Voice Science

Second Edition

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Foreword

In our time, knowledge expands at a rate that probably has never been achieved before. Some years ago, it was claimed that the number of active scientists equaled the total number of scientists who have ever been active throughout history. Thus, much effort is spent today on understanding better various aspects of the world in which we live.

This interest in scientific research is not difficult to understand. Many bad things that have happened, and that keep happening, reflect lack of understanding, lack of knowledge, and lack of competence. Often we have reasons to say: "Had I only known, I would not have made that mistake," or "Had I only known how that thing works, I could have fixed it much more efficiently."

An explosion of new knowledge has occurred in our time also in the field of voice. The reason is not merely society's thirst for new knowledge. Another important reason is that the voice is one of the most frequently used communication tools. This is true in spite of the huge amount of communication transported in digital form today. That, in turn, might be related to the fact that we tend to hover in large cities. This implies that we have contact and interaction with a great number of people. In addition to that we have the phone, the conventional as well as its cellular cousin. Also important is that the voice is one of the most common working tools in our time. Therefore, voice disorders have a large impact on daily life for a great number of people who cannot work when their voices do not function properly; and sick-leave is quite expensive for society.

Doing research is one thing; but assuring that all people for whom the results are relevant get to know about them is quite another. One of a researcher's nightmare is to work in vain, to write in water. This risk is not negligible. For example, it is quite difficult for a voice physician, therapist, or teacher to follow all the journals in which results of relevance to their daily work appear. If they fail, they are likely to pursue methods less efficient than the state of the art.

The solution to this problem is text books that compile the present state of knowledge within a specific field. Exactly this is the aim of this new and substantially expanded edition of Robert Sataloff's *Professional Voice: The Science and Art of Clinical Care*. It gives a broad overview of the many scientific aspects of voice that have been developed up to present. It is a valuable up-to-date overview of the field, and it will certainly be useful as an extensive source of knowledge for those interested in various scientific aspects of voice. The book is an impressive monument of the voice as we know it today. The portions of that book contained in this student edition entitled *Voice Science* make this important information available and affordable for those without access to the entire *Professional Voice* book. This volume should be a valuable asset for teachers and students in the communication sciences.

KTH, June 2016
—Johan Sundberg

Preface

Voice Science is part of a 3-book student edition of selected chapters from the fourth edition of *Professional Voice: The Science and Art of Clinical Care*. That compendium fills over 2000 pages including 120 chapters and numerous appendices, and it is not practical for routine use by students. However, *Professional Voice: The Science and Art of Clinical Care*, Fourth Edition was intended to be valuable to not only laryngologists but also speech-language pathologists, voice teachers, nurses, performers, students, teachers and anyone else interested in the human voice. *Clinical Assessment of Voice* and other volumes of the student edition have been prepared to make relevant information available to students in a convenient and affordable form, suitable for classroom use as well as for reference.

Chapter 1 provides introductory information about the physics of sound and helps students understand concepts and terms such as decibels and hertz. **Chapter 2** has been added and contains fascinating basic information on laryngeal development. **Chapter** 3 on embryology is unchanged and summarizes the development of the larynx. **Chapter 4** contains substantial additions and provides extensive discussion of medical genetic issues that can affect the voice. **Chapter 5** offers extraordinary insight into the complex topics of genomics and proteomics as they relate to the larynx. **Chapter 6** is an extensive and comprehensive chapter on the clinical anatomy and physiology of the voice. It contains a great deal of information about laryngeal anatomy, neuroanatomy, respiratory function, and other topics that have not been synthesized in similar detail in a single source elsewhere. It contains a great deal of new information not present in previous editions. **Chapter 7** offers additional insights into neuroanatomy and physiology synthesized by Dr. Christy Ludlow. **Chapter 8** is an exceptionally interesting chapter on Music and the Brain. It reviews much of what is known currently about central development and processing of musical information; and this science should be extremely valuable in expanding the vision of voice therapists and researchers. It has been updated extensively and is an exceptionally interesting chapter. **Chapter 9** on arytenoid cartilage movement presents unique clarification of this often misunderstood subject. In **Chapter 10**, Susan Thibeault and colleagues summarize their extraordinary insights into the structural response to vocal fold injury. This information is essential in understanding vocal fold scar. In **Chapter 11**, Ashley Ferster and Leslie Malmgrem crystalize current knowledge regarding cellular and molecular mechanics of vocal fold aging. **Chapter 12**, Baken's overview of laryngeal function, presents this complex topic with remarkable clarity. In **Chapter 13**, Ronald Scherer expands on Baken's information from chapter 12 and provides insights into more complex aspects of laryngeal function. Johan Sundberg has synthesized and summarized his many contributions to our understanding of vocal tract resonance in **Chapter 14**. **Chapter 15,** Chaos and the Voice, contains basic information on chaos theory and new ideas on application of nonlinear dynamics to voice care and research. All of these chapters have been updated. In **Chapter 16**, Baken discusses applications of Chaos theory to understanding and caring for the human voice. **Chapter 17** is new to this book and completely rewritten by new authors for the 4th edition of the Professional Voice book. It discusses exercise physiology and includes the most recent concepts and literature on this topic. Understanding exercise physiology is critical to understanding voice training and rehabilitation. **Chapter 18** by Harry Hollien capsulizes his extraordinary updated insights into the voice and forensic voice science and its potential for future application to clinical voice assessment.

Every effort has been made to maintain style and continuity throughout the book. Although the interdisciplinary expertise of numerous authors has been invaluable in the preparation of this text, contributions have been edited carefully where necessary to maintain consistency of linguistic style and complexity; and I have written or co-authored 5 of the 18 chapters. All of us who have been involved with the preparation of this book hope that readers will find it not only informative but also enjoyable to read.

—Robert T. Sataloff, MD, DMA

Acknowledgments to the Second Edition

I remain indebted to the many friends and colleagues acknowledged in the first edition of this book. As always, special thoughts and thanks go to the late Wilbur James Gould whose vision and gentle leadership formed the foundation on which so many of us have continued to build, and to the late Hans von Leden.

I am especially indebted to the many distinguished colleagues who have contributed to this edition. Those who had contributed to previous editions worked diligently to revise and update their chapters. Those who had not contributed to previous editions have added insights and expertise that have made it possible to realize my vision of what I thought this book should be.

As always, I am indebted to the National Association of Teachers of Singing for permission to use material freely from my "Laryngoscope" articles which appear in the *Journal of Singing* (formerly the *NATS Journal),* and to Vendome for permission to republish articles and color pictures from my monthly "clinic" in *Ear, Nose, and Throat Journal.* I am also grateful to John Rubin and Gwen Korovin and to Plural Publishing for permission to republish a few chapters from our book (Rubin JR, Sataloff RT, Korovin G. *Diagnosis and Treatment of Voice Disorders,* 4th ed, Plural Publishing, Inc; San Diego, CA, 2015). In addition, I am indebted for permission to republish material from *Choral Pedagogy,* 3rd ed (Smith B, Sataloff RT. Plural Publishing Inc, San Diego, CA; 2013), *The Performer's Voice* (Benninger MS, Murry T, and Johns MM, Plural Publishing, Inc, San Diego, CA, 2016), Sataloff's Comprehensive Textbook of Otolaryngology and Head and Neck Surgery (Jaypee, New Delhi, 2016), and Sataloff RT, Brandfonbrener A, Lederman R, *Performing Arts Medicine,* 3rd ed (Science and Medicine, Narberth, Pennsylvania, 2010).

Lastly, as always, I cannot express sufficient thanks to Mary J. Hawkshaw, RN, BSN, CORLN, for her tireless editorial assistance, proofreading, and scholarly contributions. I am also indebted to Christina Chenes for her painstaking preparation of the manuscript and for the many errors she found and corrected, and to my associates, Karen Lyons, MD, Amanda Hu, MD, Robert Wolfson, MD, and Frank Marlowe, MD, and to my laryngology fellows. Without their collaboration, excellent patient care, and tolerance of my many academic distractions and absences, writing would be much more difficult. I remain forever grateful to my father and partner Joseph Sataloff, MD, D.Sc., who taught me to write and edit, and who encouraged me to write my first papers and book, and mentored me throughout our years of practice together, as well as to my other primary mentors in training, Drs. Walter Work, Charles Krause and Malcolm Graham. My greatest gratitude goes to my wife Dahlia M. Sataloff, MD, FACS, and sons Ben and John who patiently allow me to spend so many of my evenings, weekends, and vacations writing.

About the Author

Robert Thayer Sataloff, M.D., D.M.A., F.A.C.S. is Professor and Chairman, Department of Otolaryngology-Head and Neck Surgery and Senior Associate Dean for Clinical Academic Specialties, Drexel University College of Medicine. He is also Adjunct Professor in the departments of Otolaryngology-Head and Neck Surgery at Thomas Jefferson University and the University of Pennsylvania, as well as Adjunct Clinical Professor at Temple University and the Philadelphia College of Osteopathic Medicine; and he is on the faculty of the Academy of Vocal Arts. He served for nearly four decades as Conductor of the Thomas Jefferson University Choir. Dr. Sataloff is also a professional singer and singing teacher. He holds an undergraduate degree from Haverford College in Music Theory and Composition; graduated from Jefferson Medical College, Thomas Jefferson University; received a Doctor of Musical Arts in Voice Performance from Combs College of Music; and he completed Residency in Otolaryngology-Head and Neck Surgery and a Fellowship in Otology, Neurotology and Skull Base Surgery at the University of Michigan. Dr. Sataloff is Chairman of the Boards of Directors of the Voice Foundation and of the American Institute for Voice and Ear Research. In addition to directing all aspects of these two non-profit corporations, he has led other non-profit and for-profit enterprises. He has been Chairman and Chief Executive of a multi-physician medical practice for over 30 years; and he served as Vice President of Hearing Conservation Noise Control, Inc. from 1981 until the time of its sale in 2003. He has also served as Chairman of the Board of Governors of Graduate Hospital; President of the American Laryngological Association, the International Association of Phonosurgery, and the Pennsylvania Academy of Otolaryngology-Head and Neck Surgery; and in numerous other leadership positions. Dr. Sataloff is Editor-in-Chief of the *Journal of Voice*; Editor-in-Chief of *Ear, Nose and Throat Journal*; Associate Editor of the *Journal of Singing* and on the editorial boards of numerous otolaryngology journals. He has written approximately 1,000 publications, including 59 books, and has been awarded more than $5 million in research funding. His medical practice is limited to care of the professional voice and otology/neurotology/skull base surgery. Dr. Sataloff has developed numerous novel surgical procedures including total temporal bone resection for formerly untreatable skull base malignancy, laryngeal microflap and mini-microflap procedures, vocal fold lipoinjection, vocal fold lipoimplantation, and others. He has invented more than 100 laryngeal microsurgical instruments produced by Microfrance and Integra Medical, ossicular replacement prostheses produced by Grace Medical, and novel laryngeal prostheses with Boston Medical. Dr. Sataloff is recognized as one of the founders of the field of voice, having written the first modem comprehensive article on care of singers, and the first chapter and book on care of the professional voice, as well as having influenced the evolution of the field through his own efforts and through the Voice Foundation for nearly 4 decades. He has been involved extensively throughout his career in education, including development of new curricula for graduate education. Dr. Sataloff has been instrumental in training not only residents, but also fellows and visiting laryngologists from North America, South America, Europe, Asia and Australia. His fellows have established voice centers throughout the United States, in Turkey, Singapore, Brazil, and elsewhere. He also is active in training nurses, speech language pathologists, singing teachers, and others involved in collaborative arts medicine care, pedagogy and performance education. Dr. Sataloff has been recognized by Best Doctors in America (Woodward White Athens) every year since 1992, Philadelphia Magazine since 1997, and Castle Connolly's "America's Top Doctors" since 2002. Dr. Sataloff's books include:

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To Dahlia, Ben and John Sataloff my patient and long suffering family who allow me the time to write and to Mary J. Hawkshaw, my dear friend and invaluable collaborator and to my fellows who have given me so much inspiration and pride.

1

The Physics of Sound

Robert Thayer Sataloff

Fortunately, one need not be a physicist in order to function well in professions involved with hearing, sound, and music. However, a fundamental understanding of the nature of sound and terms used to describe it is essential to comprehend the language of otolaryngologists, audiologists, music acousticians, and engineers. Moreover, studying the basic physics of sound helps one recognize complexities and potential pitfalls in measuring and describing sound. These concepts are important to musicians interested in understanding concert hall acoustics, evaluating studies of risk from musical noise exposure, understanding the effects of vocal efficiency (like going from pressed to flow phonation), and other situations surrounding the professions above.

Sound

Sound is a form of motion. Consequently, the laws of physics that govern actions of all moving bodies apply to sound. Because sound and all acoustic conditions consistently behave as described by the laws of physics, we are able to predict and analyze the nature of a sound and its interactions. Sound measurement is not particularly simple. The study of physics helps us understand many practical aspects of our daily encounters with sound. For example, why does an audiologist or otologist use a different baseline for decibels in his or her office from that used by an engineer or industrial physician who measures noise in a factory? Why is it that when hearing at high frequencies is tested, a patient may hear nothing and then suddenly hear a loud tone when all the examiner did was move the earphone a fraction of an inch? Why is it when 2 machines are placed close together, each making 60 dB of noise, the total noise is not 120 dB?

Sound Waves

Sound is the propagation of pressure waves radiating from a vibrating body through an elastic medium. A vibrating body is essential to cause particle displacement in the propagating medium. An elastic medium is any substance or particles returned to their point of origin as soon as possible after they have been displaced. Propagation occurs because displaced particles in the medium displace neighboring particles. Therefore, sound travels over linear distance. Pressure waves are composed of areas of slightly greater than ambient air pressure compression and slightly less than ambient air pressure (rarefaction). These are associated with the bunching together or spreading apart of the particles in the propagating medium. The pressure wave makes receiving structures such as the eardrum move back and forth with the alternating pressure. For example, when a sound wave is generated by striking a tuning fork, by vocalizing, or by other means, the vibrating object moves molecules in air, causing them to be alternately compressed and rarefied in a rhythmical pattern. This sets up a chain reaction with adjacent air molecules and spreads at a rate of approximately 1100 ft/sec (the speed of sound). This is propagation of the pressure waves.

Sound requires energy. Energy is used to set a body into motion. The energy is imparted to particles in the propagating medium and is then distributed over the surface of the receiver (eardrum or microphone) in the form of sound pressure. Energy is equal to the square of pressure ($E = P^2$). However, we are unable to directly measure sound energy. Only the pressure exerted on the surface of a microphone can be quantified by sound-measuring equipment.

Characteristics of Sound Waves

Sound waves travel in straight lines in all directions from the source, decreasing in intensity at a rate inversely proportional to the square of the distance from their source. This is called the *inverse-square law*. This means that if a person shortens his or her distance from the source of a sound and moves from a position 4 feet away to only 2 feet from the source, the sound will be 4 times as intense rather than merely twice as intense. In practical application, this inverse-square law applies only in instances in which there are no walls or ceiling. It is not strictly valid in a room where sound waves encounter obstruction or reflection, and increasing the distance of a whisper or a ticking watch from the subject can rarely be truly accurate or reliable.

Sound waves travel through air more rapidly than through water. They are conducted through solids also at different speeds. An ear placed close to the iron rail of a train track will detect the approach of a train before the airborne sounds can reach the observer. Thus, sounds travel through different media at different speeds; the speed also varies when the medium is not uniform. However, sound waves are not transmitted through a vacuum. This can be demonstrated by the classic experiment of placing a ringing alarm clock inside a bell jar and then exhausting the air through an outlet. The ringing will no longer be heard when the air is exhausted, but it will be heard again immediately when air is readmitted. This experiment emphasizes the importance of the medium through which sound waves travel.

The bones of the head also conduct sounds, but ordinarily the ear is much more sensitive to sounds that are airborne. Under certain abnormal conditions, as in cases of conductive hearing loss, a patient may hear better by bone conduction than by air conduction. Such an individual can hear the vibrations of a tuning fork much better when it is held directly touching the skull than when it is held next to the ear but without touching the head.

Distortion of sound waves by wind is common. The effect also varies according to whether the wind blows faster near the ground or above it. When sound travels through the air and encounters an obstruction such as a wall, the sound waves can bend around the obstacle almost like water passing around a rock in a stream. The behavior of sound waves striking an object depends upon several factors, including wavelength. Sound waves may pass through an object unaffected, be reflected off the object, or be partially reflected and partially passed through or around the object (shadow effect). Low-frequency sounds of long wavelength tend to bend (diffraction) when encountering objects, while diffraction is less prominent with sounds above 2000 Hz. The behavior of sound waves encountering an object also depends on the nature of the object. The resistance of an object or system to the transmission of sound is called *impedance*. This depends on a variety of factors such as mass reactants, stiffness reactants, and friction. The ability of an object to allow transmission of sound is called its *admittance*, which may be thought of as the opposite of impedance.

Components of Sound

A simple type of sound wave, called a *pure tone*, is pictured in Figure 1–1. This is a graphic representation of 1½ complete vibrations, or cycles, or periods, with the area of compression represented by the top curve and the area of rarefaction by the bottom curve. Although pure tones do not occur in nature, the more complicated sounds that we actually encounter are composed of combinations of pure tones. Understanding the makeup of this relatively simple sound helps us analyze more complex sounds. Fourier analysis is used to separate complex signals into their simple tonal components.

A pure tone has several important characteristics: One complete vibration consists of one compression and one rarefaction (Figure 1–2). The number of times such a cycle occurs in a given period of time

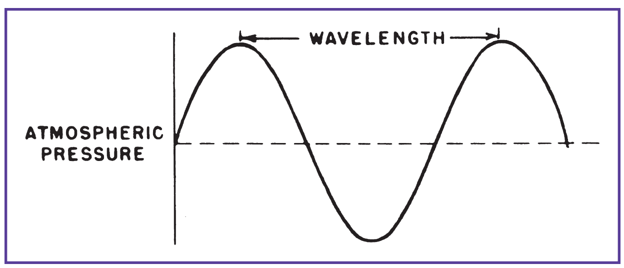

Figure 1–1. Diagram of a pure tone (sine wave).

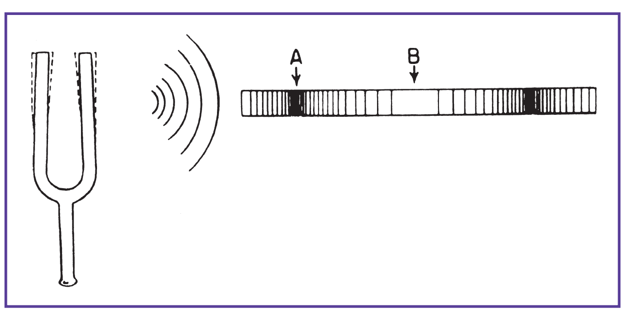

Figure 1–2. Areas of compression (A) and rarefaction (B) produced by a vibrating tuning fork.

(usually 1 second) is called frequency. Frequency is usually recorded in cycles per sound, or hertz. The perceptual correlate of frequency is pitch. In general, the greater the frequency, the higher is the pitch, and the greater the intensity, the louder is the sound. However, there is a difference between actual physical phenomena (such as frequency or intensity) and peoples' perceptions of them (pitch and loudness). A tuning fork is constructed so that it vibrates at a fixed frequency no matter how hard it is struck. However, although it will vibrate the same number of times per second, the prongs of the tuning fork will cover a greater distance when the fork is struck hard than when it is softly struck. We perceive this increased intensity as increased loudness. In the sine wave diagram of a pure tone, a more intense sound will have a higher peak and lower valley than a softer sound. Greater intensity also means that the particles in the propagating medium are more compressed. The height or depth of the sine wave is called its *amplitude*. Amplitude is measured in decibels (dB). It reflects the amount of pressure (or energy) existing in the sound wave.

Wavelength is the linear distance between any point in one cycle and the same point on the next cycle (peak to peak, for example). It may be calculated as the speed of sound divided by the frequency. This is also 1 period. Wavelength is symbolized by the Greek letter lambda (λ) and is inversely proportional to frequency (Figure 1–3). This is easy to understand. If it is recalled that sound waves travel at about 1100 ft/sec, simple division tells us that a 1000-Hz frequency will have a wavelength of 1.1 ft/cycle. A 2000-Hz tone has a wavelength of about 6.5 inches. A 100-Hz tone has a wavelength of about 11 feet. The wavelength of a frequency of 8000 Hz would be 1100 divided by 8000, or 0.013 feet (about 1 inch). Wavelength has a great deal to do with sound penetration. For example, if someone is playing a stereo too loudly several rooms away, the bass notes will be clearly heard, but the high notes of violins or trumpets will be attenuated by intervening walls. Low-frequency sounds (long wavelengths) are extremely difficult to attenuate or absorb, and they require very different acoustic treatment from high-frequency sounds of short wavelengths. Fortunately, they are also less damaging to hearing.

Any point along the cycle of the wave is its phase. Because a sine wave is a cyclical event, it can be described in degrees like a circle. The halfway point of the sine wave is the 180-degree phase point. The first peak occurs at 90 degrees, etc. The interaction of two pure tones depends on their phase relationship. For example, if the two sound sources are identical and are perfectly in phase, the resulting sound will be considerably more intense than either one alone (constructive inference). If they are 180 degrees out of phase, they will theoretically nullify each other and no sound will be heard (destructive interference) (Figure 1–4). This is the principle behind the concept of antisound, which is a sound generated to silence an unwanted sound that is equally loud but of opposite phase (180° phase). Interaction of sound forces also depends on other complicated factors such as resonance, which is affected by the environment and

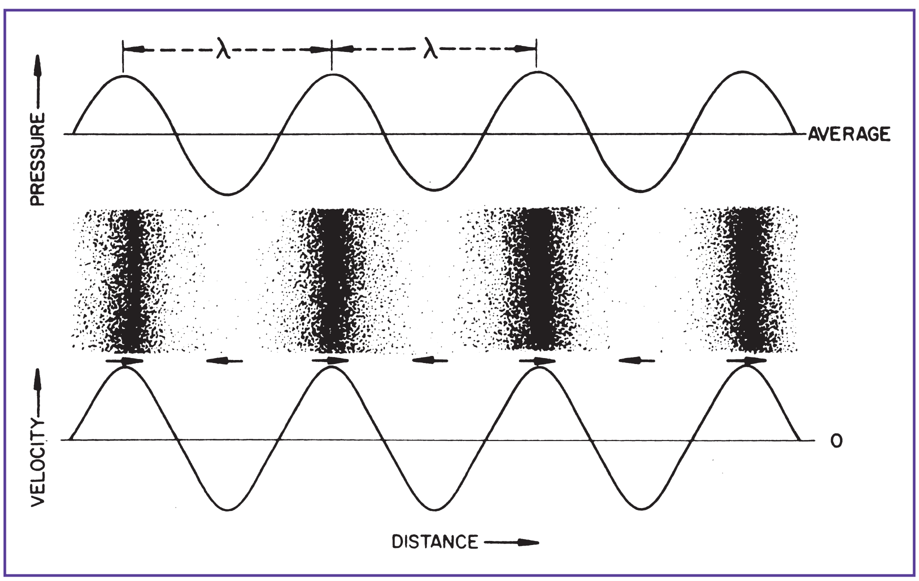

Figure 1–3. Wavelength in relation to other components of a sound wave. (Adapted from Van Bergeijk.[1])

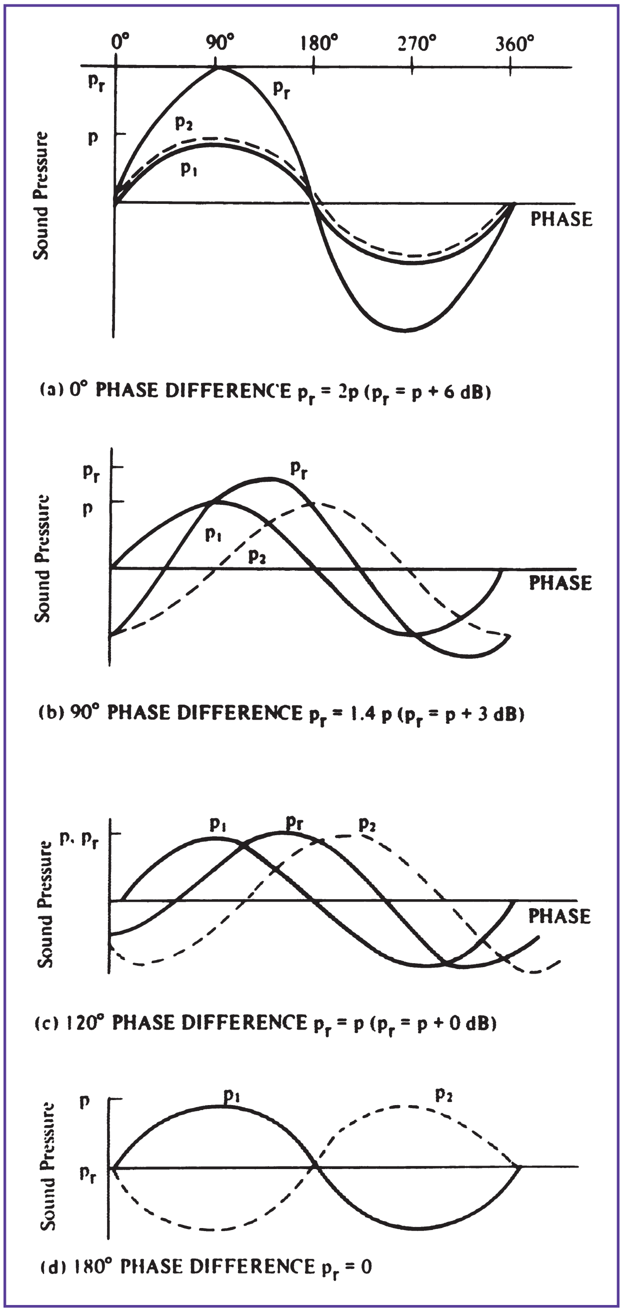

Figure 1–4. Combination of two pure tone noises (p_1 and p_2) with various phase differences.

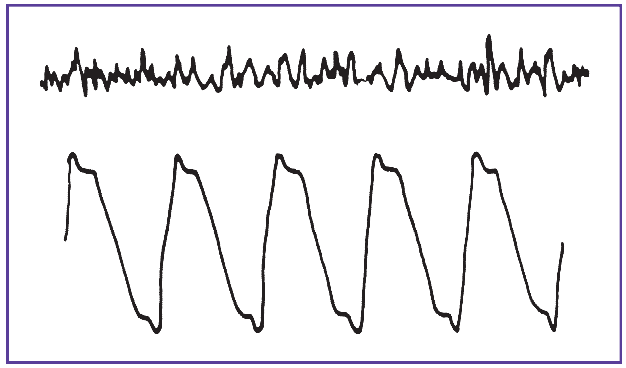

Figure 1–5. Upper graph, typical street noise. Lower graph, C on a piano.

the characteristics of the receiver (such as the ear canal and ear).

Speech, music, and noise are complex sounds rather than pure tones. Most sounds are very complex with many different wave forms superimposed on each other. Musical tones are usually related to one another and show a regular pattern (complex periodic sound), whereas street noise shows a random pattern (complex aperiodic sound) (Figure 1–5).

It is somewhat difficult to accurately define noise, because so much of its meaning depends on its effect at any specific time and place, rather than on its physical characteristics. Sound in one instance or by one individual may be considered as very annoying noise, whereas on another occasion or to another observer the same sound may seem pleasant and undeserving of being designated "noise." For the purpose of this book, the term *noise* is used broadly to designate any unwanted sound.

An interesting aspect of sound waves is a phenomenon called the standing wave. Under certain circumstances, two wave trains of equal amplitude and frequency traveling in opposite directions can cancel out at certain points called *nodes*. Figure 1–6 is a diagram of such a situation. It will be noted that when a violin string is plucked in a certain manner, at point "n" (node) there is no displacement. If this point falls at the eardrum, the listener will not be aware of any sound because the point has no amplitude and cannot excite the ear. This phenomenon occasionally occurs in hearing tests, particularly in testing at 8000 Hz and above. These higher frequencies are likely to be involved, because the ear canal is about 2.5-cm long and the wavelength of sound at such high frequencies is of the same order of magnitude. The point of maximum displacement is called the *antinode*.

Furthermore, when sound waves are produced within small enclosures, as when an earphone is placed over the ear, the sound waves encounter many reflections and much of the sound at high frequencies is likely to be in the form of standing waves. Such waves often do not serve as exciting stimuli to the inner ear, and no sensation of hearing is produced because of the absence of transmission of sound energy.

Sometimes, by simply holding the earphone a little more tightly or loosely to the ear in testing the higher frequencies, suddenly no sound may be produced at all when it should be loud, or a loud sound may be heard when a moment before there seemed to be no sound. This phenomenon occurs because of the presence of standing waves. During hearing testing, one often uses modulated or "warbled" tones to help eliminate standing wave problems that might result in misleading test results. Analogous but more complex problems may occur in acoustical environments such as concert halls.

In addition, resonant characteristics of the ear canal play a role in audition. Just like organ pipes and soda bottles, the ear may be thought of as a pipe. It is closed at one end and has a length of about 2.5 cm. Its calculated resonant frequency is approximately 3400 Hz (actually 3430 Hz if the length is exactly 2.5 cm and if the ear were really a straight pipe). At such a resonant frequency, a node occurs at the external auditory meatus (opening to the ear canal), and an antinode is present at the tympanic membrane, resulting in sound pressure amplification at the closed end of the pipe (eardrum). This phenomenon may cause sound amplification of up to 20 dB between 2000 and 5000 Hz. The resonance characteristics of the ear canal change if the open end is occluded, such as with an ear insert or muff used for hearing testing; and such factors must be taken into account during equipment design and calibration and when interpreting hearing tests.

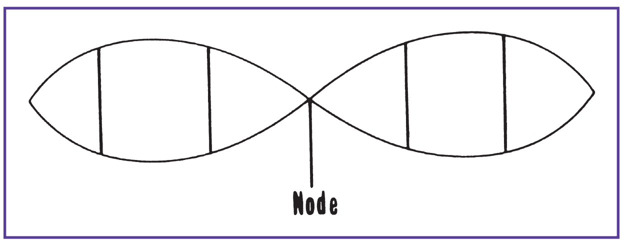

Figure 1–6. Diagram of a standing wave, showing the nodal point at which there is no amplitude.

The form of a complex sound is determined by the interaction of each of its pure tones at a particular time. This aspect of a sound is called a *complexity* and the psychological counterpart is *timbre*. This is the quality of sound that allows us to distinguish between a piano, oboe, violin, or voice, all producing a middle "C" (256 Hz). These sound sources differently combine frequencies and consequently have different qualities.

Measuring Sound

The principal components of sound that we need to measure are frequency and intensity. Both are measured with a technique called *scaling*. The frequency scale is generally familiar because it is based on the musical scale, or octave. This is a logarithmic scale with a base of 2. This means that each octave increase corresponds to a doubling of frequency (Figure 1–7). Linear increases (octaves) correspond with progressively increasing frequency units. For example, the octave between 4000 and 8000 Hz contains 4000 frequency units, but the same octave space between 125 and 250 Hz contains only 125 frequency units. This makes it much easier to deal with progressively larger numbers and helps show relationships that might not be obvious if absolute numbers were used (Figure 1–8).

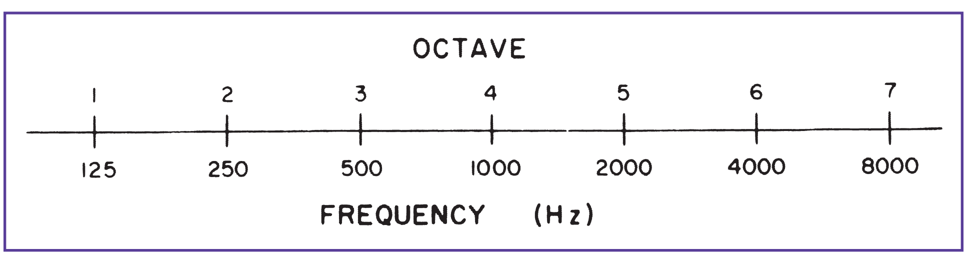

Figure 1–7. Scaling for octave notation of frequency levels.

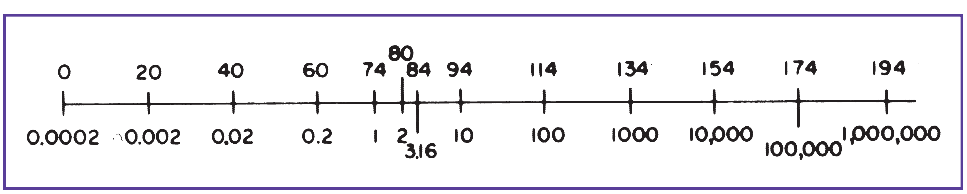

Figure 1–8. Decibel scaling (SPL). (Adapted from Lipscomb.[2])