Speech and Voice Science

THIRD EDITION

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Alison Behrman, PhD, CCC-SLP

With Contributions By Donald Finan, PhD

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Preface to the Third Edition

I have three distinct, yet interwoven, professional roles: teacher, research scientist, and clinician. This book grew out of my clinical practice. How odd, you might think, for this book is a basic science textbook written primarily for students of speech-language pathology. The role of teacher or research scientist would appear to be a more likely candidate as motivation for this book. Yet I have been struck constantly by the realization of principles of physics and physiology in my interactions with my patients. In truth, the answers for many of the clinical questions raised by speech-language pathologists can be found in the science of voice and speech production and perception. How does one address a deficit in a voice- or speech-disordered individual? Why does a therapeutic technique work for one patient and not for another?

In sum, a solid grounding in speech science makes a speech-language pathologist a better clinician. This book was motivated by my desire to provide students of speech-language pathology with a strong fund of knowledge in speech science—so that they would have this part of the necessary tools with which to become outstanding clinicians and so that they, too, could experience the delightful process of clinical inquiry, problem solving, and, yes, clinical *creativity*. For it is only with a fund of knowledge larger than the moment—greater than one accesses on a day-to-day basis—that one can truly have the freedom to be creative in therapeutic approaches and techniques.

This book is intended primarily for undergraduate and graduate students in speech-language pathology. It should also be of interest to doctoral students and to research scientists as a basic reference text. It is my hope that seasoned clinicians, too, will find this book valuable as a reference source when they encounter patients with speech and voice disorders that present therapeutic challenges.

This book addresses the physics, acoustics, and physiology of voice and speech production. An effort is made to provide a sense of history (remote and recent) and, thereby, a sense of the future direction of the field. I have tried to incorporate some interesting and even amusing notes in the shorter side boxes to help lighten some of the admittedly dense material. Other side boxes are central to understanding the content of the chapter. Printed textbooks remain quite linear in their presentation of material. Most college students, however, have become acclimated to the nonlinear information-gathering style of the Internet, and so I suspect that they will enjoy the side boxes without finding them distracting.

New to the Third Edition

Some exciting new changes have been made to this third edition. Clinical cases, with discussion questions, have been added at the beginning of Chapters 4, 5, 7, 8, and 9 and two more at the end of Chapters 7 and 8. These cases serve to emphasize to the student the clinical utility of speech and voice science and to stimulate thinking and, hopefully, some lively classroom (in-person or virtual) discussions. Discussion questions are provided at the end of each clinical case. Although each clinical case focuses upon the content of the chapter in which it occurs, information is also drawn from other chapters, with some of the discussion questions addressing topics of other chapters. Thus, instructors may find it useful to help the students reexamine each clinical case in subsequent chapters.

Two new chapters have been added to this third edition. Don Finan has provided a much-needed chapter on instrumentation (Chapter 12). It covers basic information about digital signal processing, the instrumental array, consideration of instrumental specifications, and how to obtain valid and reliable acoustic and biophysical data. It demystifies the data acquisition process while, hopefully, stimulating students to try their hand at data gathering themselves.

A new chapter on prosody (Chapter 9) has been added in response to growing interest in prosodic differences among speakers with different native language backgrounds, as well as prosodic disturbances associated with disease processes. Some of the information contained in that chapter had previously been located at the end of the chapter on consonants. Now in its own chapter, coverage of prosody has been expanded to include the acoustic properties that contribute to stress, prominence, and speech rhythm, and its clinical relevance is highlighted.

New to this third edition is the use of the PluralPlus companion website. For students, material includes study aids such as key terms and review questions for each chapter (except for Chapter 1) and a speech science version of a game called Taboo—a lighthearted way to help students study. After all, speech science should be fun (at least a little). For instructors, suggestions for classroom learning activities and lab assignments using free, downloadable acoustic analysis software are offered to provide more effective learning experiences for both undergraduate and graduate students. Revised and updated slides are provided for traditional classroom lectures, and responses to the clinical case questions are provided to help guide classroom discussions or testing.

Reorganization of the introductory material provides a new chapter (Chapter 2) on the physics of motion. This chapter appeared in the first edition and then mysteriously disappeared in the second addition. It has been brought back due to popular demand.

How to Use This Book

The curriculum for speech and voice science varies considerably at the undergraduate and graduate levels across university programs. As such, this book offers some flexibility for faculty. The order of the chapters is organized for a full course in undergraduate speech science. The basic physics of sound (Chapters 2 and 3) lays the groundwork for the students' understanding of speech and voice production. Subsequent chapters mirror somewhat the process of speech production—the respiratory, phonatory, resonatory, and articulatory subsystems (Chapters 3 through 8)—and the interplay of those subsystems in prosody (Chapter 9). Once the students have that basic understanding of speech and voice production, they are ready to ponder the theories of speech production and perception (Chapters 10 and 11).

The chapters on voice production (Chapter 5 and 6) are quite in-depth, and the content may be beyond what some instructors need for (or have time in) an undergraduate course in speech science. The chapters are designed such that the more advanced information on phonatory biomechanics and measurement can easily be omitted. And these two chapters work well as part of the curriculum of a graduate-level course in voice disorders.

Don Finan's excellent new chapter on instrumentation (Chapter 12) can be used in several ways. Some instructors may want to cover this chapter early in the semester, after Chapters 2 and 3, to prepare students for discussion of the instrumentation sections at the end of Chapters 4 through 8. Other instructors may prefer to address the topic in the order in which it is presented in the book, so that students have a basic knowledge of speech and voice production within which to explore the gathering of instrumental data. The chapter was written to work well with either of these approaches. The chapter also stands well on its own as a reference for graduate- and doctoral-level students who are conducting research.

Chapters 4, 5, 7, and 8 each contain a short review of the relevant anatomy. It is presumed that students will have taken a course in anatomy and physiology of the speech mechanism or are taking that course concomitant with speech science. Therefore, here, the anatomy is presented as a refresher for students and for easy reference, rather than at a level of detail expected for novel learning of the material. The anatomy sections also serve to highlight some important anatomical features that prepare the students for the subsequent speech and voice science topics.

For Chapters 1 through 11, I have used "we" throughout this book in lieu of "I" even though the chapters were largely sole authored. The reason for the plural pronoun is that the knowledge and authority with which I wrote those chapters is drawn from a legion of speech and voice scientists who have contributed the vast amount of data upon which this book is based. They have done all the good cooking. I am just carrying it to the table.

As always, I welcome comments, criticisms, and suggestions for changes to future editions to keep this textbook as useful as possible for instructors and students. You can find me at Alison.Behrman@lehman.cuny.edu

Acknowledgments

Many individuals contributed to the creation of the three editions of this textbook, and without them this project would never have come to fruition. I am quite indebted to the following people:

To Donald Finan, who contributed a fabulous chapter on instrumentation to this third edition.

To Maury Aaseng, whose delightful illustrations bring alive the book.

To Andrew Pancila, who revised the spectrograms in Chapter 8 to make them more legible for this third edition.

To Karen J. Kushla, who provided helpful editing on some of the hearing science topics in Chapters 3 and 11.

To Philip Doyle, James and Zaida McDonough, and Sarah Sheridan, whose thoughtful commentary on the first edition made this book more readable.

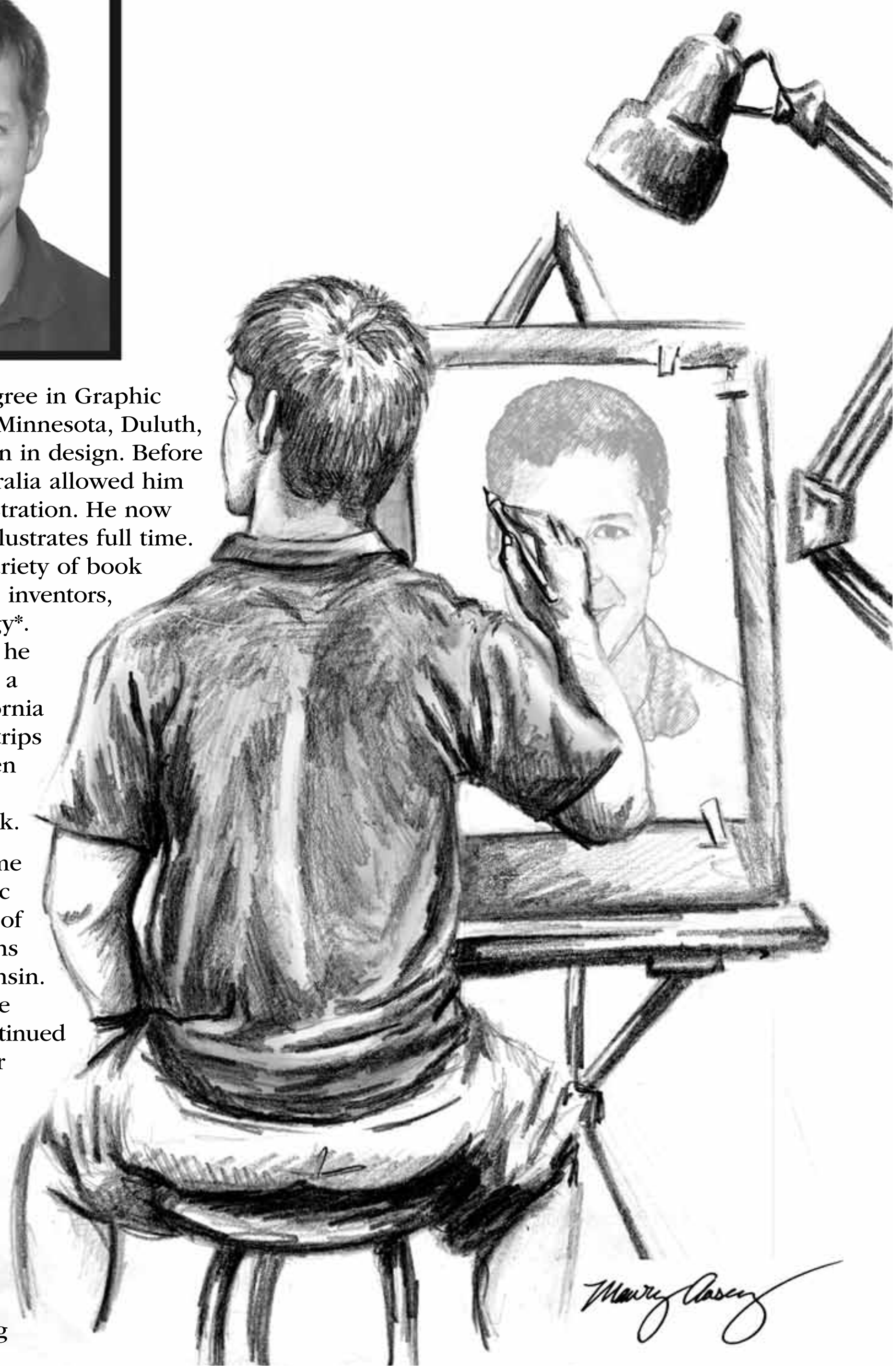
To my students across the years, who inspire and teach me, perhaps more than I teach them.

And a large thank you to the Plural Publishing family (some of whom, sadly, are no longer with us): Angie and Sadanand Singh, Sandy Doyle, Valerie Johns, Kalie Koscielak, and Linda Shapiro.

About the Contributor

Donald Finan, PhD, is a Professor in the Audiology and Speech-Language Sciences program at the University of Northern Colorado. He is a speech scientist with a background that encompasses speech-language pathology and audiology, speech physiology, neuroscience, and instrumentation. His research interests include the measurement of noise in relation to auditory exposure, normal speech motor control over the lifespan, the use of technology in clinical and research settings, and the development of original tools and pedagogies for speech science instruction. Dr. Finan is the co-developer of the innovative course Musical Acoustics and Health Issues taught at the University of Northern Colorado. In this course, students explore acoustics by constructing cigar box guitars and PVC pipe didgeridoos, among other hands-on projects related to the speech and hearing sciences. Dr. Finan is the inaugural Coordinator of ASHA's Special Interest Group 19, Speech Science, and he moderates the Facebook page "Speech Science Toolbox" (https://www.facebook.com/SpeechScienceToolbox/) where resources for teaching speech science are shared.

About the Illustrator



Maury Aaseng received his degree in Graphic Design from the University of Minnesota, Duluth, with an emphasis on illustration in design. Before graduation, a semester in Australia allowed him to focus on exotic wildlife illustration. He now lives in San Diego, where he illustrates full time. He has created images for a variety of book topics, such as diseases, nature, inventors, forensics, and speech pathology*. In addition to book illustration, he makes custom paintings and is a member of the Southern California Cartoonists Society. His many trips to the San Diego Zoo have been the inspiration behind his zoo-themed comic strip, Nolan's Ark.

Aaseng enjoys spending his time outdoors, and is an enthusiastic naturalist. Drawing and a love of animals developed into passions during his childhood in Wisconsin. Frequent camping trips into the California countryside have continued to fuel both interests. His other hobbies include SCUBA and snorkeling, bowling, reading, and biking.

*Note: This is definitely the first book he's illustrated such complex ideas as a punk rocker's tongue, a pig talking on a cell phone, and the uncontrollable, maddening craving for toast.

3

Sound Waves

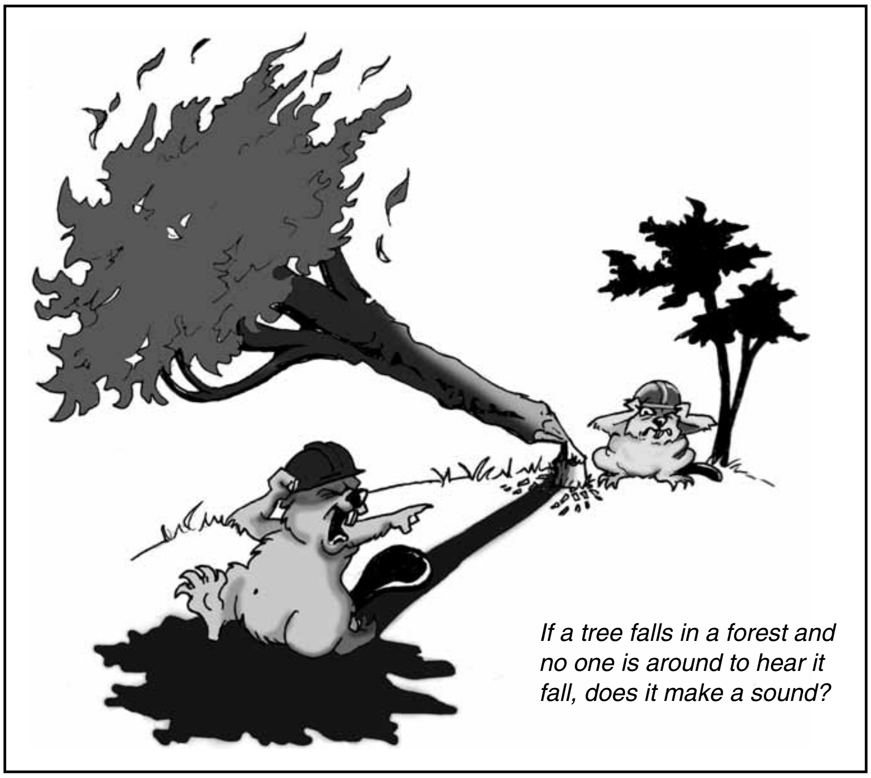


Figure 3–1. If a tree falls in a forest and no one is around to hear it fall, does it make a sound?

Mr. Watson - come here - I want to see you.
The first audible words spoken over the telephone.

—Alexander Graham Bell, Scottish Inventor of the telephone and audiometer, among many other inventions (1847–1922)

Does a tree falling in the forest create a sound if no one is around to hear it fall? We shall leave that oft-debated question to the philosophy classes; however, as speech-language pathologists, we will define sound as a pressure wave that is audible to the human ear with normal auditory sensitivity. The nature of that pressure wave, its production and perception, are the heart of the content of this textbook and, indeed, the heart of clinical speech-language pathology. And so the sound wave bears closer examination.

3.1 Vibration

What is vibration? At its most simple, **vibration** (**oscillation**) is a back-and-forth motion. Pretend you have a small ball attached to a spring suspended from a bar. The ball has a certain mass (a measure of the quantity of its matter), and we refer to this setup as a mass-spring system. Initially, the ball will stretch the spring to a point where it will sit quietly at rest, suspended on the spring. The ball-spring system is then said to be at **equilibrium**. When not disturbed by an outside force, the ball will maintain this rest position. We know this fact because Newton's first law of motion tells us so. If the spring is distorted by some agent pulling it downward and then releasing it, the mass and spring will immediately recoil upward. Why? Because Newton's third law of motion tells us that a force will act upon the system equally and opposite to the initial downward distortion. The potential energy that is built up in the system by the downward pull will be released as kinetic energy in the upward movement. The force that causes the mass-spring system to be restored to its prior, undistorted position is called a **restorative force**. The initial force that caused the mass-spring system to move from its position of equilibrium can be referred to as a **displacement force**. When the system is undisturbed at rest, it is at equilibrium, which means that the net restoring forces acting upon it are zero. The greater the displacement force, the greater proportionately the restorative force. Stretch the spring a little and the force that acts to restore the mass to equilibrium is small. Displace the spring a great deal, and the restorative force is large. (Displace the mass too much and the spring breaks—a special situation we will ignore.)

Now we know that if the mass is displaced by pulling on the spring, it will not simply move back to its initial rest position and stop. If an object is distorted and then released, elastic restorative forces accelerate the mass upward toward its equilibrium position (Figure 3–2). As the mass approaches equilibrium, the net restoring force decreases, and eventually when the mass reaches equilibrium, the net restoring force is zero. But why does the mass not stop at that point? Why does it maintain its upward trajectory? Inertial forces cause the mass to continue moving upward. Remember that inertia is the tendency of an object to resist change in movement. And we know that the momentum of an object is a product of its mass and acceleration. Thus, inertia causes the mass to overshoot the equilibrium position and continue moving upward. As the mass continues to overshoot equilibrium (that is, the negative displacement is increasing), the restorative force increases. The increasing restorative force acts to slow the upward movement of the mass—the restorative force acts to decelerate the mass. Finally, it stops at its topmost point and is pulled back toward equilibrium. However, the inertia of the displaced mass causes it to overshoot the rest position and distort in the opposite direction. Again, elastic restorative forces cause the mass to return to its original position. And again, the inertia of this second displacement causes the object to overshoot the rest position and distort in the initial direction. This cycle of vibration continues to repeat itself. However, frictional forces (forces that oppose movement) will cause the vibration to lose energy with each cycle, unless an outside force provides energy, and eventually the mass will stay in its rest position (Figure 3–3).

3.2 The Nature of Waves

Speech is composed of sound waves, which is why we spend so much time studying waves.

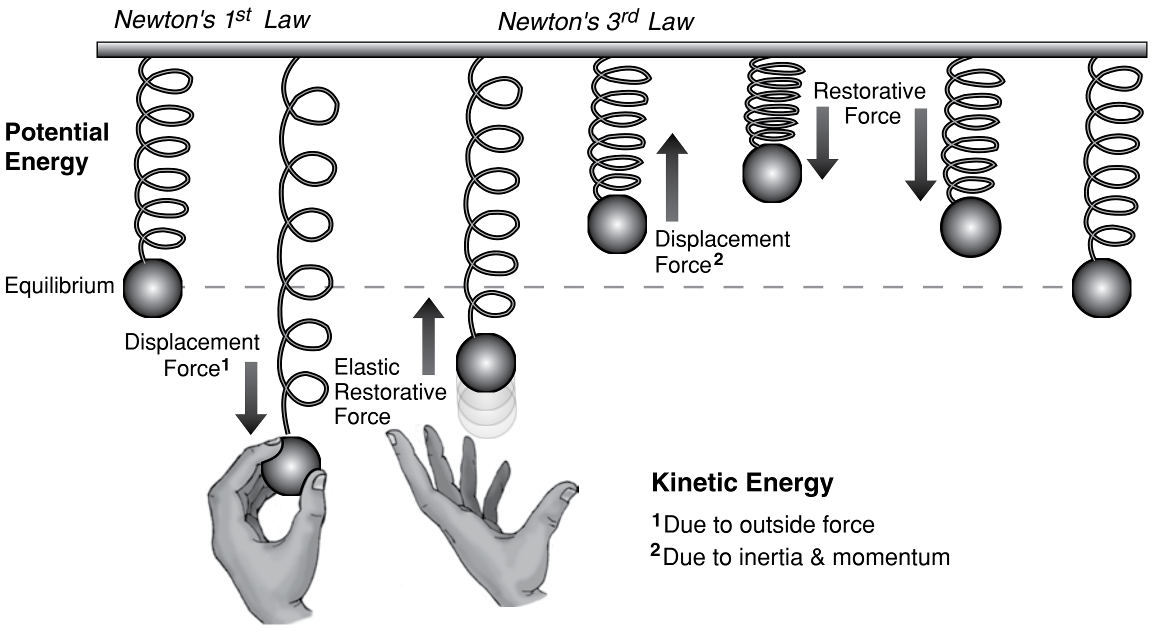


Figure 3–2. A description of vibration.

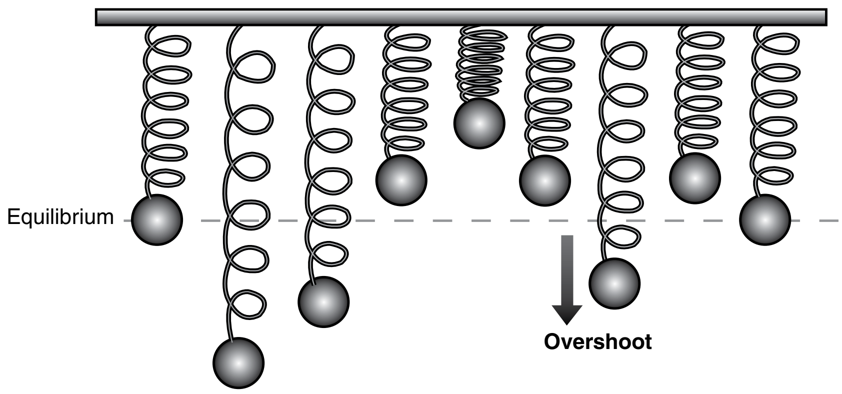


Figure 3–3. Frictional forces will cause the vibration to lose energy with each cycle, unless an outside force provides energy, and eventually the mass will stay in its rest position.

Waves are all around us, more ubiquitous probably than most people realize. Waves are composed of vibrations that move energy from Point A to Point B without actually moving an object or material from A to B. How is this so?

Waves are created by a disturbance. A wave is a disturbance that travels through a medium, transporting energy from one location to another. The medium is the material through which the wave passes; it is that which carries or transports the wave. Throwing a stone into a pond causes waves. The stone (and the force with which it has been thrown) is the disturbance, and the medium that transports the disturbance is water. The medium is simply a series of interconnected particles that interact with one another. The particles of the water wave are the water molecules. Say hello to your friend and your friend hears you because of the sound wave you produced. Your vocal folds created the disturbance (much more about that later). The medium that transports the disturbance is air. The particles of air that interact with one another to carry the energy of your "hello" to your friend are the air molecules. In old-time western movies, the cowboy would put his ear against the railroad track to feel for bilabials are produced with both lips coming together to occlude the airway, as in /p, b, m/. The labiodental consonants are produced with the lower lip against the upper front teeth, as in /f, v/. The dental consonants are produced with the tongue tip or tongue blade against the upper front teeth, as in the sounds /θ, ð/. The alveolar consonants are produced with the tongue blade against the back of the alveolar ridge, as in /t, d/. Some speakers place the tip of the tongue behind the lower front teeth and others place it up near the alveolar ridge. However, the tongue blade is always placed at or behind the alveolar ridge for alveolar sounds. Palatal consonants are produced with the tongue blade against the hard palate, as in the sound /ʃ, ŋ, j/. Velar consonants are produced with the back of the tongue against the soft palate, as in /k, g/. The retroflex consonant /r/ can be produced with the back of the tongue against the alveolar ridge. A significant amount of variability, however, exists with the retroflex sound among different speakers. American English has only one pharyngeal fricative, the /h/, which is sometimes classified as a glottal sound.

Manner of Articulation

The manner of articulation refers to the degree of constriction in the vocal tract and its effect upon the airflow. The constriction may be transiently complete, in which case the airflow is fully stopped momentarily, such as occurs for **stops** (synonymously, **plosives**, in American English) and **affricates**. The constriction may be incomplete, such that the airflow is impeded to a greater or lesser extent, either for a short duration or for a relatively long period (long relative to the production of phonemes within running speech). When the constriction is incomplete and airflow continues, the consonant is said to be a **continuant**. The continuants include fricatives, glides, liquids, and nasals. Table 8–1 lists the consonants of American English by place, manner of articulation, and voicing.

Table 8–1. The Consonants of American English, Organized by Manner and Place of Articulation and Presence (+V) or Absence (–V) of Voicing

	Labial		Labiodental		Dental		Alveolar		Palatal		Velar		Pharyngeal or Glottal	
	–V	+V	–V	+V	–V	+V	–V	+V	–V	+V	–V	+V	–V	+V
Stops	p	b					t	d			k	g		
Fricatives			f	v	θ	ð	s	z	ʃ	ʒ			h	
Affricates									tʃ	dʒ		ŋ		
Nasals		m						n						
Liquids lateral								l						
Liquid retroflex								r						
Glides (semi-vowels)		w								j				

Study Questions

1. Distinguish an upstream constriction from a downstream constriction in the vocal tract.
2. Identify the three sources of speech sounds and the types of sound waves generated by these sources.
3. Define anticipatory and retentive coarticulation.
4. Traditionally, consonants are identified by three features. Name them.
5. What are the articulatory points of contact that identify place of articulation? Provide an example of each. Which points specify tongue contact and which do not?
6. To what does manner of articulation refer? List the seven manners of articulation and provide an example of each.
7. Which manners of articulation are considered continuants? Why?

8.4 Acoustic Representation of Consonants

Stops

In the **stop**, **or plosive**, a complete constriction of the vocal tract occurs, causing cessation of the airflow. Upon release of the constriction, the airflow resumes in a burst of sound. (Think of an explosion of escaping air; hence "plosive.") The bilabial, alveolar, and velar stops, in the voiceless and voiced cognate pairs, are /p, b/, /t, d/ and /k, g/, respectively (Figures 8–4 and 8–5). The stop consonants are complex sounds with many allophonic variations. No single, invariant (always present) set of acoustic features exists to alert the listener to stop production. Four acoustic cues are important for perception of the stop: the silence, the burst noise, the voice onset time, and the poststop vowel formant transition. These features are each discussed below.

Stop Gap

Silence, also called the **stop gap**, occurs during production of the plosive prior to release of the airflow (Figures 8–4, 8–5, and 8–6). For the voiceless stops /p, t, k /, complete silence occurs momentarily. For the voiced stops /b, d, g/, vocal fold vibration may continue through part or all of the stop, producing a low-amplitude sound. Recall from Chapter 4 that vocal fold vibration can occur only in the presence of a transglottal pressure drop. On complete closure of the vocal tract during stop production, the supraglottal pressure will quickly equilibrate to the lung pressure, at which time phonation will cease. During running speech, the duration of the voiced stop is often short enough that the supraglottal pressure never reaches the same level as the lung pressure. In that case, the voicing continues throughout the closed portion of the voiced stop. In other cases, however, pressure equilibration occurs and the voicing ceases prior to release of the stop. The presence of voicing during the closed portion often is referred to as the **voice bar**, as indicated in the spectrogram in Figure 8–5. The voiced sound produced during the closed portion of the stop, however, is substantially damped by the vocal tract, and so it is a low-energy, soft sound. The waveforms in Figures 8–4 through 8–6 show the low-amplitude sound pressure corresponding in time to the voice bar in the spectrogram.

Release Burst

A brief transient burst noise occurs upon release of the occlusion and the impounded air. (This is the "pop" sound you often hear when someone is speaking into a microphone and has held the microphone too close to the mouth.) During

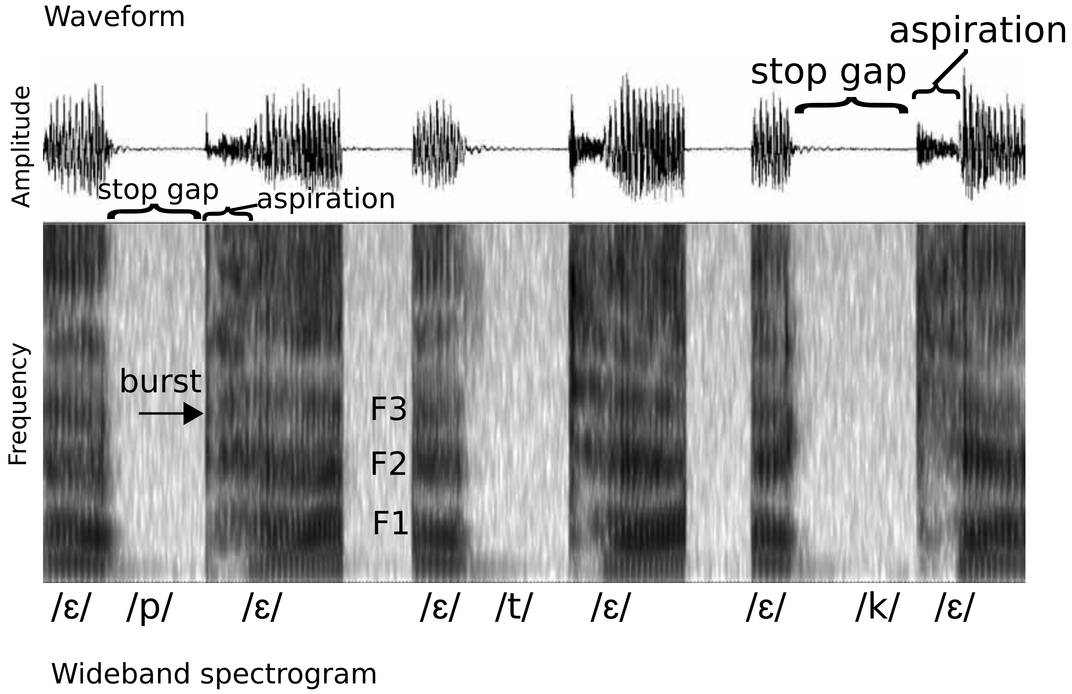


Figure 8–4. Acoustic features of the voiceless stops.

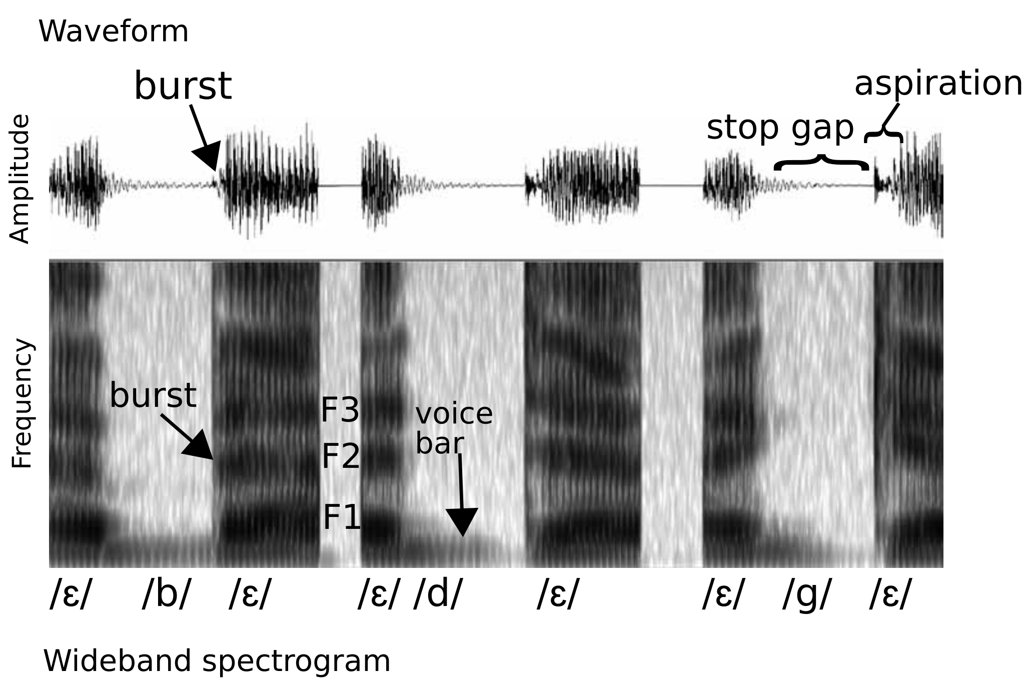


Figure 8–5. Acoustic features of the voiced stops.

9

Prosody

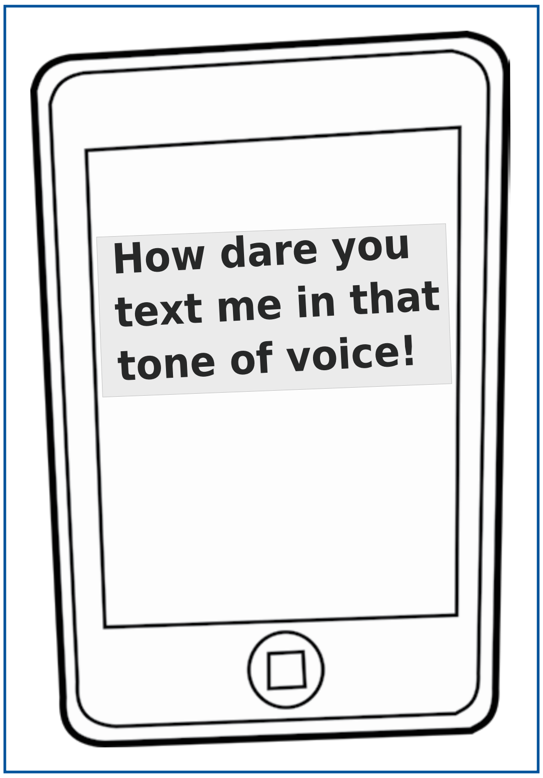


Figure 9–1

I've always felt, even as a songwriter, that the rhythm of speech is in itself a language for me.
—Cyndi Lauper, American singer-songwriter (1953–)

Clinical Case 7: Parkinson's Disease

Clinical cases are based upon real patients whom the author has treated. Evaluation and treatment information has been edited to focus upon specific features related to the chapters. Note that clinical cases incorporate information that is covered in this and other chapters (and some information about diagnosis and therapy that you will learn in future courses). You are encouraged to review this case before you begin your study of this chapter and once again after you have completed the chapter. You may also want to revisit this case later in the semester after you have covered additional chapters.

Cheung is a 74-year-old retired lawyer. He is fully bilingual (Mandarin/English), having specialized in international Chinese American import-export law. He speaks in both Mandarin and English with his wife and adult sons. He is trying to teach his two grandchildren Mandarin, although they don't show much interest in learning it. Cheung was diagnosed with Parkinson's disease 2 years ago, a neurological disorder of the basal ganglia that causes tremors, rigidity, slowness of movement, and impaired sensory (and often cognitive) perception. He takes medication to control the symptoms, and he participates in daily physical activity (walking, riding a stationary bicycle), as recommended by his neurologist, to maintain flexibility and strength. However, recently his wife and children have complained that his speech is difficult to understand and that he mumbles and speaks too quietly. Cheung's wife reported that his speech in Mandarin was even harder to understand than his English, which she attributed to his lack of tone variation. (Mandarin is a tonal language and therefore variation in tone is essential to meaning.) Cheung's neurologist recommended a speech-voice evaluation and therapy to minimize the effects of Parkinson's disease on Cheung's speech and to maintain maximum intelligibility.

The speech-voice evaluation revealed consistently reduced intensity, delayed onset of utterances within conversational context, reduced articulatory precision, and excessive coarticulation. Prosody was moderately impaired, with decreased f_o and intensity contours, and decreased phrasal prominence. Speech rhythm was characterized by increasing rate of speech over the course of an utterance, with increased pause time at phrase endings. Upon questioning, Cheung denied speech problems and attributed his wife and children's complaints to lack of effort to listen carefully to him. Overall, speech intelligibility was moderately impaired. Stimulability testing for increased intensity and prosodic variation revealed small improvement, but significant cueing was required.

The SLP conducting the evaluation knew that Cheung's speech deficits were characteristic of people with Parkinson's disease. Denial of speech problems was also a common occurrence associated with the neurological deficits of the disease. A course of speech-voice therapy was initiated, focusing upon increased speech intensity and articulatory precision and decreased rate of speech, together with increasing Cheung's awareness of the need to use significantly greater effort to speak loudly and clearly. Increased depth of preutterance inhalation and increased opening of the mouth during speech were used to help Cheung increase speech intensity. To help Cheung improve his prosody in English, the SLP prepared phrases that were relevant to his daily activities and asked him to select the most important word in the phrase and then use greater intensity for that word, even while maintaining increased intensity for the entire phrase. (In other words, speaking loudly for the whole phrase and even louder for the most important word.) The SLP did not know Mandarin. However, to help him increase his intelligibility in Mandarin, he invited Cheung's wife to participate in the therapy. Using a list of Mandarin words, Cheung was instructed to exaggerate tonal changes, while his wife reported on the accuracy of the words. After 1 month of twice-weekly therapy, Cheung demonstrated significantly increased self-monitoring skills, and his wife and children reported that his speech was significantly easier to understand in both languages.

Clinical Case Discussion Questions

1. What key features of prosody did the SLP address with Cheung in Mandarin and English? Which prosodic features were not addressed?
2. Explain the differences in the prosody approach used by the SLP for Mandarin and English. (Be aware of the difference between f_o contour, word stress, and phrase prominence.)
3. What is the relationship between intensity, increased depth of inhalation, and increased mouth opening (see Chapters 5 and 7)?
4. How is the acoustic theory of speech production relevant to Cheung's speech-voice deficit?

9.1 Introduction to Prosody

Email and text are efficient methods of communication—most of the time. But we have all had the experience of being misinterpreted in both media. Humor, sarcasm, anomalous sentences, and subtleties of interpretation are difficult to transmit to the "listener" because we communicate these features beyond the phonetic level of written characters. Thus, we often resort to emoticons, the pictorial representation of a facial expression, such as the happy face or punctuation such as :). Emoticons represent not only facial expression, however; they also represent, although not always effectively, the expressiveness in our speech that transmits our intent. Such expressiveness is the topic of prosody.

The vowels and consonants that we have been considering over the course of the previous chapters are speech segments, which form the nuclei and boundaries of syllables. The syllables, in turn, are grouped together to build an utterance. The utterance can be composed of a single syllable (as in "No!") or a longer grouping that comprises a fully grammatical sentence. From an acoustic viewpoint, the meaning of the utterance is communicated at two broad levels. One level is the phoneme, the smallest meaningful segment, and the coarticulation of combinations of phonemes. The other level of meaning is carried by features that are *superimposed* upon the segments. In other words, the intent of the utterance is communicated both at the segmental and the suprasegmental level. The **suprasegmental level** or, synonymously, **prosody** is defined by Sanderman and Collier (1996) as "the ensemble of phonetic properties that do not enter into the definition of individual speech sounds" (p. 321). For ease of reference throughout this chapter, we use the term prosody.

The segmental features of vowels and consonants discussed in Chapters 7 and 8 are inherent characteristics of the phonemes, either in isolation or due to coarticulatory effects. Prosodic features, in contrast, are defined by their relative values to one another. For example, the segmental acoustic feature of voice onset time for /bit/ can be measured meaningfully without reference to the voice onset time of another voiced plosive. In contrast, the meaning, or communicative function, of the amount of stress (a prosodic feature we have yet to define) that the speaker places upon the plosive, as in, "I said beet, not Pete!" can be interpreted meaningfully only in comparison to another segment within the phrase. In this chapter, we consider the ways in which meaning is communicated through prosody and the acoustic manifestation of prosody.