William A. Yost and the Psychoacoustics of Human Sound Source Perception

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We think of our eyes as the primary channel through which we perceive the world, "seeing is believing," but, in fact, most of our surroundings at any given moment are out of view. For much of the information about the world around us, we depend on our ears. We hear the approaching bus in the din of traffic and avoid stepping into the street; we hear a familiar voice in the clamor of the crowd and recognize an old friend; we hear music playing, glasses clinking, people laughing, a cocktail party is underway next door. Such seemingly simple acts of recognition are so automatic that we rarely give them any thought, but they are examples of an extraordinary ability to perceive the world through sound, unmatched in accuracy and scale by our most sophisticated machine-recognition systems (Szabo et al., 2016).

William A. (Bill) Yost (shown with his family in **Figure 1**) is a hearing scientist who, for over half a century, has been a leader in the effort to understand this extraordinary ability. As of writing this, Bill has published over 100 peer-reviewed research articles, 6 authored or coauthored books, and 50 book chapters on or related to the topic. The number of major scientific organizations giving their highest form of recognition to Bill's work is too long to list here. You may know Bill from his many years of service to the Acoustical Society of America (ASA). He has held every elected office in the Society including president and was the recipient of the Society's Gold Medal in 2018 (see https://asa.scitation.org/doi/pdf/10.1121/1.5036155). Among other important roles, he has served as president of the Association for Research in Otolaryngology (ARO); program director of the National Science Foundation: Sensory Physiology and Perception; chair of the National Research Council and National Academy of Sciences Committee on Hearing, Bioacoustics and Biomechanics (CHABA); and cochair of the Task Force on Developing the National Strategic Plan for the Establishment of the National Institute on Deafness and Other Communication Disorders (NIDCD) of the National Institutes of Health. For more about Bill, see https://asa.scitation.org/doi/pdf/10.1121/1.5036155.

This article provides an overview of Bill's research and, more broadly, the topic of human sound source perception. Readers wishing to delve more deeply into the subject can find review chapters of works by other prominent authors in one of Bill's books, *Auditory Perception of Sound Sources* (Yost et al., 2008).

Impossible Sound Source Perception

Before talking about Bill's research, it is first necessary to get a sense of why human sound source perception is so remarkable. Bill tells his students the reason is "because it's impossible." As provocative as this answer might seem, it is not far from the truth. We have many examples to choose from; sound source perception can involve something as simple as recognizing the "ping" of a tuning fork or as complex as parsing an entire "auditory scene" (imagine any busy street in downtown Chicago). Let's

Figure 1. *Bill Yost on an Alaskan cruise with his family celebrating his 50th anniversary.* ***Left to right:*** *daughter Alyson, Bill, wife Lee, and daughter Kelly.*

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start with the tuning fork. Tuning forks we recognize as U-shaped metal bars with a stem. Knowing certain properties of the fork and the way it is held and struck, the prominent modes of vibration, their relative amplitudes, and rate of decay can be estimated from known equations of motion (Russell, 2020). Theoretically, any or all of this information might be used by a listener to correctly perceive the sound as belonging to a tuning fork (Lutfi, 2008). The problem is that, in the real world, the properties of unseen sources are not known beforehand. Instead, they are what we are trying to determine from sound. In the equations of motion, different combinations of properties can produce identical solutions, so if there are no constraints, that ping of the tuning fork could just as easily have come from a hollow flagpole, pogo stick, or ceramic plate. The problem is indeterminate; it has not one but many solutions.

Now consider that busy street in downtown Chicago. You hear traffic, people walking around you, and a siren wailing in the distance. What reaches your ears is the superposition (sum) of the sound pressure wave fronts emitted by all of these sources; you have access only to this sum, but somehow you extract from it and recognize individually the sounds emitted by each source. The problem is principally the same as having to solve for x, y, and z in the expression $x + y + z = 20$. Again, there is no single solution.

In both examples, the only way perception can be correct is to bring additional information to bear on the problem. Understanding what that information is and how it is encoded in the auditory nervous system has been the fundamental challenge for research on sound source perception and the focus of Bill's work.

Early Influences and Signal Detection Theory

Bill received his undergraduate degree from Colorado College, Colorado Springs, Colorado, in 1966 with a major in psychology and a minor in mathematics. He knew then that he wanted to be a professor and researcher studying objective, quantifiable ways of explaining how the brain works. That same year, Green and Swets (1966) published their seminal book on signal detection theory (SDT; see Yost et al., 2021). For Bill, the timing was perfect. SDT recognized that perception is covert, that the judgments of subjects in perceptual studies are merely their personal impressions, opinions, or beliefs regarding what they see or hear. SDT would provide a way to convert these subjective impressions into entirely objective measures of perception; in the words of Green (2020), "as objective as any of the quantities used in the so-called hard sciences." This development would bring a sea change in the conduct of perceptual research that would have a lasting impact on Bill's work and on the work of many other scientists of the time.

Figure 2. *Bill's academic family tree.* ***Left to right:*** *Lloyd Jeffress (academic grandfather), Don Robinson (academic father), and Bill.*

After graduating from Colorado College, Bill furthered his studies in the Psychology Department at Indiana University (IU), Bloomington, under the tutelage of James Egan, another giant of SDT. He then finished his PhD with Don Robinson (**Figure 2**) after the early departure of Egan from IU. After receiving his doctorate, Bill received a National Science Foundation postdoctoral award to work with Green at the University of California, San Diego. The influence of this early training is evident in Bill's consistent approach to research: model oriented, precise, and given to clear outcomes based on quantitative data. Although there would still be a place for qualitative data in Bill's research, he would be among the first in the field to apply the lessons of SDT to the study of human sound source perception.

"The Basis for Hearing"

Bill published a call to action, encouraging researchers to focus more attention on sound source perception (Yost, 1991). The title would leave little doubt as to the importance he attached to the subject, "Auditory Image Perception and Analysis: The Basis for Hearing." The article underscored the role of sound source perception in communication and survival and offered compelling examples of how we rely on it every day to navigate our environment. Bill would make the case to a broader audience in three subsequent publications (Yost, 1992, 1993, 2008). In these publications, Bill identifies three major areas of research making up the bulk of the work on human sound source perception, still active today. What follows is an abbreviated review of the highlights of the work in each area, concentrating on the key contributions made by Bill.

Pitch

Of the three primary qualities we perceive in sound, (pitch, loudness, and timbre), pitch is most closely tied to the properties of the sound source. Loudness varies with distance from the source, the driving force for vibration, and any obstacles that might block the sound's path on the way to our ears. Timbre is affected by room acoustics, how the source is supported, and how it is driven to vibrate. Pitch, however, is much less subject to these extraneous factors and depends more on the properties of the resonating source itself.

The long history of research on pitch shows that it corresponds largely to our perception of periodicity in sound. Many sounds in nature, particularly those having the most significance for us, are periodic, or at least roughly so. Speech and music are the most notable examples. These sounds have a harmonic structure whose periodicity is given by a fundamental frequency (F0) that with few exceptions dominates our perception of pitch. So strong is this tendency that we hear a pitch at F0 when there is little or no energy at F0; and even when the sound is inharmonic, we tend to hear a pitch corresponding to the closest match to F0 (see Yost, 2009, for a review and http://auditoryneuroscience.com/pitch for online demos).

Pitch contributes to sound source perception in a variety of ways. It tells of an animal's size through their vocalizations, generally lower pitch vocalizations corresponding to larger size. Larger sized animals are more attractive to potential mates and are a greater threat to competitors. In humans, pitch affects the meaning of a spoken sentence through prosody and conveys information about the talker's gender and even their emotional state. It also plays an important role in helping to segregate sound sources perceptually. The individual spectral components of multiple sources sounding simultaneously are conflated in a complex spectrum reaching the ears. But a separate pitch is heard for each source, effectively segregating the sounds by their harmonic structure. A popular demonstration of this is when a single component of an otherwise harmonic complex is slightly mistuned. The pitch of the mistuned component will "stand out" from that of the harmonic complex such that two pitches are heard simultaneously (Moore et al., 1986). The literature includes a variety of examples of segregation based on pitch (reviewed by Carlyon and Gockel, 2008).

Bill's work on pitch has focused on how it is encoded in the auditory system, the second part of the fundamental goal of research on sound source perception. The question has prompted an ongoing dispute, dating back to Helmholtz (1863, 1954), between two theories: one centering on the features of the time waveform and the other on its spectrum. Because the spectrum is a translation of the time waveform, early tests of the two theories based on acoustics alone proved difficult. Modern theory has since contributed what we have learned about the transformations of the signal taking place in the auditory periphery. We now know that individual fibers in the auditory nerve are selectively responsive to different frequencies, providing a *place code* for the sound spectrum. Temporal features of sound are also represented in the group *synchronous* response of nerve fibers to signals. The combination of these processes results is a neural activation pattern (NAP) in frequency and time that preserves much of the spectral and temporal information present in the airborne sound.

Figure 3, *left*, was derived from the NAP model of Patterson et al. (1995). It shows the simulated neural response to a 200-Hz harmonic complex, which produces a strong perception of pitch at 200 Hz. Looking horizontally, one can readily see the oscillations, shifted in phase vertically, and having a periodicity of 5 ms, the reciprocal of 200 Hz. Looking vertically, one can also make out the representation of the harmonic spectrum as neighboring activation maxima, with a spacing of 200 Hz. **Figure 3**, *right*, shows the simulated response to a special signal that Bill popularized and termed iterated rippled noise (IRN). IRN is created by passing random noise through a delay and add-back circuit and applying multiple iterations of the circuit (see Yost, 2009). There were three iterations of a delay of 5 ms for the signal in **Figure 3**.

IRN poses a challenge for models of pitch because it has no clear spectral or temporal structure but nonetheless

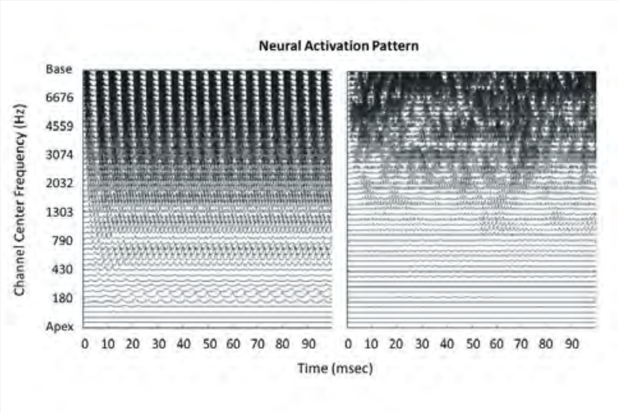


Figure 3. ***Left:*** *Neural activation pattern (NAP) of a 200-Hz harmonic complex from model of Patterson et al. (1995).* ***Right:*** *NAP of an iterated rippled noise (IRN), three iterations with 5-ms delay. Adapted from Yost (2009). See text for detailed discussion.*

produces a pitch corresponding to the inverse of the delay. Bill has investigated extensively how the pitch and pitch strength of IRN changes with its various parameters and has concluded that a temporal model that extracts periodicities in the fine structure of IRN best accounts for the data. Bill's work on IRN is his most frequently cited and has contributed to making IRN a standard stimulus in many other areas of research on hearing.

Temporal Modulations in Sound

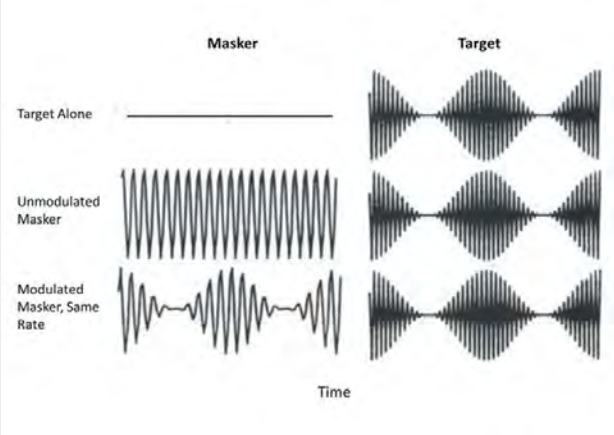
Most sounds of interest to us in nature change over time. The messages we convey through speech, the pleasure we take in music, and the actions we track in the sound events unfolding around us all derive from modulations in the sound spectra over time. Without these dynamics, the sounds about us would combine to produce a single unpleasant drone.

Two parallel and largely independent lines of research have evaluated the influence of temporal modulations on sound source perception. The first has focused on the phenomenon of *auditory streaming* (Bregman, 1990). This refers to the listener's subjective impression of when a sequence of sounds, typically tones, is heard to split into separate perceptual objects or entities (streams). Striking examples occur when the tones in the sequence are made to differ in frequency and rhythmic pattern (for demos, see http://auditoryneuroscience.com/index.php/scene-analysis).

The second line of research has focused on *auditory masking*, an objective measure of the influence one sound (the masker) has on the listener's ability to detect, discriminate, or recognize another (the target). The early view of auditory masking, dating back to Fletcher (1940), was that it is caused by the overlap of neural excitation produced by the target and masker in the auditory periphery. Bill would publish one of the early studies, indicating that the process is much more complex and possibly connected to auditory streaming (Yost et al., 1989).

Figure 4 shows three conditions of that study. The listener's task was to detect an increase in the base modulation rate of a target tone (**Figure 4,** *right*). The target was either presented alone (**Figure 4,** *top*), presented with an unmodulated masking tone (**Figure 4,** *center*), or presented with the masking tone modulated at the same base frequency as the target (**Figure 4,** *bottom*). Little masking was expected in the two masking conditions because there was always a two-octave separation between target and masker; indeed, the unmodulated masker had little effect on threshold, consistent with that expectation. The modulated masker, on the other hand, produced a significant, unexpected increase in threshold, suggesting a perceptual interference created by the common modulation. The results are reminiscent of those from the streaming experiments where common temporal modulations in the frequencies of tones cause those tones to fuse into a single auditory image (Bregman, 1990). Bill's results on the effects of temporal modulations on masking and those of many other studies

Figure 4. *Three conditions adapted from the study by Yost et al. (1989). See text for discussion.*



conducted at this time would lead to a dramatic change in thinking about the factors that affect auditory masking.

Spatial Attributes of Sound

As discussed, Bill views sound source perception as the primary function of our sense of hearing. He has argued that identifying the sources of sound in our environment is paramount to survival (Yost, 2008). From an evolutionary perspective, the job of the perceptual system is to make sense of the world so that the organism can interact effectively with it. More specifically, identification is required for organisms to discriminate predators, prey, and potential mates so that they can act accordingly to survive. But using pitch, temporal, and other cues to deduce that a sound source is a potential predator, for example, would not be especially helpful if we were not able to also identify its location and then avoid it.

Sound source localization arises from our ability to process relatively small differences in the auditory signals between the two ears. A sound coming from the left of a listener will arrive at the left ear sooner in time than it will at the right ear. The sound will also generally be louder at the left ear than the right due to the head shadow. These interaural differences of time (ITDs) and level (ILDs) are the cues used to localize sound sources in the horizontal plane. Bill has contributed a wealth of information to our understanding of these spatial cues in numerous papers spanning over 40 years (e.g., Green and Yost, 1975; Yost and Pastore, 2019). For example, thanks to Bill's efforts, we better understand ILD and ITD sensitivity across frequency (e.g., Yost and Dye, 1988), by cochlear implant users (e.g., Doorman et al., 2014), and in the presence of time-varying amplitude fluctuations (e.g., Yost et al., 1989).

In addition to facilitating sound source localization, spatial cues can also provide additional benefits for detection, discrimination, and identification tasks that occur in the presence of one or more additional concurrent, spatially separated sound sources or maskers. When the task is speech perception, it is often described as solving the "cocktail party problem," a term coined by Cherry (1953). There are other terms for the general perceptual benefits that arise from spatial separation of sound sources, including spatial release from masking (SRM) and the masking level difference (MLD).

Bill has made significant contributions to the literature characterizing the MLD, which was first described nearly simultaneously by both Licklider (1948) and Hirsh (1948). If the same tone is presented to both ears using headphones (described as "homophasic" because the tone has the same phase to both ears) and then one adds a homophasic noise, the signal-to-noise ratio (SNR) can be manipulated so that the listener can just detect the tone. If the phase of the tone is changed in one ear so that it is different than that in the other ear (an "antiphasic" condition), the perceived location of the tone in the listener's head will change because of the interaural phase delay. Interestingly, the level of the noise will have to be increased to produce the same amount of masking. In this example, the difference in SNR between the homophasic and antiphasic conditions is the MLD.

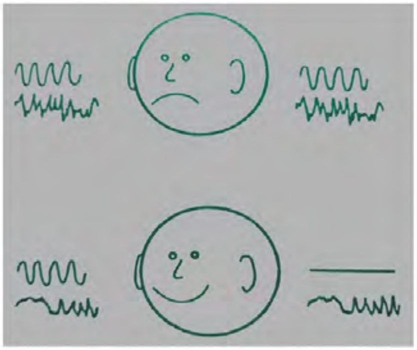


Figure 5. *Conditions in a typical masking level difference (MLD) experiment.* ***Top:*** *both the tone and noise are diotic or homophasic.* ***Bottom:*** *the noise is homophasic while the tone is presented monaurally to the left ear only, or antiphasic. Adapted from Green and Yost (1975).*

Figure 5 depicts an even simpler and more striking example. In **Figure 5**, *top*, the tone and noise are both homophasic and the sad face indicates that the listener is having difficulty detecting the tone. In **Figure 5**, *bottom*, the tone has been turned off in one ear and the noise remains homophasic, a condition in which the amount of masking (the MLD) is reduced, as indicated by the happy face. To summarize, simply eliminating the tone in one ear made the tone more easily detected!

The MLD is a particularly elegant example of taking a complex phenomenon (the perceptual benefits of spatially separated targets and maskers) and reducing the problem to its essence so that it can be studied systematically. Since

Hirsh's and Licklider's initial papers in 1948, Bill has explored the various conditions under which the MLD does and does not occur (Yost, 1988). The effect has been shown by various researchers for tones, speech, and other signals, using both interaural phase (or time) differences and ILDs, and even in temporal masking paradigms, in which the signal and noise are not presented concurrently. In addition to publishing many influential articles on various aspects of the MLD, Bill along with his friend and colleague Tino Trahiotis in 1998 organized *The MLD: A Collection of Seminal Papers* to commemorate the 50th anniversary of the Licklider and Hirsh papers and to highlight and celebrate the vibrant psychoacoustics community, many of whom contributed to our understanding of this interesting phenomenon. The image in **Figure 5** was taken from the cover of this collection.

Bill's more recent work has focused on the maximum number of spatially separated sound sources in an auditory scene that listeners are able to successfully process (Yost et al., 2018, 2019b). These studies have found that for talkers simulating a cocktail party or noisy restaurant auditory scene, the maximum size of the auditory scene appears to be four. More specifically, listeners were relatively accurate in both identifying and discriminating the total number of talkers and reporting talker locations when there were up to four talkers. Listeners could also judge loudness differences based on individual source levels when there were four or fewer sources. With five or more sources, discrimination of the total number of talkers and localization accuracy approached chance, and listeners tended to use overall level to perform the loudness difference task rather than individual source levels, indicating an inability to "hear out" individual sources or streams.

Most recently, Bill and his team have been interested in auditory motion and the effect of head turns on sound source localization, with a focus on cochlear implant (CI) users who are well-known for being poor localizers (Brown, 2018). It was established some time ago that head movements are integrally related to localization (Wallach, 1940). The work by Pastore et al. (2020) in this area established that head turns significantly improved localization abilities for single-sided deafened individuals implanted with a CI with their CI both off (monaural condition), and on (so-called bimodal listening condition). In fact, auditory motion is a sorely understudied topic. One very good reason for this is the many technical challenges and other difficulties that interfere with the ability to exert sufficient scientific rigor so that the results are generalizable while also maintaining ecologically valid conditions. Ever fearless, Bill undertook the challenge, and the result is a listening room at Arizona State University, Tempe, that has been custom designed and purpose-built for auditory motion experiments (**Figure 6**). The room is sound deadened and contains a custom chair that allows precise measurement and control of rotational velocity and an array of loudspeakers with custom software that allows sound source motion to be accurately simulated.

Using this facility, Bill has collected a trove of interesting data, most of which have been used in published studies on the relationship between localization, source movement, and listener movement (e.g., Yost and Pastore, 2019). One goal of this work was to establish how individuals can use spatial cues during motion. Interaural difference cues are inherently head-centric and thus change with head turns as well as with any other movement of the source or the listener. How then does a listener disentangle a relatively complex scene wherein both the listener and the sound source are moving? Supported by compelling data, Bill has argued in several papers that sound source localization is not a purely a psychoacoustic phenomenon but rather is based on an integration of input from several systems, including auditory, visual, and very likely vestibular (e.g., Yost et al., 2019a, 2020).

Figure 6. *Bill's sound insulated room with rotating chair and surrounding speakers for studying auditory motion perception.*

No End to an Era

In articles in *Acoustics Today* honoring prominent members of our Society (see https://bit.ly/3HC1udm), their retirement has sometimes been talked of as marking the end of an era. This does not apply to Bill. After 50 years of steady scholarly contributions and continuous service to the advancement of our science, he shows no sign of slowing down. In those 50 years, we have seen tremendous progress in our understanding of human sound source perception, in large part thanks to Bill. For those important questions that remain, all indications are that he will continue to be on the forefront of the research providing answers. In a recent special session of the Acoustical Society of America honoring Bill, the title of the first speaker's talk asked, "Does He Ever Sleep?" You might say he does but hasn't made a habit of it. Our science is better for the tireless efforts of Bill and for that we are most thankful.

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