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Introduction

Hearing is the sense that obtains information about the world around us using the pressure fluctuations in the air (sounds) that are produced by vibrating objects. In most situations in which we find ourselves, the air is full of sound, and it is therefore full of *information*. The ear evolved to make use of that information, to make us better at coping with the "struggle for existence," as Charles Darwin put it (Darwin, 1859). I start by explaining why I think that hearing is a worthwhile subject for study, and introduce some of the ways in which we can investigate the auditory system.

1.1 WHY STUDY HEARING?

In most undergraduate psychology courses, the study of hearing is neglected in favor of the study of vision. Is this bias justified? I argue that it is not. Hearing is a crucial sense for humans. Speech is the main means by which we communicate with one another. Music is one of the most important forms of entertainment and recreation, as well as being an important form of communication itself—it allows the expression of powerful emotions. Hearing is, therefore, *central* to the interaction of human beings with other human beings. Hearing is also of importance to our interactions with our environment. Sounds warn us of danger: In many situations, we hear an approaching car before we see it. Sounds also are used in our interactions with objects. They wake us up in the morning and provide information about the operation of machines, from car engines to microwave ovens.

We study hearing to understand how the ear and the brain make sense of these stimuli, which are such an integral part of our daily lives. Despite the importance of knowledge in itself for our culture (and the promise that "pure" research will eventually lead to useful applications), hearing research is not driven by curiosity alone. If we understand how the auditory system responds to sounds, then we can use that knowledge to help design sound-producing devices, such as telecommunication systems, entertainment systems, and devices that produce auditory alerts and warnings. Furthermore, we can use our knowledge of how the human auditory system works to design artificial devices that mimic aspects of this system, such as speech recognition programs that enable us to talk to our machines. Last but not least, this knowledge helps us to understand and treat hearing disorders. About one in six people are hearing impaired, and the design of hearing aids is dependent upon perceptual research.

There is a great deal of ignorance about hearing, probably more than there is regarding vision. Many people are aware of how the eye works, at least in general terms. They know that light from an object is focused by the lens onto the retina. How many people know what happens to sounds in the ear? Very few, on the basis of my experience. Even if you believe that vision is the most important sense and that this should be reflected in teaching practices, I hope you will agree that we should not neglect hearing. If you are approaching this subject for the first time, I would like to convince you that auditory science is not only *important*, but also *fascinating*.

1.2 HOW IS HEARING INVESTIGATED?

Hearing research covers a wide range of scientific disciplines. Physical acoustics tells us about the characteristics of sounds and how they propagate and interact with objects. It tells us about sound waves reaching the ear from a given sound source: about the nature of the stimulus, in other words. Physical acoustics also helps us to understand how sounds are modified by structures in the ear. The biological processes involved in hearing can be studied in many ways and at different levels of detail. At a low level, molecular biology tells us about the machinery of cells in the auditory system; the special molecules that cause the unique behavior of these cells. For understanding the overall function of the auditory system, however, two disciplines dominate: physiology and psychophysics.

1.2.1 Auditory Physiology

At a general level, physiology is concerned with the internal workings of living things: the functions of biological systems. Auditory physiology is concerned with

the internal workings of the auditory system: how sound is processed by the cells and structures in the ear and brain. Research is based on direct measurements of the biological systems that underlie hearing. Because many of these experiments are "invasive," requiring some degree of surgery, they are often performed on anaesthetized animals or on *in vitro* preparations of tissue that has been removed from an animal.

Most of the complex processing in hearing occurs in the central nervous system, which is composed of billions of specialized cells called *neurons*. *Neurophysiological* techniques can be used to measure the electrical activity of neurons in the auditory system, to determine how sounds are represented and analyzed in terms of the electrical impulses that underlie brain function. These experiments are often conducted on anaesthetized animals, such as the guinea pig. In one popular technique, a tiny electrode (a *microelectrode*) is inserted into the auditory nerve or into the brain and, in this way, the electrical responses of individual neurons may be recorded. By controlling the sounds that are played to the animal while the recording is taking place, the experimenter can determine the sounds to which a neuron is most sensitive, how it *represents* those sounds, and, hence, what the function of the neuron might be. Electrical measurements also can be made of the combined activity of millions of neurons by using electrodes placed on the scalp, for example. Experiments such as these can tell us about how sounds are represented across a large number of neurons. Modern "brain imaging" techniques, such as functional magnetic resonance imaging (fMRI), can also be used to determine the parts in the brain that are active when a particular sound is played. Because these last two techniques are "non-invasive," they can be employed with conscious human listeners.

Auditory physiologists also can explore sound processing that occurs *before* the acoustic signal is converted into neural impulses. The conduction of sound to the eardrum can be recorded using small microphones. The vibration of the eardrum can be measured by reflecting laser light from the eardrum. Using this technique, it is even possible to measure the vibration of delicate structures in the cochlea, such as the basilar membrane. The overall electrical activity in the cochlea can be measured using an electrode placed at the round window, one of the two membrane-covered openings to the cochlea. The electrical activity of individual cells in the cochlea also can be recorded using microelectrodes.

These examples only illustrate a fraction of the number of ingenious techniques that are used by physiologists to probe the workings of the ear and the auditory system. However, these techniques cannot tell us much about the experience of the listener. To relate the biological mechanisms to our sensations, we must combine physiological experiments with experiments that employ *behavioral* techniques.

1.2.2 Psychoacoustics

Auditory psychophysics, or *psychoacoustics*, is the psychological or behavioral study of hearing—*behavioral* in that the participant is required to make a response to the sounds that are presented. As the name suggests, the aim of psychoacoustic research is to determine the relation between the *physical* stimuli (sounds) and the *sensations* produced in the listener. The listener is usually human, but behavioral techniques can be used with other animals. In a typical experiment, a listener may be asked to make some judgment about sounds that are played (e.g., which of two sounds has the higher pitch) and to produce a response (e.g., by pressing a button corresponding to which sound is chosen). These experiments are usually conducted in a sound-attenuating booth which shields the listener from external sounds, and the stimuli are usually presented over headphones. By controlling very carefully the sounds that are presented, and the instructions given to the listener, we can find out a surprising amount about how the ear and brain work. That we measure the *behavioral* responses of listeners is essentially why psychoacoustics is regarded as a branch of psychology, although many of the problems addressed by psychoacousticians have little to do with the popular conception of psychology. Psychoacoustic techniques can be used to study very "low-level" or "physiological" processes, such as the mechanical processes underlying the separation of sounds in the cochlea.

It is possible that the term "psychoacoustics" was first coined by T.W. Forbes when he described the research he and his team were conducting in the United States during the Second World War (Burris-Meyer & Mallory, 1960). A secret government project was set up to investigate, in part, the potential of acoustic weapons. To the disappointment of warmongers everywhere, the team were unable to produce anything close to an acoustic death beam, although it did develop a sound system for broadcasting propaganda from aircraft.

1.3 ABOUT THIS BOOK

This book provides an introduction to auditory perception, explains how sounds are represented and analyzed in the auditory system, and how these processes cause the sensations that we experience when we listen to sounds. To start, however, a little background is needed for readers who are not familiar with the physics of sound. Chapters 2 and 3 are devoted to physical acoustics, and describe the nature of sound and introduce the spectrum—a very important concept for understanding the function of the ear. Resonance, sound propagation, and signal processing are also discussed, as a familiarity with these topics will be of benefit later. Chapter 4 provides an overview of the anatomy and physiology of the auditory system, explains how the cochlea separates sound into different frequency components and describes the transduction process, by which vibrations are converted into electrical impulses in the auditory nerve. The crucial topic of frequency selectivity is explored further in Chapter 5, in which our sensations are related to processes in the cochlea and at other stages in the auditory system.

The next few chapters cover auditory sensations that should be familiar to most readers. Our perception of sound magnitude, or loudness, is discussed in Chapter 6. Our perception of sound periodicity, or pitch, is presented in Chapter 7.

Chapter 8 describes temporal aspects of hearing, the ability to respond to rapid changes in sounds, and the ability to combine acoustic information over time. Chapter 9 explains how we identify the location of sounds. In Chapters 6–9, our sensations are explained, whenever possible, in terms of what we know about the underlying physiological mechanisms. The final two chapters move on to higher-level aspects of perception involving extremely complex and, in some cases, little understood, brain processes. The remarkable ability of the auditory system to separate sounds from different sources is described in Chapter 10. The main end result of hearing—sound identification—is discussed in Chapter 11, with a description of speech perception. Chapters 10 and 11 show that complex auditory processes make use of the more basic analysis mechanisms described in the previous chapters. To conclude, Chapter 12 summarizes what we know and what we do not know about auditory perception.