David M. Green and Psychoacoustics

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In July 2019, people from all over the world attended a symposium honoring a former Acoustical Society of America (ASA) president and Gold Medal recipient, David M. Green (**Figure 1**). Dave retired as professor emeritus from the University of Florida, Gainesville, in 1996, so one might wonder why he was being honored 23 years later and why so many people attended the symposium. Because we have known Dave a long time (the authors were in Dave's lab in 1970-1971 during Dave's tenure at the University of California, San Diego, La Jolla, from 1966 to 1973; see **Figure 2**), we would not be surprised if Dave's answer was something like, "Of course they showed up, I know these people and they all like a good party." The enjoyable symposium, "Greenfest," was sponsored by the Knowles Hearing Center at Northwestern University, Evanston, Illinois (the organizers were Bev Wright [Chair], Bob Lutfi, Jungmee Lee, Ann Eddins, David Eddins, and Beth Strickland).

Dave was being honored for several reasons. Foremost, for his many important, often pioneering, and still timely contributions to understanding hearing. In addition, he was being honored for his numerous contributions to the ASA and his service on national committees that addressed important societal topics. A recent *Acoustics Today* online article about Dave's tenure as ASA president describes several aspects of his career and accomplishments (available at bit.ly/2OPTqzK). Many people also attended Greenfest because they were one of the very large number of students, postdocs, and colleagues whom Dave has mentored over the years.

David Green's prolific theoretical and empirical contributions cover a very wide range of topics in the behavioral sciences, especially those related to psychoacoustical investigations of hearing. Dave is probably most well-known for his work on signal detection theory (SDT), which has had wide-ranging applications in the behavioral sciences and for many societal issues. He also developed and tested models of auditory detection, discrimination, and identification and made contributions to many other topics, including his work on what has become known as *profile analysis*.

Figure 1. *David M. Green at a previous home in Florida, 2007.*

Figure 2. *Green's Research Group (GRG), 1970-1971.* ***Back row (left-to-right)****: Sharon Able, Dave Green, Bill Yost, Roy Patterson, and Lynn Penner.* ***Front row (left-to-right)****: Neal Viemeister, Larry Feth, and Chuck Robinson. Photo was taken at Dave's home/pool in August 1970, by Elle Feth, Larry Feth's wife. David's swimming pool was more than a party local. It was the "lab" used in Norman et al. (1971, with assistance from the Roy Patterson study on hearing underwater.)*

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Dave's Contributions to the ASA, Society, and Acoustics

Dave has been a tireless contributor to his discipline and society. In addition to being an ASA president and Gold Medal recipient, he was, among other things, a former chair of the Psychological and Physiological Technical Committee, an associate editor of *The Journal of the Acoustical Society of America* (*JASA*), and an ASA Biennial and Silver Medal honoree. Dave also served on several committees of the National Academies of Sciences (NAS) and the National Research Council (NRC). Among his many honors, he was elected a NAS member in 1978.

These efforts produced important contributions concerning issues confronting society. In 1978, Dave led a team that participated in the "reenactment" of the not fully explained 1963 assassination of President John F. Kennedy in Dallas, Texas. Dave's team also reviewed the testimony of the 178 witnesses to the Kennedy assassination. The team consisted of Fred Wightman, now retired but then at Northwestern University, and Dennis McFadden, from the University of Texas at Austin, also retired. In Dave's Congressional testimony (available at bit.ly/3seyRdQ), he reported on witnesses' observations, on issues related to the possible location of the gunshots, and briefly at the end of his testimony, on the possible number of gunshots. Dave explained how the perception of the acoustics of a bullet fired from a high-powered rifle made it difficult to explain many of the witnesses' observations. He described his team's opinion that the location of the gunshots during the reenactment was relatively easy for them to determine for some locations and less so for others. Dave pointed out that the team knew that gunshots would be fired and were experts in perceiving sounds, including their source locations, whereas the gunshots would have been a surprise to the witnesses who were unlikely to have been skilled observers in perceiving sound. He also indicated that there was no sufficient scientific literature to address issues regarding the number of gunshots, but echoes and the acoustics of high-powered rifle shots probably led to some reports of multiple gunshots.

Then in 1994, Dave chaired a NRC committee dealing with issues related to acoustic thermometry of ocean climate (ATOC) and marine wildlife (see nap.edu/read/4557/chapter/1). The issues, as many ASA members might remember, were that the ATOC project would have produced high-intensity, low-frequency underwater sounds so that acoustic changes over long distances might provide estimates of global warming of a large area of the earth's surface (e.g., a lot of the Pacific Ocean); however, marine mammals (and fishes) are sensitive to these same sounds. The committee noted that not enough was known about marine mammal and fish auditory processing to adequately address the extent to which ATOC signals might adversely affect marine animals. The NRC committee made recommendations about what research might be undertaken and how regulatory requirements could be changed to assist in getting this research done.

Dave's Students, Postdocs, and Colleagues

Many who attended Greenfest and probably more than 60 others have studied and conducted research with Dave in his labs as students or postdocs or while on a sabbatical or another form of leave. These researchers have, in turn, passed on lessons learned from Dave to their students, postdocs, and colleagues. As John Swets pointed out in the Encomium for Dave's ASA Gold Medal in 1994: "Dave most visibly took on this unusually generous interest in the beginner's growth and recognition. He regards them all as having their stories to tell—and after a few years of his tutelage they really do" (acousticstoday.org/david-green-gold-medal-1994).

Dave and Signal Detection Theory

Dave's pioneering work on the SDT is contained in the highly cited book by Dave and Swets (1966; hereafter

Figure 3. *Dave Green (**left**) and John Swets (**right**) at Bolt, Beranek, and Newman in 1965, a year before Green and Swets (1966) was published. Thanks to Chris Conroy for providing this picture.*

referred to as *Green and Swets*; see **Figure 3**). The SDT was originally developed by the Electronic Defense Group (EDG) at the University of Michigan, Ann Arbor, in the 1950s. Wesley Peterson and Ted Birdsall at the EDG wrote mathematical papers about ideal signal detectors. Spike Tanner applied those ideas to psychophysical issues. At this time, Dave (a graduate student) and Swets (a starting assistant professor; see Swets' autobiography, 2010) helped advance the SDT in general, but over time, they extended Tanner's ideas and developed a general psychophysical theory of detection and discrimination of sensory stimuli, especially sound. One of the first auditory papers was a detailed technical report by Tanner, Swets, and Green in 1956 (available at bit.ly/2PSvLiG).

Although the SDT was developed mainly to deal with behavioral experimental design and results, it was also applied to other decision tasks (see Swets, 2010), such as decisions radar operators have to make. A radar operator must decide if a "blip" on a noisy radar screen is a "signal" representing a plane that may pose a danger ("Yes," there is a plane) or is merely "noise" not indicating any danger ("No," there is no plane).

Similarly, subjects in hearing experiments are often asked to decide (Yes or No) if a sound presented on a trial is one that contains a target signal mixed with noise (Signal plus Noise [SN]) or is only the noise (Noise Alone [NA]). In detection based on sonar stimuli and on sound in a hearing experiment, one has to "trust" the operator's/subject's response (Yes or No) regarding the occurrence of a signal. That is, to what extent does the response represent the observer's *sensitivity* to the signal (e.g., a radar blip representing a plane, a sound representing a particular tone)? If the detection response is not a reliable estimate of sensitivity, then an enemy plane may go undetected and responses indicating that a particular sound occurred may not provide useful information about auditory processing (e.g., a person's hearing loss may be missed). The SDT provides a theory for reliably estimating an observer's sensitivity in making detection decisions when a weak signal is presented in a noisy background.

Although Dave has not been "active" in the field since his retirement, Greenfest triggered a return to SDT. Dave published a Letter to the Editor of *JASA* (Green, 2020) in what he referred to as a "homily." Dave's "complaint" was, "I am somewhat disappointed about how SDT commonly is portrayed and taught." In his homily, Dave refers to the history of psychophysical measurements. The term psychophysics (psychoacoustics is the application of psychophysics to acoustics) was used by Gustave Fechner in his two-volume book *Elemente der Psychophysik* (1860) to define quantifiable functional relationships between objective measures of psychological sensations/perceptions and physical stimulus variables that might excite the senses. Fechner argued that there are procedures (psychophysical procedures, cataloged in his book) that allow for objective behavioral measures of sensations and perceptions that can be measured similarly to those of the physical objects themselves.

However, in Dave's words (Green, 2020), "The sensations produced by the stimuli were subjective; they were private or covert. The only objective fact was the observer's response on that particular trial." In detecting weak signals occurring in noisy backgrounds (i.e., differentiating between SN and NA), we might know, using a psychophysical procedure described by Fechner, that an observer says he/she detected the signal. The psychophysical procedures cataloged by Fechner (1860) provided ways to estimate correctly detecting the signal when it was presented (Hits), and Hits were used as a measure of sensitivity. However, what happens when the signal is not presented (when a response indicates that a signal was presented when it was not; a False Alarm)? Clearly, being able to avoid False Alarms would be important in obtaining an estimate of sensitivity. Fechner and many after him suggested ways to estimate observers' sensitivity in indicating that they detected a signal when it was presented (Hits) and when it was not (False Alarms). False Alarms were then used in various ways to "correct" Hits as a measure of sensitivity, although such "corrections" were only approximations.

SDT starts with the simple idea that combining Hits and False Alarms provides measures of sensitivity in a more reliable and objective manner than just measuring Hits, even if Hits are corrected by False Alarms. A stimulus-response table (**Figure 4**) describes the raw data from a detection task. The four cells indicate the four conditional probabilities (*P*; "Response"/Stimulus), indicating an observer's responses (Yes or No, a signal was presented) as a function of the stimulus (either SN or NA). Hit and Miss probabilities sum to one as do False Alarm and Correct Rejection probabilities, and, as a result, SDT only uses

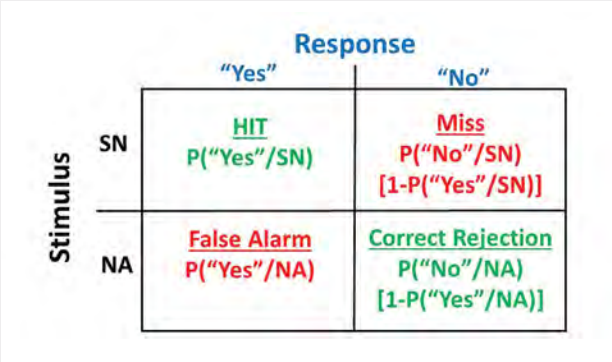


Figure 4. *Stimulus-response table indicating Hits, Misses, False Alarms, and Correct Rejections and their conditional probabilities, i.e.,* P *("Response"/Stimulus), in detecting ("Yes" or "No") whether a signal plus noise (SN) or noise alone (NA) was presented.*

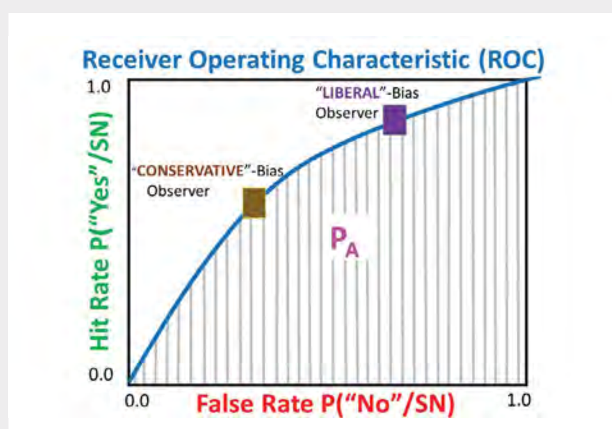
Hits and False Alarms. Clearly, if the Hit probability is high and the False Alarm probability is low, the observer had little difficulty correctly determining when the signal was and was not presented, and, thus, the observer was sensitive to the signal being presented.

However, consider a "conservative" observer who is reluctant to indicate the presence of a signal independent of his/her sensitivity versus a "liberal" observer who is very willing to indicate that a signal is present. Clearly, the observers have different response "*biases*" for indicating if a signal was or was not present. Assuming that the observers are equally *sensitive*, the conservative observer will have lower Hit and False Alarm probabilities than the liberal observer. Thus, Hits and False Alarms vary with changes in both sensitivity and response bias (they are independent measures of performance). How might Hit and False Alarm probabilities be combined to provide a single measure of how well the observer detected the signal (i.e., estimate sensitivity) independent of response bias?

Early in *Green and Swets* (1966, see Chap. 2) and in Dave's homily, a receiver operating characteristic (ROC; **Figure 5**) is defined, on which Hit proportion is plotted as a function of False Alarm proportion. A ROC contour is derived from a major assumption of the SDT that observers sample some aspect of the stimulus that forms a decision variable. A further assumption is that to maximize being as correct as possible in the long run in their decisions, observers use a particular value of the decision variable as a criterion for responding (C), so that if the sampled decision variable is greater than C, respond Yes the signal was present; if less than C, respond No; and if equal to C, guess. Thus, the conservative observer has a higher value of C than does an equally sensitive liberal observer. If only the noise is presented, the decision variable is distributed according to an underlining NA probability density function, and if the SN is presented, the decision variable is distributed according to an underlying SN probability density function. For any value of the decision variable, the SN distribution has higher probabilities than the NA distribution. The theory does not specify the kind of underlying distributions, only that the two distributions are overlapping probability density functions and that the decision variable is a monotonic function of the likelihood ratio formed from the probabilities of the two distributions.

The ROC contour in **Figure 5** shows the Hit proportion plotted as a function of the False Alarm proportion for arbitrary SN and NA distributions as C varies from −∞ (**Figure 5,** *bottom left corner*) to +∞ (**Figure 5,** *top right corner*), with the two points shown on the contour representing possible Hit and False Alarm proportions for a conservative and a liberal observer. Thus, C is represented by different Hit and False Alarm proportion combinations (different points)

Figure 5. *A receiver operating characteristic (ROC) contour showing Hit proportion as a function of False Alarm proportion (see* **Figure 4***). Combinations of Hit and False Alarm proportions for observers with different response biases (e.g., "Conservative" and "Liberal") are points on a ROC contour, whereas the area under the ROC curve* (P_A) *is a bias- and distribution-free measure of sensitivity.*



on a ROC contour, whereas the area under a ROC contour (P_A) can be used as a bias- and distribution-free measure of sensitivity (e.g., as the Hit proportion increases and the FA proportion decreases, P_A would increase independent of response bias, indicating an increase in sensitivity alone).

One way to test for the observer's sensitivity is the two-interval AB test. In this test, observers are presented two successive sounds: the signal occurs in either the first or the second interval (NA followed by SN or SN followed by NA, randomly determined), and observers indicate which interval contained the signal. One hundred percent correct responses indicate that an observer clearly detected the signal, whereas 50% correct responses indicate that the signal was inaudible. In Green and Swets (1966) and in Dave's homily (2020), Dave proves that the percentage of correct responses in the AB test is equal to the P_A.

This proof is nonparametric, that is, it is independent of any assumptions about the form of the NA and SN distributions. In many papers on SDT, a common first assumption is that the underlying distributions are both Gaussian and of equal variance (see Egan, 1975). If we assume that the observer has no bias to favor one interval or the other, the AB test becomes a second measure of the observer's sensitivity to the signal without having to make any assumptions about the form of the underlying NA and SN distributions. To paraphrase Green (2020), the moral of his homily is that although perceptual experiences are covert, percent correct and P_A both provide objective measures of the observer's sensitivity.

Dave often described SDT (e.g., Green, 1960, 1964) as "a combination of two distinct theoretical structures: *decision theory* and the theory of *ideal observers*." Some aspects of decision theory have been briefly described. Ideal observer theory (e.g., Green, 1960, 1964) "provides a collection of ideal mathematical models which relates the detectability of the signal to definite physical characteristics of the stimulus."

In considering a particular ideal observer (a particular mathematical model), a *detection model* can be developed. In such a model, the form of the NA and SN probability density functions (the "definite physical characteristics of the stimulus") is precisely defined. In many cases, Fourier series, bandlimited, white, Gaussian noise forms the NA distribution, and the SN distribution is this noise distribution plus a sinusoidal tone (see Green, 1960, 1964 for a detailed discussion of these assumptions). Using both the decision and ideal observer aspects of SDT, a detection model for describing the detection, discrimination, and identification of auditory signals presented in noisy backgrounds was developed, and Dave performed many psychoacoustic experiments testing the model (see Swets, 1964 for chapters describing some of these experiments, many authored by Dave). Papers published by Dave and many others established detection models as valuable for accounting for many aspects of human observers' detection, discrimination, and identification of a variety of auditory signals often masked by noise (e.g., Swets, 1964; Green and Swets, 1966).

SDT has also been used to evaluate the performance of humans and other animals in different sensory tasks, to measure decisions based on memory and attention, and to characterize how neural elements respond to stimulation (e.g., Swets, 1964; Green and Swets, 1966). In addition, SDT has been used in many nonlaboratory situations such as deciding when a radiological image may or may not indicate a tumor, when a jury may or may not decide that an innocent person is innocent, or when an alarm may or may not lead to a decision that there is a dangerous situation (e.g., see Swets, 2010). Thus, SDT is a powerful decision paradigm with wide application.

Dave and "Profile Analysis"

Although Dave published many experiments based on the SDT early in his career, he investigated a wide range of topics over the rest of his career. One of the many topics led to the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988). This book is about auditory intensity discrimination in general and when changes in intensity across a sound's spectrum can be discriminated, i.e., when there is a spectral "profile" that can be perceptually "analyzed." Most everyday sounds have complex spectra in which intensity varies as a function of frequency, and the perceptual differences between and among such sounds are often based on "spectral profiles."

Dave's interest in profile analysis was sparked by Murray Spiegel, a postdoc who received his PhD from Washington University in St. Louis, Missouri, working with Chuck Watson. Murray worked with Chuck on "10-tone pattern" perception (Watson, 2005). In an attempt to generate complex stimuli that had many properties of real-world sounds but whose acoustics could be carefully controlled, Chuck generated a temporal sequence of 10 brief (e.g., 40-ms), equal-amplitude tones presented sequentially, each with a different randomly determined frequency spaced far enough apart to be distinguishable. In one set of experiments, two 10-tone patterns were presented in succession, with the two patterns being the same or one pattern having the frequency of just one of the tones changed. The listeners determined whether the two patterns were the "same" or "different."

If highly trained listeners were presented the same 10-tone pattern (same frequency components fixed over time) over and over, they could, after considerable practice, distinguish a frequency difference for each tone in a pattern nearly as well as they could when the tones were presented alone rather than as part of a pattern. However, when the frequencies of the 10 tones were not fixed over time but varied randomly, the listeners were uncertain about the spectral changes that occurred. The more aspects of the patterns that were randomly varied, the greater the uncertainty and Watson (2005) showed that discrimination performance for 10-tone patterns depended on the amount of uncertainty. It did not take Murray long to get Dave interested in the role uncertainty played in these 10-tone pattern experiments.

Dave presented tones with different frequencies simultaneously rather than in a temporal sequence, and he asked the listeners to make an intensity rather than a frequency discrimination. Dave worked with several students and postdocs (Dave was at Harvard University and then the University of Florida at this time) in the development of the profile analysis paradigm (e.g., Chris Mason, Donna Neff, Tom Buell, Murray Spiegel, Bruce Berg, and, especially, Gerald Kidd). A basic spectral "profile" stimulus is shown in **Figure 6** in which the spectrum of 5 sinusoidal tones is plotted as decibel sound pressure level (SPL) as a function of tonal frequency plotted on a log scale. The tones are at equal log-frequency intervals, with a spectrally centered target tone.

Dave often used a two-interval task in which a profile of equal intensity tones ("flat" profile) was presented in one interval (randomly determined), and the other interval contained the same tones but with the target tone presented at a higher intensity ("target-incremented" profile). The intensity of the target tone required to discriminate one profile from the other was determined.

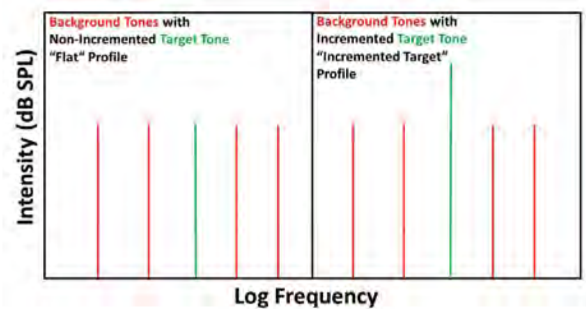


Figure 6. *Typical profile stimuli shown as spectra (intensity as a function of log frequency) of a 5-tone complex with a target tone (**green**) and background tones (**red**) spaced regularly on the log-frequency axis. **Left:** all tones are of equal intensity. **Right:** the target tone's intensity is increased relative to those of the background tones, forming a spectral profile. SPL, sound pressure level.*

However, if the stimuli were just like those shown in **Figure 6**, the interpretation of the results would be confounded because there are at least three "cues" that the listeners could use to make the discrimination. When the target tone's intensity is increased, the overall intensity of that profile is greater than the flat profile (this could be an appreciable difference for a small number of tonal components). Given that the tones were relatively far apart in frequency, the listeners could (after some practice) attend to the target tone and note that its intensity changed without regard to the intensity of the other tones. Alternatively, the listeners could note that the intensity of the target *relative* to that of the other tones was either the same or different. Dave's interest was the extent to which the listeners could make the relative level judgment across frequency for any one profile (i.e., are the listeners sensitive to the spectral profile generated by the increased target intensity?). To ensure that the listeners could use only a relative intensity cue to make their discrimination judgment, the overall intensity of the sounds was randomly roved by 20 dB or more. Such a random rove of overall stimulus intensity might produce the four profiles shown in **Figure 7**. With the random intensity rove, neither overall intensity nor the intensity of just the target tone could reliably indicate which profile had the incremented target intensity. Only by comparing the target intensity relative to the other component intensities within

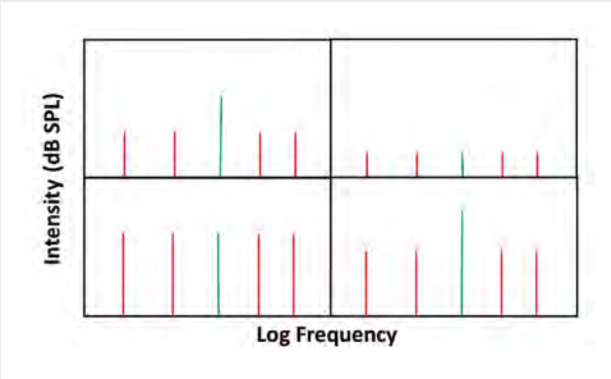


Figure 7. *Four spectral profiles (see* **Figure 6***) are shown, each at a different overall intensity. Two are "flat" spectral profiles (***top right and bottom left***) and two are "target-incremented" spectral profiles. (***top left and bottom right***).*

a profile could that judgment be made. Dave showed in several experiments described in his book (Green, 1988) that trained listeners were sensitive to the relative intensity changes in a spectral profile.

In addition to spectral changes between two profiles, the time-domain waveform will also differ, and it could be a basis for distinguishing between profiles. To investigate this possibility, Green and Mason (1985) randomly varied the phases of the spectral components in several ways, which changes the time-domain waveforms but leaves the amplitude spectra unchanged. Phase variations made little difference in the trained listeners' ability to discriminate one profile from another. Thus, profile analysis is most likely due to differences in the stimuli's amplitude spectra as opposed to the time-domain waveforms.

Of all the aspects of profile stimuli that Dave studied, he was clearly impressed with one general finding: that when there were many background tones that were very different in frequency from the target tone, there was a large effect on profile discrimination performance. This is in contrast to what was often found in masking and discrimination experiments, where target detection or discrimination performance in these cases was affected mainly by spectral components close in frequency to the target component.

The general idea is that stimuli that are close together in frequency directly interact in the biomechanical inner ear transduction of sound into neural action potentials that flow to the brainstem via the auditory nerves. Each auditory nerve is tuned to a particular frequency range (each auditory nerve has a tuning curve) such that if stimuli have frequencies within that range, the nerve responds, but if components have frequencies outside the range, the nerve is unresponsive. A perceptual consequence of the tuning curve is the *critical band.* A critical band is a spectral region such that only components with frequencies within the critical band affect detection or discrimination performance of a target component. Thus, the profile analysis finding that components with frequencies well outside the target's critical band affected discrimination performance was not consistent with "traditional" critical-band accounts of detection and discrimination.

A conclusion of research on profile analysis is that auditory spectral processing is not necessarily limited by critical-band processing but can be "wideband." Although at the time of writing *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988) there were only a few examples of such wideband spectral processing in auditory detection and discrimination experiments, Dave did study the detection of tones of different frequencies in a noisy background early in his career (Green, 1958). In this study, he concluded that a wideband approach of integrating across critical bands could account for his results. In his profile analysis research, Dave pointed out that wideband processing is consistent with what must be required to perceive complex sounds such as speech and music, and profile analysis provides a means of investigating wideband perceptual processing of real-world sounds.

Shortly after the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988), several authors pointed out that the perceptual parsing of complex sounds is likely based on how sources produce sound, particularly when the sources produce nearly simultaneous sounds. Bregman's book "*Auditory Scene Analysis*" (1990) brought this view to the forefront. *Auditory Scene Analysis* describes the acoustic world as a scene of sound sources, and auditory perception involves determining the sound sources in such a scene. In Bregman's view, to do so requires not only an ability to process sounds produced by sources but also requires information gained from experience that has been stored in memory and then accessed through attentional processes. Perceiving sounds in an auditory scene often requires wideband processing, and profile analysis, along with several other paradigms that were subsequently developed, increased the understanding of the processes involved in auditory scene analysis.

End of an Era?

Dave continued to study profile analysis, spectral shape discrimination, and many other topics well after the publication of *Profile Analysis: Auditory Intensity Discrimination* (Green, 1988). Dave retired as the field of psychological acoustics was changing. From the time of Fechner to the development of auditory scene analysis, a great deal of the study of psychological acoustics was strictly psychoacoustical, where studies focused on the direct functional relationship between acoustic variables and performance measures of detection, discrimination, and identification. SDT provided quantifiable performance measures (e.g., P_A), and ideal observer theory is a quantifiable means of obtaining psychophysical functional relationships between a performance measure and an acoustical variable.

Today, however, the questions often being asked in the field of psychological acoustics have moved beyond psychoacoustics as it was studied by Dave and his students, postdocs, and colleagues. For instance, many current psychological acoustic studies involve independent variables other than just acoustic parameters such as the age, gender, hearing ability, musical experience, species, or other characteristics of the subjects. In some sense, the strict study of psychoacoustics began with Fechner and began to end when Dave retired. There is much more to learn about auditory perception, but it is likely that the new knowledge will not be strictly psychoacoustical.

Throughout Dave's career, he worked with many students, postdocs, and colleagues. This ever-so-brief mention of just a few of Dave's numerous contributions probably indicates that his story may be longer and more consequential than most. However, to paraphrase Swets, many who passed through his lab had their own stories to tell, and after a few years of Dave's tutelage, they were in an excellent position to tell them.

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