PSYCHOACOUSTICS

Auditory Perception of Listeners With Normal Hearing and Hearing Loss

Second Edition

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Introduction

The second edition of *Psychoacoustics* retains the modular organization, with each chapter including relevant information around a specific topic. Within each chapter, acoustics, physiology, and perception by adult listeners with normal hearing and those with hearing loss, as they relate to that topic, are presented. The book retains its focus on applications of psychoacoustics to clinical audiology. The many changes and updates are as follows:

- Chapters 2 through 7 remain similar to the first edition, but I have added a section on the perceptual consequences of SNHL on everyday listening to each chapter. Other changes include:
  - in Chapter 2, a reorganization to be more modular, additional content related to acoustics, ROC analysis, and the effects of hearing loss on the long-term average spectrum of speech (LTASS),
  - a section on the LTASS and treating hearing loss as a filter in Chapter 3,
  - review of auditory neuropathy spectrum disorders in Chapter 5,
  - more figures and additional text throughout, to clarify some points.
- Chapter 8 (Psychoacoustics and Advanced Clinical Auditory Assessment) has been revamped. This chapter now exclusively addresses elements within diagnostic audiology that are based on psychoacoustics, with added content on tinnitus assessment, automated (Békésy) audiometry, retrocochlear and pseudohypacusis evaluation, and the identification of dead regions.
- Chapter 9 (Improving Auditory Perception for Listeners with Hearing Loss) is a new chapter that exclusively focuses on the perception by individuals wearing hearing aids and cochlear implants. The content related to conventional hearing aids has been expanded, focusing on compression, digital noise reduction, and directional microphones. A section on cochlear implants has been added.
- More demonstrations, general exercises, and laboratory exercises have been added to the text and companion website. Icons new to the text remind the reader of the resources available on the website. I hope that these icons will allow these resources to be more accessible to users of this textbook, particularly students.
- With the idea of being more inclusive, person-first language is now used (including a change to the subtitle of the text), and I have added versions of some demonstrations to be more accessible to individuals with hearing loss. Chapter 1 includes a new section on the contributions of women and BIPOC scientists to the field of psychoacoustics.
- A few corrections to the text and figures have also been made, thanks to the feedback provided to me by colleagues and students.

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1 History

LEARNING OBJECTIVES

Upon completing this chapter, students will be able to:

- List the main pioneers in psychoacoustics
- Describe how the history of psychoacoustics has influenced the field of audiology
- Explain the history of audiometric threshold measurement

INTRODUCTION

Humans have been curious about music, hearing, perception, and communication throughout much of the history of our species. Yet, the primary roots of psychoacoustics date back to the early 1700s, when the philosophers of the time began to lay the foundation for the field of experimental psychology, which studied human behavior. This chapter provides a historical perspective of psychoacoustics by first presenting a history of experimental psychology and then discussing how those developments led to the fields of psychoacoustics and audiology, which were, in some ways, developed together. For this chapter, I have particularly relied on the publications by Boring (1961) on the history of experimental psychology, Schick's (2004), and Yost's (2015) articles on the history of psychoacoustics, and Jerger's (2009) book on the history of audiology.

This chapter reviews the origins of modern psychoacoustics by covering:

- The roots of psychophysical measurement
- The development of psychoacoustics
- The role of Bell labs
- Connecting psychoacoustics, Bell labs, and audiology
- The history of the audiogram
- Women and BIPOC pioneers in psychoacoustics

EARLY INVESTIGATION OF PERCEPTION

The connection between sound and auditory perception and has been around for millenia: In Europe, archaeologists have discovered prehistoric flutes dating from at least 35,000 years ago (Conard et al., 2009). Ancient flutes have also been uncovered in Asia, North and South America, Africa, and Australia. Early cultures developed a variety of instruments that were blown (e.g., trumpets in Egypt), struck (e.g., bell chimes in China; stones, or lithophones, from India and Vietnam), and rotated (e.g., the bullroarer found across the world). Creating these instruments required skill and craftmanship but also knowledge of how to generate sound with different perceptual characteristics. Although the Western world may consider the advent of ***psychoacoustics***, the study of the relationship between sound and its perception, to have begun in the 1800s, we should credit prehistoric and ancient cultures, including those that are non-European, for their groundbreaking developments in our understanding of auditory perception. Without the development of musical instruments that could generate different types of sounds and the curiously of prehistoric and ancient humans, Western science would not have achieved the advances of the 19th and 20th centuries.

The application of rigorous and systematic tools to the assessment of perception and its relationship to the physical world began in the early 1800s, and the field of ***psychophysics*** was born. At this time, scientists were interested in the sense of hearing, but they also evaluated the senses of touch and vision. Many of the techniques used to study auditory perception were originally developed for the purposes of evaluating other sensory modalities. Some techniques, particularly the scientific instruments but also the measurement methods, were designed specifically for the assessment of hearing. In a reciprocal relationship, those other disciplines adopted and modified the tools that were originally created for the hearing sciences. The purpose of this chapter is to give the reader a brief overview of principles of psychoacoustics from a historic perceptive and to illustrate how these discoveries have impacted modern audiology.

As we travel back in time to the early 1800s, we observe the development of the field of psychophysics and more specifically, psychoacoustics, which involved the evaluation of the perception of sound. These early investigators asked questions such as "under what parameters can humans:

- *detect stimuli?* Measurements in this vein usually involve manipulating various stimulus parameters (like frequency and amplitude) and measuring the ***absolute threshold***, the lowest stimulus level that evokes a sensation.
- *differentiate between two stimuli?"* These experiments measure the ***just noticeable difference (JND)***, also known as the ***difference limen***, defined as the amount a stimulus must be changed on a particular dimension before the change is detectable.
- *describe the magnitude of the stimulus or the difference between stimuli?"* In these experiments, the *loudness*, the *pitch*, or the *quality* of sounds is measured.
- *recognize sounds?"* Here, experiments adopt meaningful stimuli, and we measure the ability to identify musical instruments, words in speech, and even environmental sounds.

Our discussion of the origin of psychological measurement begins with Ernst Heinrich Weber (pronounced Vay-burr; 1795–1878), although he was not the first to connect observation of perception with a physical stimulus. Weber, however, was the first to develop a systematic method of inquiry evaluating the relationship between the magnitude of physical stimuli and their associated sensation or perception. Although his work was conducted primarily in the areas of touch and vision, in 1834 he discovered what is now known as ***Weber's law*** (see Chapter 4). He noticed that, for pressure on the skin, the JND in weight could be described as a proportion of the weight (in this case, the JND was about 1/30th of the weight).

Further evaluation has demonstrated that this principle has evidence from many other sensory modalities, including hearing and vision.

One of Weber's students, Gustav Fechner (1801–1887), formalized Weber's work with mathematics. He noted that there was a way to measure the magnitude of sensation. Fechner's work was revolutionary: His claim was that the conscious perception of a stimulus is related to size of the stimulus in the physical world and that there is a relationship between perception and physical stimuli. Although this idea may seem obvious through contemporary eyes, this claim formed the foundation for all modern psychophysics and opened the door to the measurement of perception. Because of his visionary work, he is now known as the *father of psychophysics.* Perhaps not surprisingly, he coined the term *psychophysics* and published his experiments on sensory measurements in his 1860 book *Elements of psychophysics*, where he described psychophysical methods and psychophysical relationships. His book marked the beginning of experimental psychology because it brought sensation and perception, otherwise thought to be unmeasurable, under the requirements of measurement. His three methods of measuring absolute thresholds and differential thresholds are still fundamental to psychoacoustic measurement. He developed the ***method of limits*** (which, in modified form, is the method used to measure an audiogram), the ***method of adjustment***, and the ***method of constant stimuli***, techniques discussed in Chapter 2. Variants of these methods have yielded efficient measurements of perception, many of which are in use today. His view that perception and physics are connected is a foundation of our current practice: In the fields of psychoacoustics and audiology, we manipulate sound and measure the perceptual consequences. Without his seminal contributions to the study of perception, diagnostic audiology and psychoacoustics would be very different fields.

THE ORIGINS OF PSYCHOACOUSTICS

Despite the impact that Fechner and Weber have had on the field, neither conducted experiments in hearing. Rather, Hermann von Helmholtz (1821–1894), made some of the first psychoacoustic observations in the auditory modality. His book, *On the Sensations of Tone*, published in 1863, served as the foundational text on auditory perception for decades. This book, along with Fechner's, allowed the evaluation of hearing to be more than scientific observation. Rather, experimentation allowed auditory perception to be quantified under systematic evaluation. We could now connect physical acoustics with the perception of the physical dimensions.

One important aspect of Helmholtz's view of sensory systems was the idea that physiology was the basis of perception. His views have greatly influenced contemporary psychoacoustics, which commonly strives to determine the limits of auditory perception, as well as to discern the physiological mechanisms responsible for auditory perception. Helmholtz's view laid the groundwork for physiological models, some of which were proposed in the mid-1800s. For example, Helmholtz's theory of pitch was based on the "acoustic law" developed by Georg Ohm (1789–1854) and applied the principles of ***Fourier analysis*** developed by Joseph Fourier (1768–1830). Helmholtz's theory stated that the ear conducts a form of Fourier analysis, which allows complex sounds to be divided into sinusoidal components. To test this spectral theory of pitch, Helmholtz developed the innovative *Helmholtz resonator* (shown in Figure 1–1). By varying the size of the neck opening and the volume of the cavity, the Helmholtz resonator could produce sounds of different frequencies.

Yet, August Seebeck (1805–1849) devised a clever experiment using a rotary siren (one of which is illustrated in Figure 1–2) that

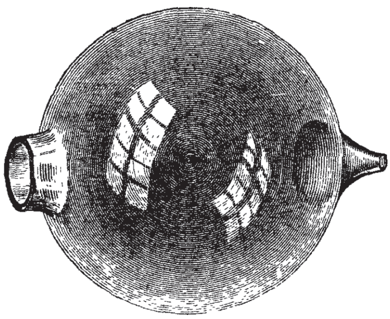

FIGURE 1–1. A Helmholtz resonator. From Helmholtz (1863).

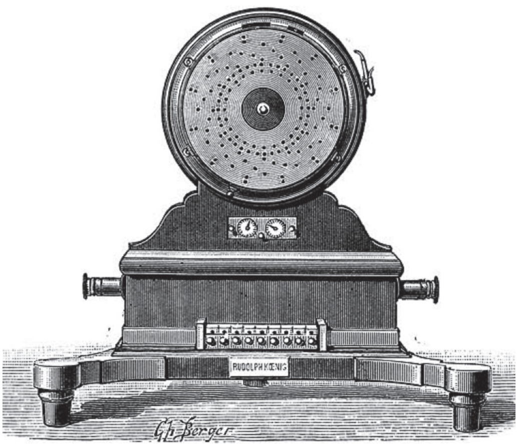

FIGURE 1–2. One of Seebeck's sirens. From Koenig (1889).

demonstrated inconsistencies in Helmholtz's spectral theory of pitch. Seebeck's results posed substantial problems for Helmholtz's theories and were bitterly disputed at the time (Turner, 1977). Unfortunately, Seebeck passed away almost a century before his experimental results were reconsidered and formalized into a theory by J. F. Schouten (1940). In contrast to the spectral representation proposed by Helmholtz, Schouten's residue theory suggested pitch perception could also be based on a temporal representation of sound. Variants of Helmholtz's and Schouten's theories are still discussed today, and both form the foundation of modern models of pitch perception (see Chapter 6).

Lord Rayleigh (James William Strutt, 1843–1919) was strongly influenced by the work of Helmholtz. He discussed acoustic problems using mathematics in his book *The Theory of Sound* (1877). This work laid the groundwork for future study linking acoustics with perception. Rayleigh was also keenly interested in the ability to localize sounds in space. He proposed that two acoustic cues are used for sound localization: intensity differences and time differences across the ears. The intensity differences were produced by the presence of the head in the sound field, which can effectively block sound transmission. The time differences were produced by the different travel times of sound across the ears. This theory, called the ***duplex theory of sound localization***, has been validated numerous times (see Chapter 7).

Although the investigations presented above are not exhaustive, these representative studies illustrate that the earliest psychoacoustic work was conducted on the perception of pitch and space. Little evaluation of loudness and its relationship to sound was conducted. If we pause to consider the environment that these pioneers were working in, we can gain a better understanding of why the early work was conducted in these primary areas. Technology such as sound level meters and earphones had not been engineered at that time. Although Fechner developed techniques to measure perception in the mid-1800s, the devices to manipulate and measure sound levels were not built until the 1920s. Controlling and characterizing the intensity of a sound was even more difficult than manipulating frequency or spatial location. For example, changing the length of strings, altering the properties of materials, or changing size of a tuning fork could manipulate frequency. A Helmholtz resonator or a siren, similar to that developed by Seebeck, could also be used to generate sounds with specific frequencies. On the other hand, techniques at that time did not allow manipulation of intensity without also varying the frequency of a sound.

Measurements of the auditory perception of intensity were therefore somewhat restricted and were extremely imprecise. Otologists quantified hearing loss by using tuning forks and made measurements of how long a patient could hear a sound or how far away an examiner could be before a patient could not hear a sound. Due to the limitations in achieving both accurate and precise intensity levels, early scientists focused their endeavors more on pitch and sound localization than other acoustic quantities.

Yet, one of Helmholtz's students, Wilhelm Wundt (1832–1920), did not let these limitations stymie his interest in sound perception and the perception of sound intensity. Notably, Wundt developed many instruments that allowed him to measure the perception of sound in a controlled way. His sound pendulum and falling phonometer allowed him to alter sound intensity without changing the frequency characteristics of a sound (Schick, 2004). Examples of these devices are shown in Figures 1–3 and 1–4. Both devices functioned by dropping an object that struck a panel. The height of the object would determine the intensity of the sound generated when the object struck the panel. He also developed a sound hammer and a sound interrupter, which allowed the quantification of intensity and time, among a variety of other devices.

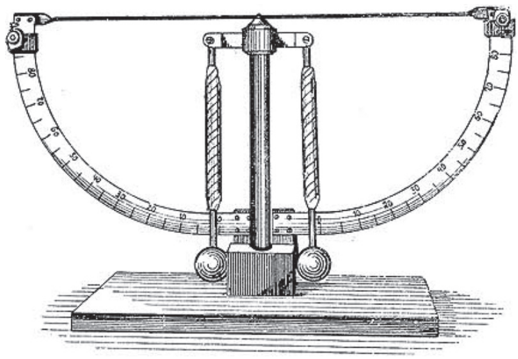

FIGURE 1–3. A sound pendulum used by Wundt. From Spindler and Hoyer (1908).

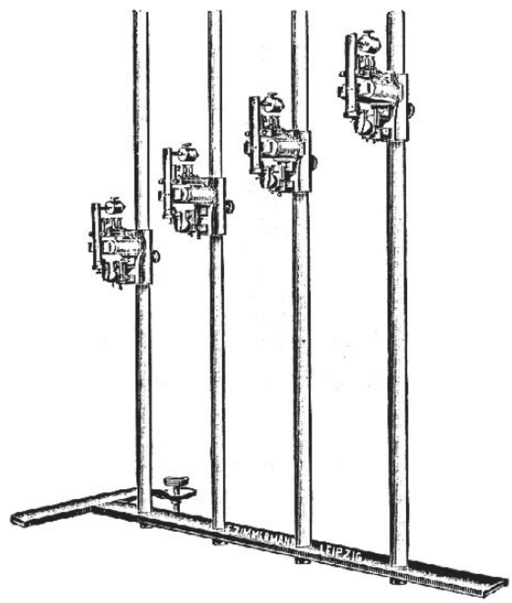

FIGURE 1–4. A falling phonometer used by Wundt. From Zimmerman (1903).

Wundt performed some of the earliest quantitative experiments evaluating the perception of tones at different levels and why some combinations of musical notes are appealing to the ear and some are not. His work, published in his writings *Principles of Physiological Psychology* (1902) came to be one of the more important texts in psychology, and he founded the first formal laboratory for psychological research in 1879 at the University of Leipzig. Wundt is considered the *father of experimental psychology*, as he treated psychology as separate from biology or philosophy and was the first to call himself a psychologist. His influence was far reaching and has had an impact on all areas of experimental psychology.

THE ADVENT OF THE TELEPHONE

Although Wundt was able to control the sound intensity in his experiments, the introduction of telephone receivers and sound level meters made measurements of the perception of sound intensity far more feasible. Alexander Graham Bell's (1847–1922) invention formed the basis of the technology that allows us to control and manipulate sound precisely and accurately. Along with Western Electric, its precursor company, Bell Telephone Labs (commonly called Bell Labs), focused on the research and development of telephone-associated equipment. The contributions of Bell Labs after its formation in 1925 have been integral to the fields of psychoacoustics and audiology. Much of their work involved the development of technologies that are now used to assess and to characterize hearing.

> Alexander Graham Bell has been both admired as the inventor of the telephone and despised as a leader in the oralism movement, which pressured deaf people to avoid learning sign language. He was also loosely connected to eugenics, as he attempted to persuade deaf people not to marry each other. Although many in the hearing community celebrate his accomplishments, many in the Deaf community feel very differently.

During this time frame, we also saw the development of the decibel as a unit to describe sound level. The unit, of course, was named to honor A. G. Bell, who passed away in 1922. Development of the decibel has had a profound impact on our ability to characterize hearing, including the use of suffixes such as dB SPL (sound pressure level), dB A (A weighted), and dB HL (hearing level), all of which are used to describe the level of sound in various ways. Some of the most seminal work in the field of psychoacoustics originated at Bell Labs. Examples include:

- Wegel and Lane (1924), who made the first quantitative measurements on masking, the process by which one sound influences the ability to detect another sound (see Chapter 3)
- Sivian and White (1933) measured some of the first calibrated auditory detection thresholds and compared measurements made over headphones with those obtained in the free field (see Chapter 2)
- Fletcher and Munson (1933), who, along with Steinberg, made the earliest measurements of equal loudness contours (see Chapter 4)
- Steinberg et al. (1940) conducted large-scale measurements of auditory detection abilities across a representative group of people living in the United States.
- Fletcher (1940) formalized theories of masking (see Chapter 3).

The investigations mentioned here represent some of the more important studies conducted at the time. Their work was innovative, inventive, and impactful. Their investigations have proven to be foundational on the topics of threshold, loudness, and masking. Interestingly, however, unlike in the previous century, the investigations at that time did not involve other auditory percepts, such as pitch and spatial hearing. Such experiments were not as relevant to the development of the telephone, where engineers were evaluating the limits of hearing to establish the constraints necessary for telephone receivers and associated equipment.

Although all of the investigators listed above deserve credit and recognition, it is worth pointing out the contributions of Harvey Fletcher (1884–1981), a research engineer at Western Electric and later Bell Labs from 1916 to 1949. Fletcher made some of the greatest contributions to both psychoacoustics and audiology during his tenure there and was also a founding member of the Acoustical Society of America, one of the premier organizations in support of acoustics. His contributions to the field were widespread and influential. Remarkably, he, along with R. L. Wegel (birth and death dates unknown), developed the first commercial audiometer, the Western Electric Model 1–A audiometer (Fletcher, 1992), which was the size of a large cabinet and therefore was not practical. Yet, none of the other audiometers in use at the time were practical either. For example, Cordia Bunch (birth and death dates unknown), a psychologist at the University of Iowa, built the first audiometer in the United States, but he and his colleagues were the only ones to use it. Fletcher and Wegel's audiometer, on the other hand, was a commercial audiometer that could test hearing up to 16,000 Hz. However, it was expensive and sold for roughly $1500, about 4 times the price of a car (a model-T Ford sold for about $400) and just slightly less than a house, at the time. Because of the steep price tag and the lack of portability, Fletcher and Wegel developed the first commercial and portable audiometer, the Western Electric Model 2–A (with test frequencies up to 8000 Hz) soon afterward.

Developing the audiometer was only one of Fletcher's many achievements. As Allen (1996) describes, Fletcher was the first to accurately measure auditory threshold, the first to measure the relationship between loudness and intensity and loudness and frequency (see Chapter 4). Further, he developed the model of masking in application still today (see Chapter 3). His two books *Speech and Hearing*, published in 1929, and *Speech and Hearing in Communication*, published in 1953, were considered authoritative at the time and, in many cases, remain so today. Fletcher also coined the term *audiogram* and developed the unit of dB hearing level (dB HL), the decibel metric in use today to describe hearing abilities (Jerger, 2009). If that were not enough, he also made substantial contributions to our knowledge of speech perception and developed the Articulation Index, now revised to the Speech Intelligibility Index (SII), that allows one to calculate the amount of speech information available in different frequency bands. The SII is able to robustly predict intelligibility scores for certain speech materials and acoustic environments (ANSI S3.5, 2017) and is now used in industrial applications and to assess the impact of hearing loss on speech perception.

Of course, research on auditory perception did not end with the development of the telephone. In fact, the 1940s really marked the beginning of a new era, as the tools to assess auditory perception were now readily available. The accomplishments of these more recently investigators are discussed throughout this text.

CLINICAL AUDITORY ASSESSMENT

During the early-mid 1900s, we saw a revolution in the way that hearing was tested. Fletcher, along with his colleague Wegel, collaborated with an otologist, Edmund Prince Fowler (1872–1966), and began their work in measuring hearing thresholds. Regarding assessing hearing, these scientists evaluated absolute threshold (the lowest detectable sound level) and quantified the upper limit of loudness in terms of the *threshold of feeling*, which they called *maximum audibility*. Along the way, they also developed the tools and units with which to quantify the threshold and developed the graphical depictions we use today.