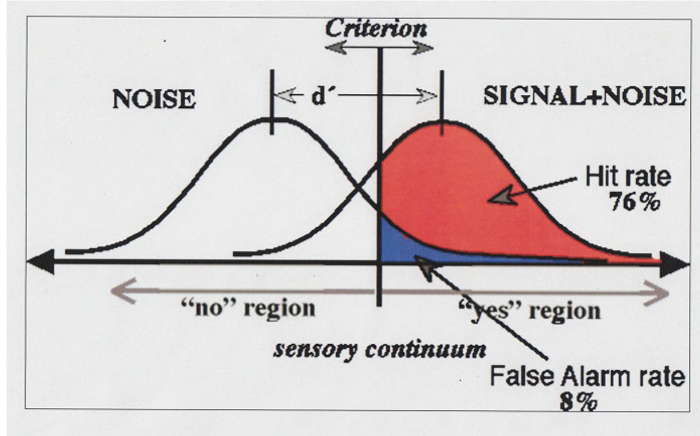


Figure 7. Calculation of the sensitivity-only measure, the normalized distance between the means of the two distributions (d'), from the theory of signal detection (TSD). The subject's criterion for responding "yes" as opposed to "no" if the signal is present or not generates the Hit and False Alarm rates from the assumed normally distributed underlying Noise and Signal+Noise distribution along a sensory continuum.

often). The threshold for detecting a tonal signal masked by a noise is proportional to the power in a critical band of masker frequencies surrounding the signal frequency. The critical band is modeled as a bandpass filter similar to the action of the biomechanical properties of cochlear processing (Moore, 1989; **Table 1**). Eberhardt Zwicker (**Table 1**) in Germany using primarily loudness data developed similar critical-band measurements. The bandwidths of Zwicker's critical bands are referred to as the Bark Scale (Zwicker and Fastl, 1991). The gammatone filter bank is a current manifestation of critical-band filters (Patterson et al., 1995).

The Fletcher-Munson (1933) equal-loudness contours and the resulting phon scale are hallmark measures of loudness. Each "equal-loudness contour" indicates all combinations of tonal frequency and level that are equal in loudness to each other and to a 1,000-Hz tone with a particular intensity. The loudness level of a tone on an equal-loudness contour is defined as a phon, where "*x*" phon is the loudness of a sound judged equally loud to a 1,000-Hz tone of "*x*" dB sound pressure level (SPL). The equal-loudness contours show that perceived loudness is dependent on both sound intensity and frequency, whereas physical sound intensity and frequency are independent of each other. Equal-loudness contours have been used in a wide variety of applied contexts (see Glasberg and Moore, 2006).

Theory of Signal Detection (1950-1970)

A lot of research after 1950 was driven by post-World War II activities such as the detection of radar and sonar signals. Operators of radar/sonar have to discern, either visually or acoustically, weak signals in a background of noisy clutter. The Electronic Defense Group at the University of Michigan studied human detection of such issues. Ted Birdsall, William (Spike) Tanner, W. W. Peterson, and others were instrumental in developing the theory of signal detection (TSD). David Green (**Table 1**) and John Swets, Michigan psychology graduate students working in Electrical Engineering and Psychology, carried the ideas of the TSD into the world of psychoacoustics and far beyond. *Signal Detection Theory and Psychophysics* by Green and Swets (1974/1966) was essentially "required reading" for any aspiring psychoacoustician in the 1960s and 1970s.

The TSD was derived from the statistical decision theory (**Figure 7**), and study of the TSD produced several different contributions to psychoacoustics and many other areas (Swets, 2010): (1) the TSD was a theory of how decisions are made in variable and uncertain contexts; (2) the TSD challenged the concept of "sensory thresholds"; (3) the TSD proposed that decisions such as discriminating between a signal-plus-noise and just the noise involved not only a listener's sensitivity but also biases in using their perceptual responses; (4) the TSD defined a way to measure sensitivity independent of response bias; (5) the TSD relied on defining "ideal observers" for evaluating decision processes; (6) many new psychophysical procedures were designed based on the TSD (these procedures replaced some originally proposed by Fechner); and (7) the TSD led to the psychoacoustic "energy detection model" that accounted for many data involving detection and discrimination of well-specified sounds. The precision of the data obtained using TSD procedures and analyses was usually well beyond what had previously been measured psychophysically or for almost any other behavioral measurement.

The TSD was developed when many psychoacousticians were psychologists and when behaviorism (promoted by B. F. Skinner) was a dominant theme in psychology. Although few psychoacousticians were "Skinnerians," many aspects of behaviorism resonated with the psychoacousticians of the day, such as (1) the need for clear operational definitions of all terms; (2) all behavior is observable and measureable; (3) behavior is a consequence of actions; (4) behavior can be studied in a strict scientific manner; and (5) an opposition to explanations based on private nonobservable events such as "cognition."

Another approach to studying psychophysical relationships was exemplified by the work of S. S. (Smitty) Stevens. Stevens (1957) developed scales of measurement and new "scaling" procedures to measure Fechnerian-type psychophysical relationships between subjective/perceptual attributes of sound and physical measures. Stevens power law is a frequently used psychophysical relationship.

Smitty was famous in an entirely different arena from psychology and psychophysics. He is often touted as the father of "short skis." Smitty was avid skier at a time when skis were expected to be as tall as one could reach. Smitty felt this was "nonsense" and that shorter skis (far shorter) would offer much more movability with only a small loss in speed. He and others with a passion for short skis convinced the ski world of their merit, and the tall skis of the past are just that, in the past.

By the 1940s, it was well understood that ITDs and ILDs controlled sound source localization in the horizontal plane (see earlier discussion of Rayleigh). By presenting sounds over headphones, ITDs and ILDs could be systematically varied and independently controlled. The perception of sounds presented over headphones is not always the same as when the same sounds are presented in an open field. Thus the study of ITD and ILD cues using headphone-delivered sounds is referred to as "lateralization" as opposed to "localization" when the sounds are presented by loudspeakers.

In 1948 in the same issue of the *Journal of the Acoustical Society of America (JASA)*, Ira Hirsh and J. C. R. Licklider ("Lick" was known for his early work on the internet and personal computing; see Waldrop, 2001; Walden, 2014; **Table 1**) each published an article showing that when a tonal (Hirsh, 1948)

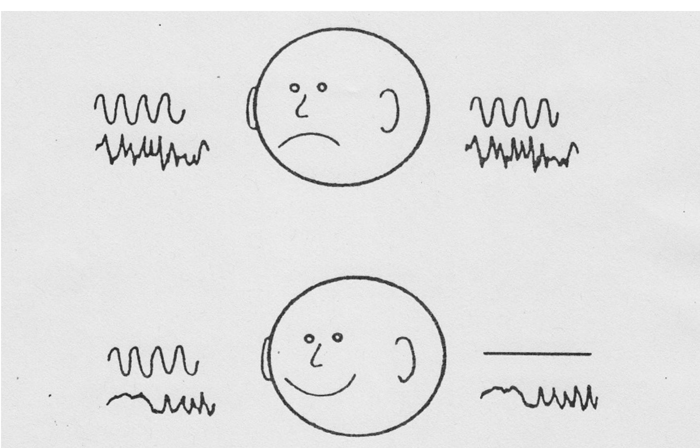


Figure 8. *Depiction of masking level difference (MLD) conditions. When the signal (top waveform) and masker (bottom waveform) are the same at both ears, detection is difficult. Deleting the signal from one ear (leading to an interaural time difference [ITD] and an interaural level difference [ILD]) renders the signal easier to detect. From Green and Yost (1975).*

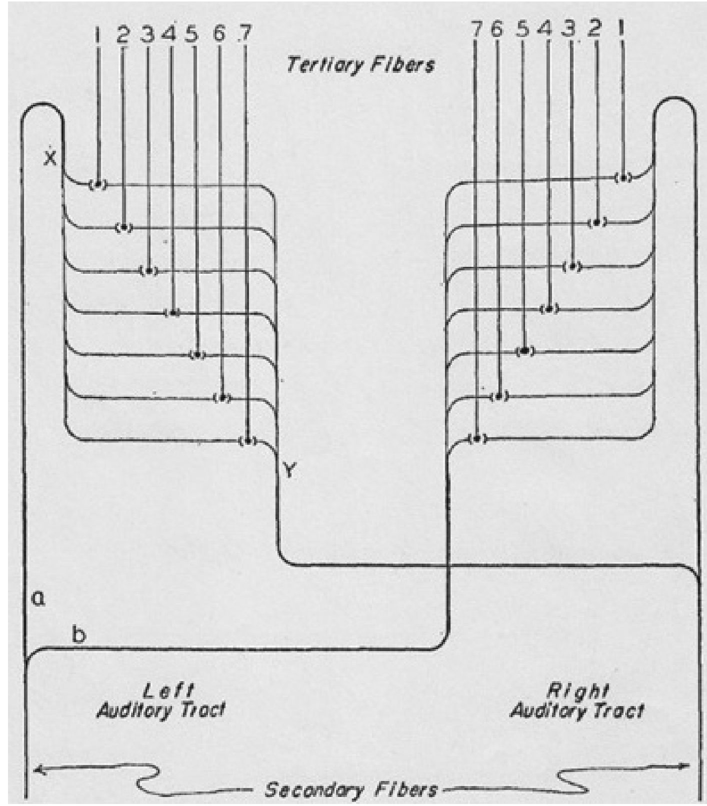


Figure 9. *"Jeffress Coincidence Network" with inputs from the left and right ears converging in a central neural area of bipolar cells. From Jeffress (1948).*

or speech (Licklider, 1948) signal was presented with a different configuration of ITDs/ILDs than those of the noise masker, the threshold for detecting the signal was lower (sometimes a whopping 15 dB lower) than when the signal and masker had the same ITD/ILD configuration. This improvement in threshold was called the "masking level difference (MLD; **Figure 8**)." Due to the connection between lateralization/localization and the MLD and the large size of the MLD, MLD-like studies have been a dominant psychoacoustic topic since the 1950s.

In 1948, Lloyd Jeffress (**Table 1**) proposed that ITDs could be produced by a neural coincidence network that could be modeled as a cross-correlator (**Figure 9**). The "Jeffress model" has been widely used and forms the basis for understanding how barn owls locate small rodents at night using only sound. Many years later, Nat Durlach (1963; **Table 1**) developed a model of the MLD, the equalization-cancellation (EC) model, which assumes that the binaural auditory system first attempts to equalize the sounds at each ear and then interaurally cancels the equalized sounds. Studies of binaural processing and testing various models occupied many pages in JASA from 1948 until today and form the basis of current models of *Spatial Hearing* (Colburn, 1973; see also Blauert, 1997; **Table 1**).

Licklider (1956) also developed a "triplex" theory of hearing in which he proposed an autocorrelator for pitch processing. Pitch perception was studied extensively in the Netherlands and Germany by psychoacousticians such as Reinier Plomp, Burt de Boer, Frans Bilsen, and Ernst Terhardt. The autocorrelation approach of Licklider (and its later variations, Meddis and Hewitt, 1991) can extract temporal regularity from a sound as a basis of pitch. However, there are equally successful models of pitch that are based on the spectral structure of a sound. Julius Goldstein, Ernst Terhardt, and Fred Wightman each developed successful spectrally based models of pitch perception. As mentioned previously, the debate about spectral versus temporal accounts of pitch perception continues today (Yost, 2009).

Neal Viemeister (see **Table 1**) developed the temporal modulation transfer function (TMTF), similar to analogous functions in vision, to explain psychoacoustic phenomena associated with temporal modulation of sound (Viemeiser and Plack, 1993). This work paved the way for the current modulation filter bank models of temporal processing (Dau et al. 1996).

Psychoacoustics and Hearing Impairment: Audiology

Most of the work described in this history is based on normal hearing. But, a great deal of psychoacoustic research is directly related to issues of hearing impairment. Many of the psychoacoustic procedures, data, phenomena, and theories have been developed to diagnose and treat hearing loss. Data from listeners with hearing loss often shed light on the mechanisms of normal hearing.

The first audiometers to measure hearing loss were developed at Western Electric in 1922 (e.g., Western Electric IA audiometer, which cost $1,500, only slightly less than a house at that time; **Figure 10**), and Fletcher coined the term "audiogram" at about the same time. Alexander Graham Bell spent a significant amount of his career developing hearing aids. Ray Carhart is often credited with being the "father of audiology" and starting the first audiology academic program at Northwestern University in the late 1940s. Before the term audiology was coined, the field was often known as "auricular training," but Hallowell Davis ("Hal" was an auditory physiologist and ASA Gold Medal winner and President) thought auricular training sounded like someone who was taught to wiggle his/her ears.

Figure 10. *Western Electric IA audiometer, the first widely used audiometer for testing hearing impairment.*

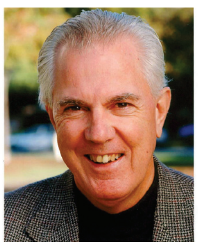
Complex Sound Processing and Auditory Scene Analysis

A great deal of psychoacoustic research from 1920 to 1970 used well-specified but unnatural stimuli such as tones, Gaussian noise, and brief transients in highly controlled experiments with very experienced listeners. By the late 1970s, psychoacousticians began to explore the limits of processing "simple" stimuli and to design stimuli and experimental conditions that better represented real-world sounds and listening situations. This was sometimes discussed as "complex sound processing" (Yost and Watson, 1987).

Although research on complex sound processing was pursued by many psychoacousticians, there was no overarching theory or organizing principle to integrate the knowledge being accumulated and to make new predictions. This changed when a series of articles, chapters, and books appeared between 1988 and 1992 (Yost, 2014). The book by Al Bregman (1990), *Auditory Scene Analysis,* captured the essence of these other authors' attempts at finding an organizing principle for complex sound processing, and *Auditory Scene Analysis* captured the imagination of perceptual scientists in hearing as well as in perceptual and cognitive psychology.

Sounds from the various sources that make up an auditory scene interact physically and arrive at the ears as a single sound field representing the physical combination of the sounds from the various sources. The auditory periphery uses biomechanical and neural processes to send a neural code to the brain representing the spectral/temporal features of that sound field. There are no peripheral mechanisms that process sounds as coming from individual sources. There is no representation in the neural code flowing to the brain that the scene may be one of a car driving by as the wind blows the leaves and a child giggles. Yet that is what we can perceive usually immediately and effortlessly. The sound is complex and the listener may be hearing some of the sounds for the first time, yet the auditory images are often vivid. These auditory images allow the listener to identify the car, the blowing leaves, and the giggling child. The brain performs auditory scene analysis. Psychoacoustics has just begun to investigate how the brain does this. It appears to be a daunting task; it is, like Helmholtz observed, trying to look down a tube at waves on a beach and determining what caused the waves. It is likely that the next chapter in the history of psychoacoustics will be written by present and future psychoacousticians who help unravel how the brain analyzes an auditory scene.

Biosketch



Bill Yost is currently Research Professor of Speech and Hearing Science at Arizona State University and was Department Chair from 2007 to 2013. He received the ASA Silver Medal in Psychological and Physiological Acoustics and is a past president of the ASA. He is a Fellow of the ASA; the American Speech, Hearing, and Language Association; the Association for Psychological Sciences; and the American Association for the Advancement of Science. He received a PhD in Experimental Psychology from Indiana University in 1970, and his research interests are in psychoacoustics and auditory perception.

References

Allen, J. (1996). Harvey Fletcher's role in the creation of communication acoustics. *Journal of the Acoustical Society of America* 99, 1825-1838.

Blauert, J. (1997). *Spatial Hearing*. MIT Press, Cambridge, MA.

Boring, E. G. (1942). *Sensation and Perception in the History of Experimental Psychology*. Appleton-Century-Croft, New York.

Bregman, A. S. (1990). *Auditory Scene Analysis: The Perceptual Organization of Sound*. MIT Press, Cambridge, MA.

Colburn, H. S. (1973). Theory of binaural interaction based on auditory-nerve data. I. General strategy and preliminary results on interaural discrimination. *Journal of the Acoustical Society of America* 54, 1458-1470.

Dau, T., Puschel, D., and Kohlrausch, A. (1996). A quantitative model of the "effective" signal processing in the auditory system: I. Model structure. *Journal of the Acoustical Society of America* 99, 3615–3622.

Durlach, N. I. (1963). Equalization and cancellation theory of binaural masking-level difference. *Journal of the Acoustical Society of America* 35, 1206-1218.

Fletcher, H., and Munson, W. A. (1933). Loudness: Its definition, measurement, and calculation. *Journal of the Acoustical Society of America* 5, 82-108.

Glasberg, B. R., and Moore, B. C. J. (2006). Prediction of absolute thresholds and equal-loudness contours using a modified loudness model. *Journal of the Acoustical Society of America* 120, 585-588.

Green, D. M., and Swets, J. A. (1966/1974). *Signal Detection Theory and Psychophysics*. Peninsula Publishing, Los Altos, CA. (Originally published in 1966 by John Wiley and Sons, New York. Reprinted with corrections in 1974 by Robert E. Kreiger Publishing Co., Melbourne, FL.)

Green, D. M., and Yost, W. A. (1975). Binaural analysis. In Keidel, W., and Neff, W. D. (eds), *Handbook of Sensory Physiology: Hearing*, Volume 5. Springer-Verlag, New York, pp. 461-480.

Helmholtz, H. (1863/1954). *On the Sensation of Tone*. English translation published in 1954 by Dover Publications, New York. (First German edition, *On the Sensation of Tone as a Physiological Basis for the Theory of Music*, published in 1863.)

Hirsh, I. J. (1948). The influence of interaural phase on interaural summation and inhibition. *Journal of the Acoustical Society of America* 20, 536-544.

Jeffress, L. A. (1948). A place theory of sound localization. *Journal of Comparative and Physiological Psychology* 41, 35-39.

Licklider, J. C. R. (1948). The influence of interaural phase relations upon the masking of speech by white noise. *Journal of the Acoustical Society of America* 20, 150-159.

Licklider, J. C. R. (1956). A triplex theory of pitch perception. In Cherry, C. (ed), 3rd London *Symposium on Information Theory*. Butterworths, London, pp. 253-268.

Lindsay, R. B. (1966). The study of acoustics. *Journal of the Acoustical Society of America* 39, 629-644.

Meddis, R., and Hewitt, M. J. (1991). Virtual pitch and phase sensitivity of a computer model of the auditory periphery: I. Pitch identification. *Journal of the Acoustical Society of America* 89, 2866–2882.

Moore, B. C. J. (1989). F*requency Selectivity in Hearing*. Academic Press, London.

Patterson, R. D., Allerhand, M., and Giguere, C. (1995). Time-domain modeling of peripheral auditory processing: A modular architecture and a software platform. *Journal of the Acoustical Society of America* 98, 1890-1895.

Rayleigh, Lord (J. W. Strutt). (1876). On our perception of the direction of a source of sound. *Proceedings of the Music Association* 75-84.

Rayleigh, Lord (J. W. Strutt). (1907). On our perception of sound direction. *Philosophical Magazine Series* 6 13, 214-232.

Schouten, J. F. (1940). The residue and the mechanisms of hearing. *Proceedings of the Koninklijke Akadmie van Wetenschap* 43, 991-999.

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review* 64, 153-181.

Stevens, S. S., and Newman, E. B. (1936). The localization of actual sources of sound. *American Journal of Psychology* 48, 297-306.

Swets, J. (2010). *Tulips to Thresholds: Counterpart Careers of the Author and Signal Detection Theory*. Peninsula Publishing, Los Altos Hills, CA.

Thompson, S. P. (1878). Phenomena of binaural audition, part II. *Philosophical Magazine Series* 5 6, 383–391.

Turner, R. S. (1977). The Ohm–Seebeck dispute, Hermann von Helmholtz, and the origins of physiological acoustics. *British Journal of the History of Science* 10, 1-24.

Viemeister, N. V., and Plack, C. (1993). Temporal processing. In Yost, W. A., Popper, A. N., and Fay, R. R. (eds), *Human Psychoacoustics*. Springer-Verlag, New York, pp. 116-155.

Walden, D. (2014). Leo Beranek: Technology, business, and civic visionary. *Acoustics Today* 10, 59-64.

Waldrop, M. (2001). *The Dream Machine: J. C. R. Licklider and the Revolution That Made Computing Personal*. Viking Penguin, New York.

Yost, W. A. (2009). Pitch perception. *Attention, Perception, & Psychophysics* 71, 1701-1715.

Yost, W. A. (2014). Psychoacoustics and auditory perception. In Popper, A. N., and Fay, R. R. (eds), *Perspectives on Auditory Research*. Springer Science+Business Media, New York, pp. 611-633.

Yost, W. A., and Watson, C. S. (1987). *Auditory Processing of Complex Sounds*. Lawrence Erlbaum Associates, Hillsdale, NJ.

Zwicker, E., and Fastl, H. (1991). *Psychoacoustics: Facts and Models*. Springer-Verlag, Berlin.