PSYCHOACOUSTICS

Perception of Normal and Impaired Hearing with Audiology Applications

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Perception of Normal and Impaired Hearing with Audiology Applications

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Introduction

NOTES ON THIS TEXT

I am writing this textbook after teaching psychological acoustics (commonly referred to as psychoacoustics) to clinical audiology students for over 15 years. Each year I have taught this course I have struggled to find a text appropriate for these students. No doubt, there are excellent texts available on the topic of psychoacoustics. However, all modern books on the topic cover only normal auditory perception and contain little to no review of perception by listeners with hearing loss. Yet, I argue that these students, and those studying auditory perception more generally, should have some exposure to the perceptual deficits imposed by sensorineural hearing loss. Not only will having this information help clinical audiologists to better care for their patients, but studies evaluating perception in listeners with sensorineural hearing loss also have contributed to our understanding of the mechanisms responsible for normal auditory perception. Consequently, this textbook provides a broad overview of auditory perception in normal-hearing listeners, and each chapter includes information on the effects that sensorineural hearing loss has on perceptual abilities.

When possible, this book will provide mechanistic explanations for the psychoacoustical findings in terms of physiology. We will ask "why?" and "how?" with a goal toward understanding what the auditory system is able to perceive and how the auditory system achieves perception. The main focus of this text is healthy auditory perception. However, as we work toward this goal, we will also evaluate the perceptual abilities of people with sensorineural hearing loss. The focus here is on listeners with sensorineural hearing loss of presumed cochlear origin, and the term ***sensorineural hearing loss*** will be used throughout the text as such.

The primary target audience is graduate students in audiology, who intend a clinical career and need an understanding of both normal and impaired auditory perception. Because the field of psychoacoustics has profoundly influenced clinical audiology, this book also discusses history of the two fields and clinical implications and applications of psychoacoustics. Students studying experimental psychology, audio engineering, engineering, and hearing science may also find that this book suits their needs. Notably, this text does not assume that students have a strong background in either acoustics or auditory physiology. However, because understanding both of these fields is important to fully understand psychoacoustics and the physiological mechanisms responsible for the perception of sound, this text provides an overview of the necessary elements of acoustics and physiology, on an "as-needed" basis.

The structure of the textbook differs from the other texts available on this topic. Traditionally, texts generally present a chapter on acoustics, one on auditory anatomy and physiology, and sometimes a chapter on methodology before delving into chapters on individual topics within the realm of psychoacoustics. In contrast, this text takes an approach similar to a problem-based approach in that each chapter presents self-contained information related to the acoustics, physiology, and methodologies as they apply to the specific topic being discussed. Naturally, certain chapters may refer back to previous chapters for a review of certain information, but the degree to which this occurs is fairly limited.

For the most part, each self-contained chapter presents the necessary information for understanding the specific topic. Essentially each chapter includes the following topics:

- Introduction to the topic and its importance
- Relevant acoustics
- Important physiological studies
- Perception by normal-hearing listeners
- Perception by listeners who have sensorineural hearing loss

In some chapters, clinical applications are discussed within the chapter, particularly those concepts that directly relate to primary audiology practice. However, the final chapter discusses the perceptual consequences of sensorineural hearing loss and more advanced clinical applications of psychoacoustics.

The self-contained organization allows students and faculty to select the areas of the most interest or relevance to the particular course or student, and students have the option of either reviewing the relevant acoustics and physiology pertinent to the topic at hand, or not. This way, students do not need to review a full chapter on acoustics or anatomy and physiology in order to obtain the necessary background for the specific topic. It also allows students a better opportunity to integrate material across the various fields and to quickly determine which acoustic or physiological principles are most relevant for the subject being discussed. Because psychoacoustics is intimately integrated into clinical audiology, the first and final chapters illustrate the deep connection between the two fields.

This text also emphasizes applied learning, as actively engaging with course material is both more effective and more efficient for learning that material. As such, ancillary materials, available online, are included for the use of both instructors and students. These materials include in-class and laboratory exercises to facilitate student engagement with course topics. At the end of each chapter, there is a set of exercises designed to develop critical thinking about psychoacoustics and to assist students in learning to apply psychoacoustic information to the more general fields of audiology and auditory perception. Together, these materials should allow students to develop a deeper understanding of psychoacoustic topics and how those topics relate to hearing loss and audiological practice.

Finally, this textbook is not intended to provide a comprehensive overview of the large variety of psychoacoustic studies or experiments. Rather, it is intended to give students sufficient information to understand how the ear achieves auditory perception, what the capabilities of the ear are, and how hearing loss influences that perception. It also provides students with a foundation for further study in the area to apply psychoacoustic principles to diagnostic audiology and audiological rehabilitation.

EVERY AUDIOLOGIST IS, AT SOME LEVEL, A PSYCHOACOUSTICIAN

The fields of audiology and psychoacoustics are intertwined. Audiometric testing originated directly from the field of psychoacoustics, and early audiologists and otologists worked closely with the early psychoacousticians in developing tools for audiological assessment. In some sense we can consider every audiologist to be a psychoacoustician. Perhaps the most obvious example of this is evident in the audiogram—a behavioral assessment of auditory abilities. The audiogram, which relates the ability to detect a sound to the frequency of that sound, forms the core of audiological assessment. Any audiologist who collects an audiogram is relying on over 100 years of psychoacoustic knowledge and methodological development. In fact, the audiogram remains the most reliable and accurate method to assess auditory sensitivity today, as physiological tests have not advanced enough to adequately replace the audiogram. In fact, this may never happen: Physiological assessment does not measure *hearing*, but rather measures the *representation* of sound within the auditory system. As a result, we continue to rely on patients' reports of their perceptions to make both scientific advancements and clinical decisions.

Although many audiologists routinely collect psychophysical data, the audiologist makes a very limited set of measurements on perceptual abilities. Primary and common assessments include the audiogram, a measurement of the speech recognition threshold (SRT), and word recognition scores. However, these measurements do not characterize the wide range of perceptual abilities that underlie the ability to communicate in everyday environments. Successful communication requires representation of sound intensity, frequency, temporal characteristics, and information from the two ears. Deficits in any one of these representations can lead to deficits in the ability to communicate in the variety of environments encountered by humans. Consequently, we can easily argue that audiologists should more thoroughly assess various auditory perceptions. A century of research tells us that the audiogram and associated speech tests (typically conducted in quiet) do not describe how well a patient perceives the acoustic characteristics of sound that are important to differentiate between sounds or extract it from background noise.

The audiogram is an historical assessment tool, developed in the early 1900s, originally used because we had limited knowledge of the ear, and we did not have access to technology that could easily generate and manipulate complex sounds in real time for audiological assessment. The recent century has repeatedly demonstrated that the audiogram does not reflect our multiple auditory perceptual abilities. The audiogram is critically important for addressing site of lesion (whether a hearing loss is conductive, in the outer or middle ear, or sensorineural) and is also widely used to guide hearing aid fitting. However, this text will illustrate that the variability in perceptual deficits experienced by listeners with sensorineural hearing loss is quite high and that the audiogram does not provide a measurement of any other level of auditory perception besides detection. As such, measurement of perceptual abilities in conjunction with the audiogram may ultimately provide crucial and important information to an audiologist, who can then recommend the most appropriate hearing aid algorithms for a specific patient.

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I would like to thank all of the students at Indiana University who took my course on psychoacoustics and taught me as much as I taught them (I hope). Some of those years were harder than others, but there is no doubt that working with them over the years showed me how to better communicate psychoacoustics material. I would also like to thank my clinical colleagues for their years of discussion on the connection between psychoacoustics and audiology. Those conversations have allowed me to better apply the principles of psychoacoustics to clinical practice. I can only begin to thank my PhD mentor, Virginia Richards, for taking a chance 25 years ago on an engineering student who knew nothing about experimental psychology and for giving me the foundation for the content of this text. The contributions of my postdoctoral advisor, Marjorie Leek, who taught me the value of scholarship and the impact of hearing loss on auditory perception, are also evident throughout this book. Last, but most definitely not least, I would like to thank my family and loved ones for their tireless support and patience.

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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

Knowledge of the association between sound and its perception has been around for many centuries. However, 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 an 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

EARLY INVESTIGATION OF PERCEPTION

The idea that one could evaluate perception using physical stimuli has been around for centuries. However, it wasn't until the early 1800s when experimental science was sufficiently advanced to produce reliable and systematic assessment of perception and its relationship to the physical world. Hence, 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 an historic view 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 should begin 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 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, in particular, 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 perception and physical stimuli are, in some sense, interchangeable. This idea formed the foundation for all modern psychophysics and opened the door to the measurement of perception. Fechner 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 in modern 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 that are discussed in Chapter 2. In some cases, modifications to these methods have yielded efficient measurements of perception. We use variants of all of these procedural methodologies in psychoacoustic measurement 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, *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 modern 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), which applied the principles of ***Fourier analysis*** developed by Fourier (1768–1830). This theory stated that the ear conducts a form of Fourier analysis, which allows complex sounds to be divided into sinusoidal components. In order 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 demonstrated inconsistencies in Helmholtz's

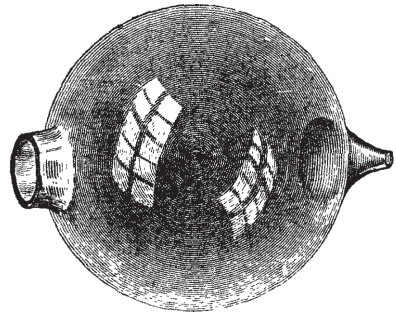

FIGURE 1–1. A Helmholtz resonator. From Helmholtz (1863).

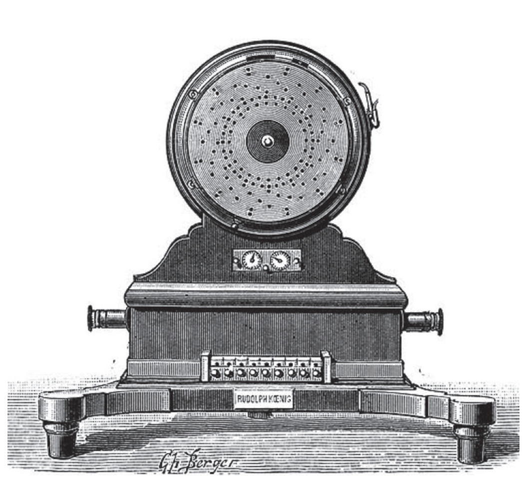

FIGURE 1–2. One of Seebeck's sirens. From Koenig (1889).

spectral theory of pitch. Seebeck's results posed substantial problems for Helmholtz's theories and were bitterly disputed at the time (Turner, 1977). Unfortunately for Seebeck, he passed away almost a century before his experimental results were reconsidered and formalized into a theory by J. F. Schouten (1940). Schouten's *residue theory* suggested pitch perception could also be based on a temporal representation (in contrast to the spectral representation proposed by Helmholtz) 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. His book *The Theory of Sound* also discussed acoustic problems using mathematics. 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 differential 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 intensity 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 developed at that time. While Fechner developed some 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 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, in particular, 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 of these devices functioned by dropping an object that struck a panel. The height of the object would determine the intensity of the sound generated when it hit the panel.

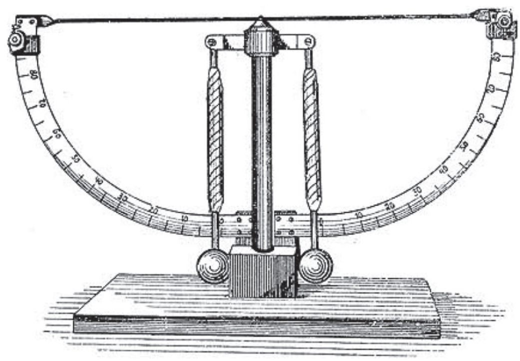

FIGURE 1–3. A sound pendulum used by Wundt. From Spindler and Hoyer (1908).

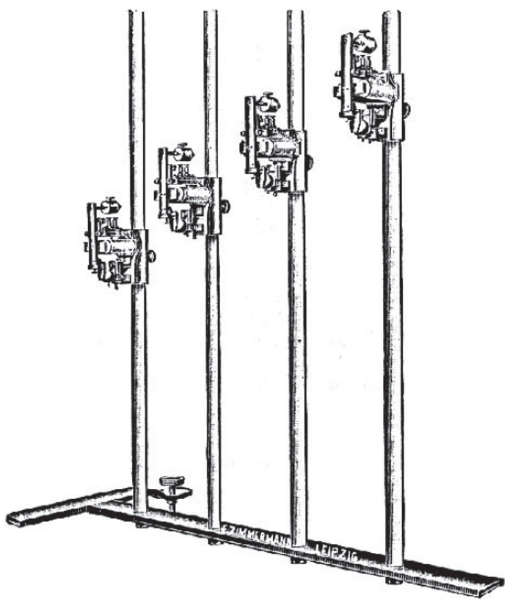

FIGURE 1–4. A falling phonometer used by Wundt. From Zimmerman (1903).

He also developed a sound hammer and a sound interrupter, which allowed the quantification of intensity and time, among a variety of other devices.

Wundt performed some of the earliest quantitative experiments evaluating why we are able to hear tones of 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* (1873–1874) 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 more feasible. Alexander Graham Bell's invention formed the basis of the technology that allows us to precisely and accurately control and manipulate sound today. 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, in particular, 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.

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, Montgomery, and Gardner (1940) conducted large-scale measurements of auditory detection abilities across a representative group of people living in the United States.
- Fletcher (1940) formalized theories masking (see Chapter 3).

The investigations mentioned here do not provide a comprehensive list of the work conducted at Bell Labs, but they 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. Note in particular, however, that 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, 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, 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, a psychologist at the University of Iowa, built the first audiometer developed 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 and sold for roughly $1500, which would be about $25,000 in modern currency. Because of the steep price tag and the inability of portability, Fletcher and Wegel developed the first commercial and portable audiometer, the Western Electric Model 2-A, soon afterward.

Yet, 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. Further, he developed the model of masking in application still today. His experiments led to the modern-day audiogram and contributed to our knowledge of loudness (discussed in Chapter 4). 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, the decibel metric in use today to describe hearing abilities (Jerger, 1990). If that were not enough, he also made substantial contributions to our knowledge of speech perception and developed a tool (originally called 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-3.5, 2017) and is now used in industrial applications and to assess the impact of hearing loss on speech perception.

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. With regard to assessing hearing, these scientists evaluated absolute threshold (the lowest detectable sound level) and quantified the highest level of hearing 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.

Thus, Fowler and Wegel developed what we now call the audiogram. At the time, it was standard to quantify frequency in cycles per second (note: the unit hertz was not established until 1930), and at the time, Wegel had already been plotting frequency in octaves, rather than using a linear scale. However, there was no standard for depicting the level (*y*) axis, and this was a topic hot for discussion. Two issues were of interest: the units to be used and the scale on which the thresholds should be plotted. At the time, auditory thresholds (as well as other auditory measurements, such as the *maximum audibility*) were plotted in sound pressure units, such as dynes/cm^2. It was fairly straightforward to use a logarithmic axis at the time, based on the works of Weber and Fechner, and was consistent with engineering tradition. Although the decibel was not in use yet, plotting auditory thresholds on a logarithmic scale was very similar to the modern practice of plotting thresholds in decibels.

An illustration of Wegel's representation is shown in Figure 1–5, which plots both auditory threshold (*minimum audibility*) and the threshold of feeling (*maximum audibility*), measured in more than 40 people. Wegel defined the range between the minimum audibility and maximum audibility curves as the *sensation area*. Wegel's sensation area had an elliptical shape because both the minimum and maximum audibility curves were frequency dependent. Today, we would call the sensation area the ***dynamic range of hearing***. From Wegel's data, we see that the dynamic range of hearing was frequency dependent and was the largest in the mid-frequency range (e.g., about 500–6000 Hz).

At that time, Wegel and Fowler also were conducting measurements of hearing in listeners with hearing loss. The auditory thresholds of a listener with hearing loss, reported by Wegel (1922), are also plotted in Figure 1–5. We observe that this patient's thresholds were higher than the minimum audibility curve and fell in the middle of the sensation range. Using data such as these, Wegel and Fowler considered that there might be an easier way to depict the amount of hearing loss in which the dynamic range of hearing was taken into account. Wegel and Fowler observed that hearing thresholds could be quantified as a percentage of the dynamic range at each frequency. They counted the number of logarithmic steps between the minimum and maximum audibility curves and then counted the number of steps between minimum audibility and the patient's threshold. Dividing these two values