

PRECLINICAL SPEECH SCIENCE

PRECLINICAL SPEECH SCIENCE

Anatomy, Physiology, Acoustics, and Perception

THIRD EDITION

**Thomas J. Hixon
Gary Weismer
Jeannette D. Hoit**





5521 Ruffin Road
San Diego, CA 92123

e-mail: info@pluralpublishing.com
website: <http://www.pluralpublishing.com>

Copyright © 2020 by Plural Publishing, Inc.

Typeset in 10/12 Palatino by Flanagan's Publishing Services, Inc.
Printed in South Korea through Four Colour Print Group

All rights, including that of translation, reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, recording, or otherwise, including photocopying, recording, taping, Web distribution, or information storage and retrieval systems without the prior written consent of the publisher.

For permission to use material from this text, contact us by
Telephone: (866) 758-7251
Fax: (888) 758-7255
e-mail: permissions@pluralpublishing.com

Every attempt has been made to contact the copyright holders for material originally printed in another source. If any have been inadvertently overlooked, the publishers will gladly make the necessary arrangements at the first opportunity.

Library of Congress Cataloging-in-Publication Data

Names: Hixon, Thomas J., 1940-2009, author. | Weismer, Gary, author. | Hoit, Jeannette D. (Jeannette Dee), 1954- author.
Title: Preclinical speech science : anatomy, physiology, acoustics, and perception / Thomas J. Hixon, Gary Weismer, Jeannette D. Hoit.
Description: Third edition. | San Diego, CA : Plural Publishing, [2020] | Includes bibliographical references and index.
Identifiers: LCCN 2018018596 | ISBN 9781635500615 (alk. paper) | ISBN 1635500613 (alk. paper)
Subjects: | MESH: Speech--physiology | Speech Perception | Speech Disorders | Respiratory System--anatomy & histology
Classification: LCC QP306 | NLM WV 501 | DDC 612.7/8--dc23
LC record available at <https://lcn.loc.gov/2018018596>

Contents

PREFACE	xix
ACKNOWLEDGMENTS	xxi
REVIEWERS	xxiii
1 INTRODUCTION	1
Focus of the Book	1
Domain of Preclinical Speech Science	1
Levels of Observation	1
Subsystems of Speech Production and Swallowing	3
Applications of Data	4
Domain of Preclinical Hearing Science	4
Levels of Observation	4
Subsystems of the Auditory System	5
Applications of Data	6
Review	7
2 BREATHING AND SPEECH PRODUCTION	9
Introduction	9
Anatomy of the Breathing Apparatus	9
Skeletal Framework	9
Breathing Apparatus and Its Subdivisions	10
<i>Pulmonary Apparatus</i>	10
<i>Chest Wall</i>	12
<i>Pulmonary Apparatus–Chest Wall Unit</i>	12
Forces of Breathing	13
Passive Force	13
Active Force	14
<i>Muscles of the Rib Cage Wall</i>	14
<i>Muscle of the Diaphragm</i>	17
<i>Muscles of the Abdominal Wall</i>	17
Summary of Passive and Active Forces	20
Realization of Passive and Active Forces	22
Movements of Breathing	22
Movements of the Rib Cage Wall	22
Movements of the Diaphragm	23
Movements of the Abdominal Wall	25
Relative Movements of the Rib Cage Wall and Diaphragm–Abdominal Wall	25
Forces Underlying Movements	25
Control Variables of Breathing	27
Lung Volume	27
Alveolar Pressure	28

Chest Wall Shape	31
Neural Control of Breathing	34
Control of Tidal Breathing	34
Control of Special Acts of Breathing	36
Peripheral Nerves of Breathing	37
Ventilation and Gas Exchange During Tidal Breathing	38
Breathing and Speech Production	40
Extended Steady Utterances	40
Running Speech Activities	44
Variables That Influence Speech Breathing	49
Body Position	49
<i>Extended Steady Utterances in the Supine Body Position</i>	50
<i>Running Speech Activities in the Supine Body Position</i>	52
<i>Speech Breathing in Other Body Positions</i>	54
Body Type	55
Age	55
Sex	57
Ventilation and Drive to Breathe	57
Cognitive-Linguistic and Social Variables	58
Review	59
References	60

3 LARYNGEAL FUNCTION AND SPEECH PRODUCTION	63
Introduction	63
Anatomy of the Laryngeal Apparatus	63
Skeletal Framework	63
<i>Thyroid Cartilage</i>	63
<i>Cricoid Cartilage</i>	64
<i>Arytenoid Cartilages</i>	65
<i>Epiglottis</i>	66
<i>Hyoid Bone</i>	66
Laryngeal Joints	66
<i>Cricothyroid Joints</i>	68
<i>Cricoarytenoid Joints</i>	69
Internal Topography	72
<i>Laryngeal Cavity</i>	72
<i>Vocal Folds</i>	72
<i>Ventricular Folds</i>	75
<i>Laryngeal Ventricles</i>	75
<i>Ligaments and Membranes</i>	75
Forces of the Laryngeal Apparatus	77
Intrinsic Laryngeal Muscles	78
Extrinsic Laryngeal Muscles	82
Supplementary Laryngeal Muscles	83
<i>Infrahyoid Muscles</i>	83
<i>Suprahyoid Muscles</i>	85
Summary of the Laryngeal Muscles	85
Movements of the Laryngeal Apparatus	86
Movements of the Vocal Folds	86
<i>Vocal Fold Abduction</i>	86

<i>Vocal Fold Adduction</i>	87
<i>Vocal Fold Length Change</i>	89
Movements of the Ventricular Folds	89
Movements of the Epiglottis	91
Movements of the Laryngeal Housing	91
Control Variables of Laryngeal Function	91
Laryngeal Opposing Pressure	92
Laryngeal Airway Resistance	92
Glottal Size and Configuration	93
Stiffness of the Vocal Folds	94
Effective Mass of the Vocal Folds	95
Neural Substrates of Laryngeal Control	95
Laryngeal Functions	97
Degree of Coupling Between the Trachea and Pharynx	97
Protection of the Pulmonary Airways	98
Containment of the Pulmonary Air Supply	98
Sound Generation	98
Laryngeal Function in Speech Production	98
Transient Noise Production	99
Sustained Turbulence Noise Production	99
Sustained Voice Production	100
<i>Vocal Fold Vibration</i>	101
<i>Fundamental Frequency</i>	104
<i>Sound Pressure Level</i>	106
<i>Fundamental Frequency–Sound Pressure Level Profiles</i>	107
<i>Spectrum</i>	107
<i>Voice Registers</i>	108
Running Speech Activities	111
<i>Fundamental Frequency</i>	111
<i>Sound Pressure Level</i>	112
<i>Spectrum</i>	113
<i>Articulation</i>	113
Variables that Influence Laryngeal Function During Speech Production	113
Age	113
Sex	116
Review	118
References	119
4 VELOPHARYNGEAL-NASAL FUNCTION AND SPEECH PRODUCTION	127
Introduction	127
Anatomy of the Velopharyngeal-Nasal Apparatus	127
Skeletal Framework	127
Pharynx	130
Velum	132
Nasal Cavities	133
Outer Nose	134
Forces of the Velopharyngeal-Nasal Apparatus	135
Muscles of the Pharynx	135
Muscles of the Velum	139
Muscles of the Outer Nose	142

Movements of the Velopharyngeal-Nasal Apparatus	143
Movements of the Pharynx	143
Movements of the Velum	144
Movements of the Outer Nose	145
Control Variables of Velopharyngeal-Nasal Function	145
Velopharyngeal-Nasal Airway Resistance	145
Velopharyngeal Sphincter Compression	146
Velopharyngeal-Nasal Acoustic Impedance	147
Neural Substrates of Velopharyngeal-Nasal Control	148
Velopharyngeal-Nasal Functions	149
Coupling Between the Oral and Nasal Cavities	149
Coupling Between the Nasal Cavities and Atmosphere	150
Ventilation and Velopharyngeal-Nasal Function	151
Nasal Valve Modulation	151
Nasal Cycling (Side-to-Side)	152
Nasal-Oral Switching	152
Velopharyngeal-Nasal Function and Speech Production	152
Sustained Utterances	152
Running Speech Activities	154
Variables that Influence Velopharyngeal-Nasal Function	156
Body Position	156
Age	157
Sex	159
Review	160
References	161
5 PHARYNGEAL-ORAL FUNCTION AND SPEECH PRODUCTION	165
Introduction	165
Anatomy of the Pharyngeal-Oral Apparatus	165
Skeletal Framework	165
<i>Maxilla</i>	165
<i>Mandible</i>	166
<i>Temporomandibular Joints</i>	167
Internal Topography	170
<i>Pharyngeal Cavity</i>	170
<i>Oral Cavity</i>	170
<i>Buccal Cavity</i>	172
<i>Mucous Lining</i>	172
Forces of the Pharyngeal-Oral Apparatus	172
Muscles of the Pharynx	172
Muscles of the Mandible	173
Muscles of the Tongue	175
Muscles of the Lips	178
Movements of the Pharyngeal-Oral Apparatus	182
Movements of the Pharynx	183
Movements of the Mandible	183
Movements of the Tongue	184
Movements of the Lips	184
Control Variables of Pharyngeal-Oral Function	186
Pharyngeal-Oral Lumen Size and Configuration	186

Pharyngeal-Oral Structural Contact Pressure	188
Pharyngeal-Oral Airway Resistance	188
Pharyngeal-Oral Acoustic Impedance	189
Neural Substrates of Pharyngeal-Oral Control	190
Pharyngeal-Oral Functions	191
Degree of Coupling Between the Oral Cavity and Atmosphere	191
Chewing and Swallowing	191
Sound Generation and Filtering	191
Speech Production: Articulatory Descriptions	192
Vowels	192
<i>Place of Major Constriction</i>	192
<i>Degree of Major Constriction</i>	194
<i>Lip Rounding</i>	194
Diphthongs	194
Consonants	194
<i>Manner of Production</i>	195
<i>Place of Production</i>	195
<i>Voicing</i>	195
Speech Production Stream: Articulatory Processes	195
Coarticulation	196
Traditional Theory of Coarticulation (Feature Spreading)	196
Problems with the Traditional Theory of Coarticulation	200
Articulatory Phonology or Gesture Theory	200
Variables That Influence Pharyngeal-Oral Function	202
Age	202
Sex	206
Review	207
References	208
6 SPEECH PHYSIOLOGY MEASUREMENT AND ANALYSIS	213
Introduction	213
Measurement and Analysis of Breathing	213
Spirometry	213
Chest Wall Surface Tracking	215
Manometry	218
Measurement and Analysis of Laryngeal Function	219
Endoscopy	219
Electroglottography	222
Aeromechanical Observations	224
Measurement and Analysis of Velopharyngeal-Nasal Function	227
Nasendoscopy	227
Aeromechanical Observations	227
Measurement and Analysis of Pharyngeal-Oral Function	230
Structural and Functional Imaging	230
<i>X-Ray Imaging</i>	230
<i>Magnetic Resonance Imaging</i>	231
<i>Ultrasonic Imaging</i>	232
Articulatory Tracking	232
<i>X-Ray Microbeam Imaging</i>	232
<i>Electromagnetic Sensing (Articulography)</i>	234

<i>Optoelectronic Tracking</i>	234
<i>Electropalatographic Monitoring</i>	235
Aeromechanical Observations	235
Health Care Professionals and Clinical Measurements	237
Review	240
References	241
7 ACOUSTICS	247
Introduction	247
Pressure Waves	247
The Motions of Vibrating Air Molecules Are Governed by Simple Forces	247
The Motions of Vibrating Air Molecules Change the Local Densities of Air	250
Pressure Waves, Not Individual Molecules, Propagate Through Space and Vary as a Function of Both Space and Time	250
The Variation of a Pressure Wave in Time and Space Can Be Measured	251
<i>Temporal Measures</i>	251
<i>Spatial Measures</i>	254
<i>Wavelength and Direction of Sound</i>	255
Pressure Waves: A Summary and Introduction to Sinusoids	255
Sinusoidal Motion	256
Sinusoidal Motion (Simple Harmonic Motion) Is Derived from the Linear Projection of Uniform Circular Speed	256
When the Linear Projection of Uniform Circular Speed Is Stretched Out in Time, the Result Is a Sine Wave	257
Sinusoidal Motion Can Be Described by a Simple Formula and Has Three Important Characteristics: Frequency, Amplitude, and Phase	258
Sinusoidal Motion: A Summary	259
Complex Acoustic Events	259
Complex Periodic Events Have Waveforms That Repeat Their Patterns Over Time and Are Composed of Harmonically Related Frequency Components	259
A Complex Periodic Waveform Can Be Considered as the Sum of the Individual Sinusoids at the Harmonic Frequencies	261
Complex Aperiodic Events Have Waveforms in Which No Repetitive Pattern Can Be Discerned, and Frequency Components That Are Not Harmonically Related	264
Complex Acoustic Events: A Summary	264
Resonance	266
Mechanical Resonance	267
<i>A Spring-Mass Model of Resonance</i>	267
<i>The Relative Values of Mass (M) and Elasticity (K) Determine the Frequency of Vibration of the Spring-Mass Model</i>	268
The Effects of Mass and Stiffness (Elasticity) on a Resonant System: A Summary	270
Acoustic Resonance: Helmholtz Resonators	270
<i>The Neck of the Helmholtz Resonator Contains a Column, or Plug of Air, That Behaves Like a Mass When a Force Is Applied to It</i>	270
<i>The Bowl of a Resonator Contains a Volume of Air That Behaves Like a Spring When a Force Is Applied to It</i>	271
Acoustic Resonance: Tube Resonators	273
Resonance in Tubes: A Summary	276
Resonance Curves, Damping, and Bandwidth	277
<i>Energy Loss (Damping) in Vibratory Systems Can Be Attributed to Four Factors</i>	277

<i>Time- and Frequency-Domain Representations of Damping in Acoustic Vibratory Systems</i>	278
<i>An Extension of the Resonance Curve Concept: The Shaping of a Source by the Acoustic Characteristics of a Resonator</i>	280
Resonance, Damping, Bandwidth, Filters: A Summary	282
Review	282
References	283
Appendix 7–A: The Decibel Scale	284
8 ACOUSTIC THEORY OF VOWEL PRODUCTION	289
Introduction	289
What Is the Precise Nature of the Input Signal Generated by the Vibrating Vocal Folds?	290
The Time Domain	290
The Frequency Domain	293
<i>The Periodic Nature of the Waveform</i>	294
<i>The Shape of the Waveform</i>	295
<i>The Ratio of Open Time to Closed Time</i>	297
Nature of the Input Signal: A Summary	297
Why Should the Vocal Tract Be Conceptualized as a Tube Closed at One End?	297
The Response of the Vocal Tract to Excitation	298
How Are the Acoustic Properties of the Vocal Tract Determined?	299
Area Function of the Vocal Tract	301
How Does the Vocal Tract Shape the Input Signal? (How Is the Source Spectrum Combined with the Theoretical Vocal Tract Spectrum to Produce a Vocal Tract Output?)	303
Formant Bandwidths	307
Acoustic Theory of Vowel Production: A Summary	308
What Happens to the Resonant Frequencies of the Vocal Tract When the Tube Is Constricted at a Given Location?	309
The Three-Parameter Model of Stevens and House	314
<i>Tongue Height</i>	316
<i>Tongue Advancement</i>	316
<i>Configuration of the Lips</i>	318
Importance of the Stevens and House Rules: A Summary	319
<i>The Connection Between the Stevens and House Rules and Perturbation Theory</i>	320
<i>Why Are the Stevens and House Rules Important?</i>	322
<i>Another Take on the Relationship Between Vocal Tract Configuration and Vocal Tract Resonances</i>	323
Confirmation of the Acoustic Theory of Vowel Production	324
Analog Experiments	325
Human Experiments	325
Review	326
References	326
9 THEORY OF CONSONANT ACOUSTICS	329
Introduction	329
Why Is the Acoustic Theory of Speech Production Most Accurate and Straightforward for Vowels?	329
The Acoustics of Coupled (Shunt) Resonators and Their Application to Consonant Acoustics	330
Nasal Murmurs	330
<i>Energy Loss in the Nasal Cavities, Antiresonances, and the Relative Amplitude of Nasal Murmurs</i>	334

Nasal Murmurs: A Summary	335
Nasalization	335
Nasalization: A Summary	338
<i>The Importance of Understanding Nasalization</i>	338
Coupled (Shunt) Resonators in the Production of Lateral Sounds	339
Coupled (Shunt) Resonators in the Production of Obstruent Sounds	339
What Is the Theory of Fricative Acoustics?	341
Fluid Flow in Pipes and Source Types	341
Aeromechanic/Acoustic Effects in Fricatives: A Summary	344
A Typical Fricative Waveform and Its Aeromechanical Correlates	345
Mixed Sources in Fricative Production	346
Shaping of Fricative Sources by Vocal Tract Resonators	346
Measurement of Fricative Acoustics	349
<i>Spectral Measurements</i>	349
<i>Temporal Measurements</i>	350
The Acoustic Theory of Fricatives: A Summary	351
What Is the Theory of Stop Acoustics?	351
Intervals of Stop Consonant Articulation: Aeromechanics and Acoustics	353
<i>Closure (Silent) Interval</i>	353
<i>Release (Burst) Interval</i>	354
<i>Frication and Aspiration Intervals</i>	355
<i>Voice-Onset Time</i>	356
Shaping of Stop Sources by Vocal Tract Resonators	356
<i>The Nature of Stop Sources</i>	357
<i>The Shaping of Stop Sources</i>	357
Measurement of Stop Acoustics	358
<i>Spectral Measurements</i>	359
<i>Temporal Measurements</i>	359
Stop Consonants: A Summary	359
What Is the Theory of Affricate Acoustics?	360
Acoustic Contrasts Associated with the Voicing Distinction in Obstruents	360
Review	361
References	361

10	SPEECH ACOUSTIC MEASUREMENT AND ANALYSIS	363
	Introduction	363
	A Historical Prelude	363
	The Sound Spectrograph: History and Technique	369
	The Original Sound Spectrograph: Summary	372
	Interpretation of Spectrograms: Specific Features	373
	<i>Axes</i>	373
	<i>Glottal Pulses</i>	375
	<i>Formant Frequencies</i>	375
	<i>Silent Intervals and Stop Bursts</i>	376
	<i>Aperiodic Intervals</i>	378
	<i>Segmentation of Spectrograms</i>	379
	Speech Acoustics Is Not All About Segments: Suprasegmentals	382
	Digital Techniques for Speech Analysis	384
	Speech Analysis by Computer: From Recording to Analysis to Output	384
	<i>Sampling Rate</i>	385

<i>Filters</i>	385
<i>Bits</i>	385
<i>Analysis and Display</i>	386
Review	388
References	388
11 ACOUSTIC PHONETICS DATA	391
Introduction	391
Vowels	391
Vowel Acoustics: Dialect and Cross-Language Phonetics	398
Within-Speaker Variability in Formant Frequencies	401
Summary of Vowel Formant Frequencies	403
A Note on Vowel Formant Frequencies Versus Formant Trajectories	404
Vowel Durations	406
<i>Intrinsic Vowel Durations</i>	406
<i>Extrinsic Factors Affecting Vowel Durations</i>	407
Diphthongs	409
Diphthongs: Two Connected Vowels or a Unique Phoneme?	410
Diphthong Duration	412
Nasals	412
Nasal Murmurs	412
Nasal Place of Articulation	415
Nasalization	418
Semivowels	421
Constriction Interval	421
Formant Transitions	422
Semivowel Acoustics and Speech Development	423
Semivowel Durations	424
Fricatives	425
Sibilants Versus Nonsibilants: Spectral Characteristics	425
Quantification of Fricative Spectra	426
Formant Transitions and Fricative Distinctions	431
Fricative Duration	432
<i>Laryngeal Devoicing Gesture and Fricative Duration</i>	435
/h/ Acoustics	436
Stops	438
Closure Interval and Burst	439
<i>Closure Interval Duration</i>	439
<i>Flap Closures</i>	440
<i>Closure Duration and Place of Articulation</i>	441
Stop Voicing: Some Further Considerations	441
<i>Laryngeal Devoicing Gesture, Stop Closures, and Voice Onset Time</i>	441
Bursts	445
<i>Acoustic Invariance for Stop Place of Articulation</i>	446
Acoustic Invariance and Theories of Speech Perception	449
Locus Equations	450
Acoustic Invariance at the Interface of Speech Production and Perception	452
Affricates	453
Acoustic Characteristics of Prosody	454
Phrase-Level F0 Contours	454

Phrase-Level Intensity Contours	456
<i>Stress</i>	457
<i>Rhythm</i>	458
Review	459
References	460
12 SPEECH PERCEPTION	467
Introduction	467
Early Speech Perception Research and Categorical Perception	467
The /ba/-/da/-/ga/ Experiment	468
Categorical Perception: General Considerations	471
<i>Labeling Versus Discrimination</i>	472
Categorical Perception: So What?	472
<i>Speech Perception Is Species Specific</i>	474
The Motor Theory of Speech Perception: Proofs and Falsifications	474
<i>Categorical Perception of Stop Place of Articulation Shows the “Match” to Speech Production</i>	474
<i>Duplex Perception</i>	475
<i>Acoustic Invariance</i>	479
The Competition: General Auditory Explanations of Speech Perception	482
<i>Sufficient Acoustic Invariance</i>	482
<i>Replication of Speech Perception Effects Using Nonspeech Signals</i>	483
<i>Animal and Infant Perception of Speech Signals</i>	485
The Competition: Direct Realism	486
Vowel Perception	488
Motor Theory (Original and Revised)	488
Auditory Theories	488
<i>Normalization</i>	489
Direct Realism	490
A Summary of Speech Perception Theories	490
Speech Perception and Word Recognition	491
Speech Intelligibility	493
“Explanatory” Speech Intelligibility Tests	495
Scaled Speech Intelligibility	496
Phonetic Transcription	498
Why Should Speech-Language Pathologists and Audiologists Care About Speech Perception?	499
Review	501
References	501
13 ANATOMY AND PHYSIOLOGY OF THE AUDITORY SYSTEM	505
Introduction	505
Temporal Bone	505
Peripheral Anatomy of the Auditory System	507
Outer Ear (Conductive Mechanism)	508
Pinna (Auricle)	508
External Auditory Meatus (External Auditory Canal)	509
Tympanic Membrane (Eardrum)	511
Middle Ear (Conductive Mechanism)	512
Chambers of the Middle Ear	512
Ossicles and Associated Structures	513

Ligaments of the Middle Ear	515
Muscles of the Middle Ear	516
Auditory (Eustachian) Tube	517
Medial and Lateral Wall Views of the Middle Ear: A Summary	518
Transmission of Sound Energy by the Conductive Mechanism	519
Inner Ear (Sensorineural Mechanism)	521
Vestibular System	522
<i>Semicircular Canals</i>	523
<i>Vestibule: Saccule and Utricule</i>	524
<i>Summary: Vestibular Structures and Mechanisms</i>	524
Cochlea	525
<i>Fluid Motion within the Scalae: A Broad View</i>	527
<i>Hair Cells and Associated Structures</i>	527
<i>Traveling Waves</i>	530
The Traveling Wave Is Transformed to Action Potentials	533
Auditory Nerve and Auditory Pathways (Neural Mechanism)	533
Auditory Nerve and Associated Structures	534
<i>Efferent Auditory System</i>	534
<i>"Tuning" of the Peripheral Frequency Response</i>	535
Ascending Auditory Pathways	536
<i>Acoustic Reflex</i>	538
Review	540
References	541

14 AUDITORY PSYCHOPHYSICS	543
Auditory Psychophysics	543
Psychophysics of Loudness	543
Auditory Thresholds	543
Equal Loudness Contours for Sinusoids	546
The Psychophysical Function Relating SPL to Scaled Loudness of Sinusoids	546
<i>Phons</i>	547
<i>Sones</i>	547
Loudness of Complex Sounds	550
<i>The Peripheral Auditory System Is a Series of Bandpass Filters</i>	550
<i>The Critical Band Concept and the Loudness of Complex Sounds</i>	556
Sensitivity of the Auditory System to Loudness Change	556
Psychophysics of Pitch	558
Pitch of Sinusoids	559
Sensitivity of the Auditory System to Pitch Change	561
Pitch of Complex Acoustic Events	563
<i>Pitch of Complex Periodic Events</i>	564
<i>Pitch of Complex Aperiodic Events</i>	565
Psychophysics of Timbre	566
Psychophysics of Time	566
Psychophysics of Sound Localization	568
Interaural Cues to Sound Location	570
Auditory Objects and Auditory Scene Analysis	572
Review	575
References	577

15	NEURAL STRUCTURES AND MECHANISMS FOR SPEECH, LANGUAGE, AND HEARING	579
	Introduction	579
	The Nervous System: An Overview and Concepts	579
	Central Versus Peripheral Nervous System	579
	Autonomic Nervous System	580
	Anatomical Planes and Directions	581
	White and Gray Matter, Tracts and Nuclei, Nerves and Ganglia	584
	<i>Gray Matter and Nuclei</i>	584
	<i>White Matter and Fiber Tracts</i>	585
	<i>Ganglia</i>	585
	Efferent and Afferent	585
	Neurons and Synapses	586
	Lateralization and Specialization of Function	586
	Cerebral Hemispheres and White Matter	589
	Cerebral Hemispheres	589
	<i>Frontal Lobe</i>	590
	<i>Parietal Lobe</i>	593
	<i>Temporal Lobe</i>	594
	<i>Occipital Lobe</i>	596
	<i>Insula</i>	596
	<i>Limbic System (Limbic Lobe)</i>	597
	Cerebral White Matter	597
	<i>Association Tracts</i>	598
	<i>Striatal Tracts</i>	601
	<i>Commissural Tracts</i>	601
	<i>Descending Projection Tracts</i>	602
	<i>Ascending Projection Tracts</i>	606
	Subcortical Nuclei and Cerebellum	607
	Basal Ganglia	607
	Cortico-Striatal-Cortical Loop	610
	Role of Basal Ganglia	611
	Thalamus	612
	Cerebellum	612
	<i>Cortico-Cerebellar-Cortical Loop</i>	613
	<i>Role of Cerebellum</i>	613
	Cerebellum and Basal Ganglia: New Concepts	614
	Brainstem and Cranial Nerves	615
	Surface Features of the Brainstem: Ventral View	615
	<i>Ventral Surface of Midbrain</i>	616
	<i>Ventral Surface of Pons</i>	617
	<i>Ventral Surface of Medulla</i>	617
	Surface Features of the Brainstem: Dorsal View	617
	<i>Dorsal Surface of Midbrain</i>	617
	<i>Dorsal Surface of Pons</i>	619
	<i>Dorsal Surface of Medulla</i>	619
	Cranial Nerves and Associated Brainstem Nuclei	619
	<i>Cranial Nerve I (Olfactory)</i>	622
	<i>Cranial Nerve II (Optic)</i>	622

<i>Cranial Nerve III (Oculomotor)</i>	622
<i>Cranial Nerve IV (Trochlear)</i>	622
<i>Cranial Nerve V (Trigeminal)</i>	623
<i>Cranial Nerve VI (Abducens)</i>	624
<i>Cranial Nerve VII (Facial)</i>	625
<i>Cranial Nerve VIII (Auditory-Vestibular Nerve)</i>	626
<i>Cranial Nerve IX (Glossopharyngeal)</i>	627
<i>Cranial Nerve X (Vagus)</i>	628
<i>Cranial Nerve XI (Spinal Accessory Nerve)</i>	629
<i>Cranial Nerve XII (Hypoglossal)</i>	629
Cortical Innervation Patterns	630
Why Innervation Patterns Matter	631
The Cranial Nerve Exam and Speech Production	633
Spinal Cord and Spinal Nerves	633
Spinal Cord	633
Spinal Nerves	635
Nervous System Cells	636
Glial Cells	636
Neurons	636
<i>Cell Body (Soma)</i>	637
<i>Axon and Terminal Button</i>	639
<i>Synapses</i>	639
Resting Potential, Action Potential, and Neurotransmitters	640
<i>Resting Potential</i>	640
<i>Action Potential</i>	642
<i>Synaptic Transmission and Neurotransmitters</i>	644
Neuromuscular Junction	645
Meninges, Ventricles, Blood Supply	647
Meninges	647
<i>Dura Mater</i>	648
<i>Arachnoid Mater</i>	649
<i>Pia Mater</i>	649
<i>Meninges and Clinically Relevant Spaces</i>	650
Ventricles	650
<i>Lateral Ventricles</i>	651
<i>Third Ventricle</i>	651
<i>Cerebral Aqueduct, Fourth Ventricle, and Other Passageways for CSF</i>	652
<i>Production, Composition, and Circulation of CSF</i>	652
Blood Supply of Brain	652
<i>Anterior Circulation</i>	652
<i>Posterior Circulation</i>	654
<i>Circle of Willis</i>	654
<i>MCA and Blood Supply to the Dominant Hemisphere</i>	655
<i>Blood–Brain Barrier</i>	658
Speech and Language Functions of the Brain: Possible Sites and Mechanisms	659
Network View of Brain Function	659
DIVA	659
<i>DIVA: Speech Sound Map (lvPMC)</i>	661
<i>DIVA: Articulatory Velocity/Position Maps (PMC)</i>	662

<i>DIVA: Auditory and Somatosensory Processing: Parietal Cortex and Frontal-Parietal Association Tracts</i>	663
<i>DIVA: Where Is Aphasia, Where Are Dysarthria Types?</i>	664
Review	665
References	666
16 SWALLOWING	669
Introduction	669
Anatomy	670
Breathing, Laryngeal, Velopharyngeal-Nasal, and Pharyngeal-Oral Structures	670
Esophagus	671
Stomach	671
Forces and Movements of Swallowing	673
Oral Preparatory Phase	674
Oral Transport Phase	676
Pharyngeal Phase	676
Esophageal Phase	677
Overlap of Phases	678
Breathing and Swallowing	678
Neural Control of Swallowing	681
Role of the Peripheral Nervous System	681
Role of the Central Nervous System	682
Variables That Influence Swallowing	683
Bolus Characteristics	683
<i>Consistency and Texture</i>	683
<i>Volume</i>	683
<i>Taste</i>	684
Swallowing Mode	684
<i>Single Versus Sequential Swallows</i>	684
<i>Cued Versus Uncued Swallows</i>	685
Body Position	686
Development	686
Aging	687
Sex	688
Measurement and Analysis of Swallowing	688
Videofluoroscopy	688
Endoscopy	689
Manometry	690
Surface Electromyography	692
Ultrasonography	692
Aeromechanical Observations	692
Client Self-Report	694
Health Care Professionals	694
Review	695
References	697
NAME INDEX	703
SUBJECT INDEX	715

Preface

The third edition of *Preclinical Speech Science* is a carefully revised and expanded version of the second edition of the textbook. The revised parts include line-by-line edits of all chapters from the second edition for greater clarity, removal of certain sections (several of which are available as supplementary materials on the textbook companion website, including the scenarios of the previous edition), and addition of new material to chapters from the second edition, including text, figures, and recent references from the research literature.

This new edition also contains three new chapters, including Chapter 6 (“Speech Physiology Measurement and Analysis”), Chapter 13 (“Auditory Anatomy and Physiology”), and Chapter 14 (“Auditory Psychophysics”). Chapter 6 was added to complement Chapter 10 (“Speech Acoustic Measurement and Analysis”) and Chapters 13 and 14 were added in response to suggestions made by colleagues and students, that this

textbook would benefit from chapter-length material on Hearing Science. With the inclusion of these two chapters on hearing science, perhaps a more accurate title for the textbook would be *Preclinical Speech and Hearing Science*. Because this is the third edition of the text, we have chosen to retain the original title to be consistent with the previous editions.

The Workbook accompanying the third edition of this textbook has also been updated with complete sets of problems and exercises for the three new chapters, and revised exercises for all other chapters. The Workbook is a self-study resource, complete with answers to the problems and exercises.

A PluralPlus companion website also accompanies this new edition of *Preclinical Speech Science*. The website has supplementary text and figures, sound files, study guides, and instructor lecture slides.

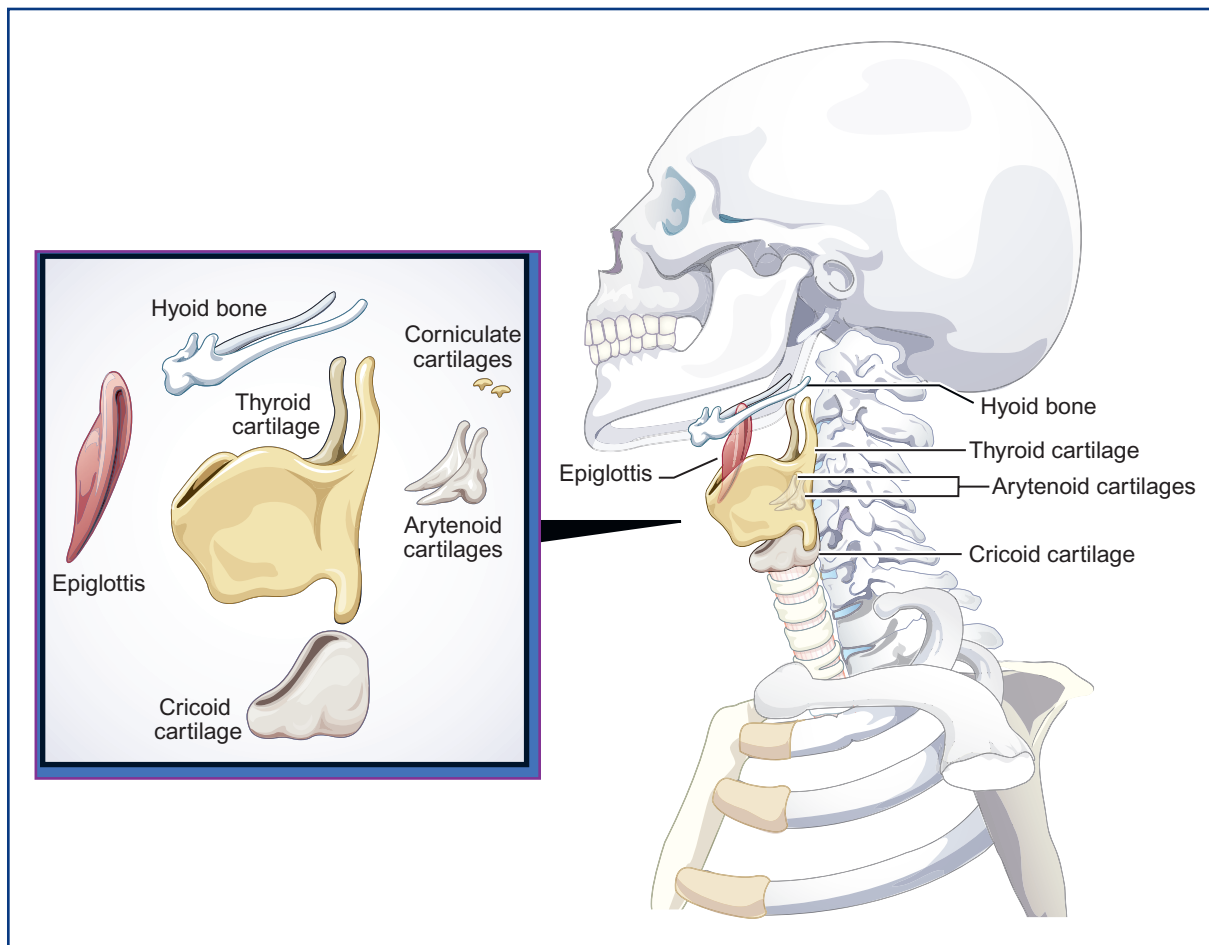


Figure 3-1. Skeletal framework of the laryngeal apparatus. This framework is composed of two paired cartilages (arytenoid cartilages and corniculate cartilages), three unpaired cartilages (thyroid cartilage, cricoid cartilage, and epiglottis), and one bone (hyoid bone).

the thyroid cartilage and diverge widely (more so in women than in men) toward the back. The configuration of the two thyroid laminae resembles the bow of a ship. The line of fusion between the two plates is called the angle of the thyroid. The upper part of the structure contains a prominent V-shaped depression termed the thyroid notch that can be palpated at the front of the neck. This notch is located just above the most forward projection of the cartilage, an outward jutting called the thyroid prominence or Adam's apple.

The back edges of the thyroid laminae extend upward into two long horns, called the superior cornua, and downward into two short horns, called the inferior cornua. The superior cornua are coupled to the hyoid bone. The inferior cornua have facets (areas where other structures join) on their lower inside surfaces that form joints with the cricoid cartilage. The

inferior cornua straddle the cricoid cartilage like a pair of legs (see Figure 3-1).

Cricoid Cartilage

The cricoid cartilage forms the lower part of the laryngeal skeleton. It is a ring-shaped structure located above the trachea. As shown in Figure 3-3, the cricoid cartilage has a thick plate at the back, the posterior quadrangle lamina, which resembles a signet on a finger ring. A semicircular structure, called the anterior arch, forms the front of the cricoid cartilage and is akin to a band on a finger ring.

Four facets are located on the cricoid cartilage. The lower two facets, one on each side at the same level, are positioned near the junction of the posterior quadrangle lamina and anterior arch. Each of these facets articulates with a facet on one of the inferior cornua

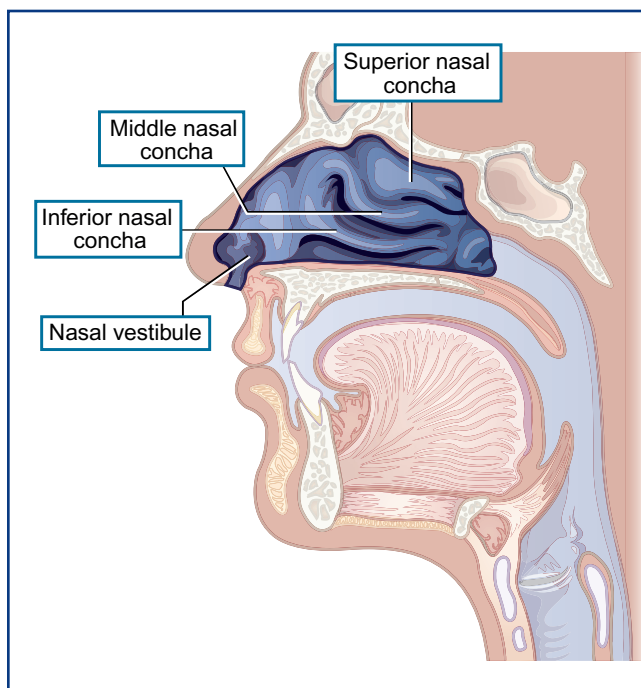


Figure 4-7. Superior, middle, and inferior nasal conchae (also called nasal turbinates). These conchae contain many nooks and crannies and create a large surface area to the inner nose.

provides a large surface area to the inner nose and has a rich blood supply. Near the front of each nasal cavity is the nasal vestibule, a modest dilation just inside the aperture of the anterior naris.

There are four sinuses (hollows) that surround the nasal cavities. Called the paranasal sinuses, they include the maxillary, frontal, ethmoid, and sphenoid sinuses, each located within the bone of corresponding name. Three of these are shown in Figure 4-8. The sphenoid, not pictured, is located behind and above the superior nasal conchae within the sphenoid bone. They are usually air filled but can become liquid filled when infected. Their relevance to speech is primarily related to their effects on the resonance characteristics of the acoustic signal during nasal sound production (see Chapter 9).

Outer Nose

Unlike the other components of the velopharyngeal-nasal apparatus, the outer nose is familiar to everyone. The outer nose is hard to ignore because it is in the center of the face and projects outward and downward conspicuously. The more prominent surface features of the outer nose include the root, bridge, dorsum, apex,

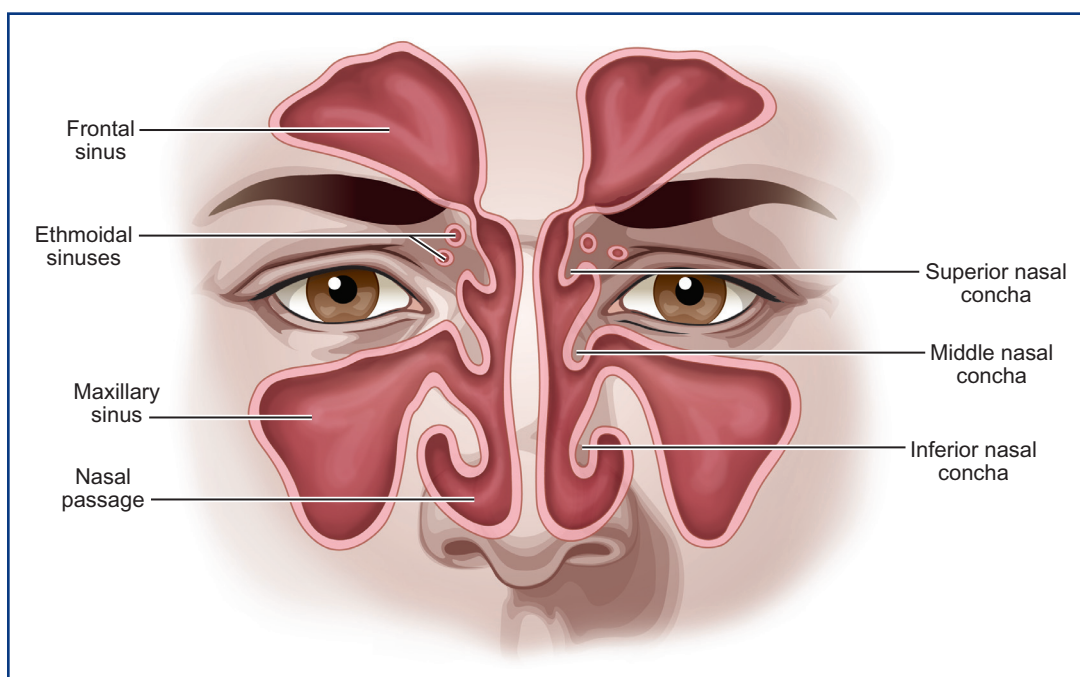


Figure 4-8. The paranasal sinuses. Shown in this figure are the maxillary, frontal, and ethmoid sinuses. Not shown are the paired sphenoid sinuses, which are located behind and above the superior nasal conchae.

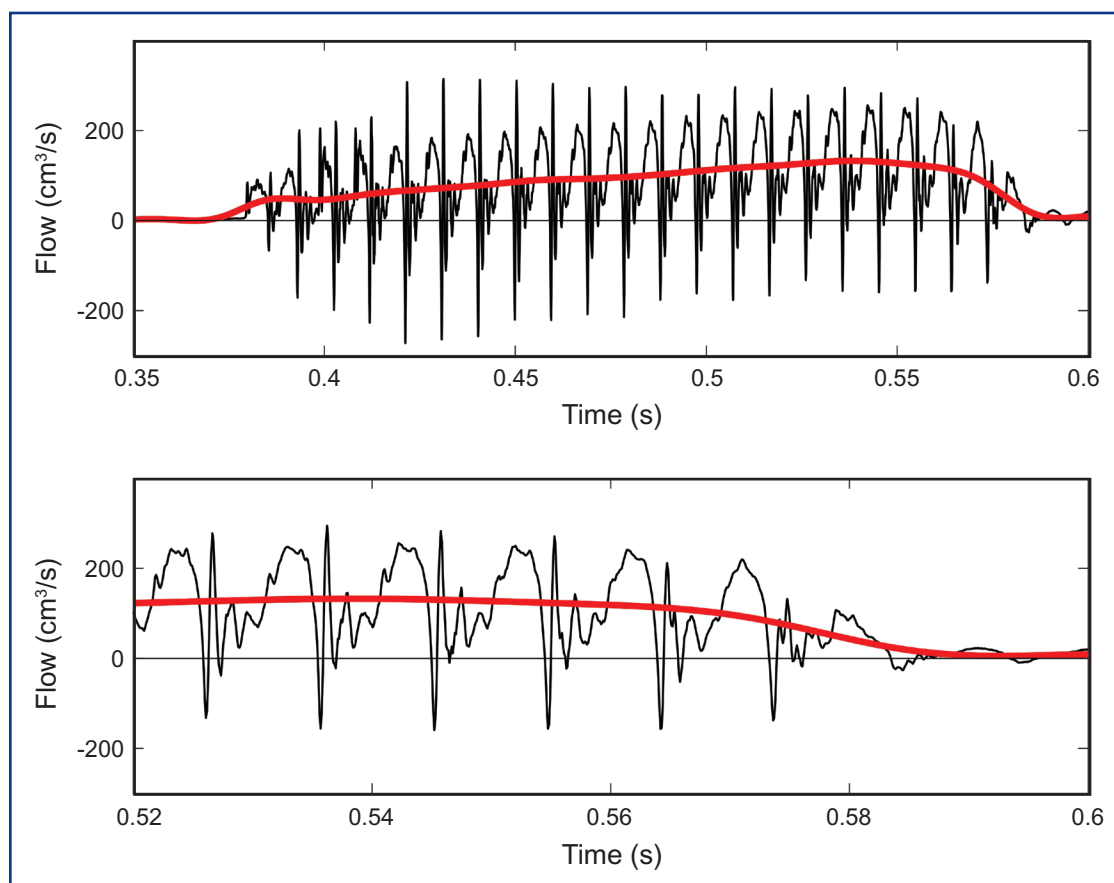


Figure 6-11. Airflow recorded at the airway opening during vowel production. The black tracings show the fast airflow events associated with each cycle of vocal fold vibration. The red tracings represent the average airflow obtained by low-pass filtering the black airflow signal (to filter out high-frequency airflow events). The bottom set of tracings are a zoomed-in image from the upper set of tracings. The fundamental frequency is about 100 Hz (courtesy of Brad Story).

airway-opening airflow to calculate laryngeal airway resistance. As shown in Figure 6-12, measurements are taken at moments that enable estimates to be made of the air pressure difference across the larynx and the airflow through it during vowel productions. Resistance is calculated by dividing the air pressure difference (estimated tracheal air pressure minus estimated pharyngeal air pressure) by the translaryngeal airflow (estimated from the airflow at the airway opening). Resistance values are typically expressed in $\text{cmH}_2\text{O}/\text{LPS}$ (centimeters of water/liters per second) and can range from very low (wide open airway) to infinite (airtight closure of the airway). Such resistance values reflect the degree of opening of the laryngeal airway during voice production (Holmberg, Hillman, & Perkell, 1988, 1999; Leeper & Graves, 1984; Smitheran & Hixon, 1981).

Phonation threshold pressure is another aeromechanical measure that can provide information about

laryngeal function, or more specifically, vocal fold function. Phonation threshold pressure is defined as the minimum tracheal pressure required to initiate vocal fold vibration and is understood to reflect the status of the vocal folds (viscosity and thickness) and their distance from one another (glottal width) (Titze, 1988). Although there are invasive ways to measure phonation threshold pressure, the most common way to estimate it is by using the noninvasive approach depicted in Figure 6-7, with the client producing the /p/-vowel syllable strings in the quietest voice possible (Verdolini-Marston, Titze, & Druker, 1990). The lower the peak oral pressures during /p/ productions (estimated tracheal pressure), while still maintaining voicing during the vowel segments, the lower the phonation threshold pressure. And the lower the phonation threshold pressure, the healthier vocal fold function is judged to be. Although this measure is relatively easy to obtain, it is not without its limitations. For example, it is common

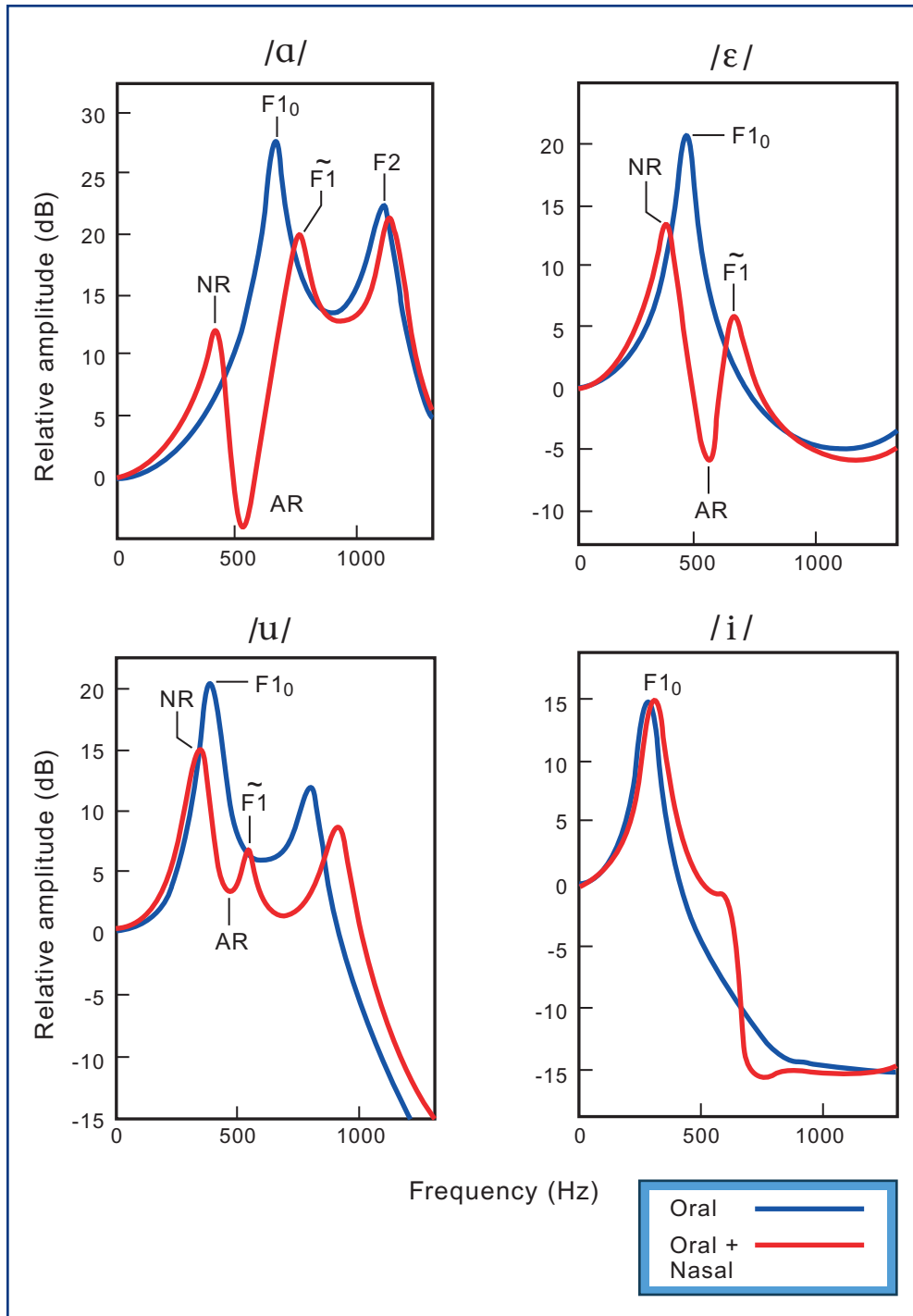


Figure 9-4. Spectra for the vowels /a/, /ε/, /u/, and /i/ for non-nasalized (blue curves) and nasalized (red curves) productions. Frequency is plotted between 0 and 1300 Hz on the x-axis and relative amplitude, in dB, is plotted on the ordinate. NR = nasal resonance. AR = antiresonance. $F1_0$ = F1 of non-nasalized vowel. $\tilde{F}1$ = F1 of nasalized vowel. For each vowel except /i/, there is a nasal resonance-antiresonance-F1 pattern in the nasalized spectra. In the case of /i/, the nasal resonance is canceled by the antiresonance because of the small coupling (small velopharyngeal port opening) between the oral and nasal cavities. From "Some acoustical and perceptual correlates of nasal vowels," by K. Stevens, G. Fant, and S. Hawkins in *In Honor of Ilse Lehiste* (p. 246), edited by R. Channon and L. Shockey, 1987, Dordrecht, Netherlands: Foris. Copyright 1987 by Foris. Modified and reproduced with permission.

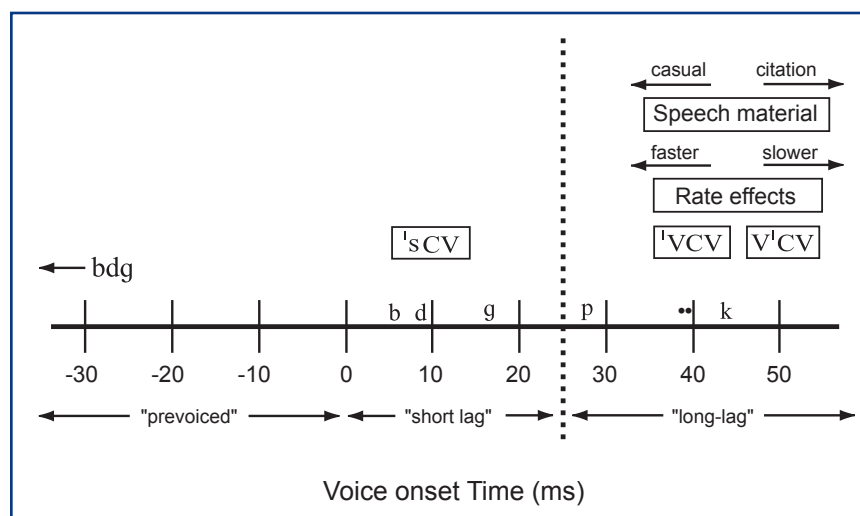


Figure 11-30. Graphic summary of VOT data from English speakers. A VOT continuum ranging from -30 to $+50$ ms is shown, and effects are indicated by the phonetic symbols and boxes above the continuum line. See text for additional detail.

glottal pulse of the following vowel, negative VOT values represent the time by which glottal pulses within the closure interval *precede* the burst.

Both positive and negative VOT values are common in voiced stop production. As noted above, negative VOTs are associated with stops produced in the utterance-initial position (no speech sounds preceding the stop); intervocalic voiced stops often have glottal pulses during the closure interval, but these are not considered prevoiced. When voiced stops have glottal pulses that are not continuous throughout the closure interval, the VOT is often positive, but very short, as shown in Figure 11-30. The prevoiced, voiced stops reported by Lisker and Abramson all had VOTs more negative than -30 ms, the last negative value on the continuum shown in Figure 11-30.

Figure 11-30 shows a vertical dotted line at 25 ms along the VOT continuum. This line designates a boundary between typical positive VOTs for voiced and voiceless stops. Voiceless stops can be expected to have VOTs exceeding 25 ms (*long-lag* VOTs), whereas voiced stops have VOTs less than 25 ms (*short-lag* VOTs) (Weismer, 2006).

The boxes above the VOT continuum and to the right of the 25 ms boundary identify factors that cause VOT to vary in systematic ways. These boxes are in the long-lag range of the VOT continuum because the effects are most prominent for voiceless stops, with much smaller effects on the short-lag VOTs of voiced stops. VOT is affected by the position of a voiceless stop relative to a stressed vowel. Longer VOTs are

measured when the stop precedes, compared with follows, a stressed vowel. The box containing the V'CV frame has been placed to the right (longer VOTs) of the 'VCV box to indicate this effect. In fact, VOTs for voiceless stops in 'VCV frames may be so short as to place them in the short-lag range (Umeda, 1977). The effect of speaking rate on VOT, indicated in Figure 11-30 by the box and arrows immediately above the stress effects, are predictable from the direction of rate change. Slower rates produce longer VOTs for voiceless stops (shown by the arrow pointing to the right), and faster rates produce shorter VOTs (left-pointing arrow) (Kessinger & Blumstein, 1997). The reduction (shortening) of long-lag VOTs at very fast speaking rates is rarely so dramatic as to encroach on the short-lag range (Kessinger & Blumstein, 1997; Summerfield, 1975). Finally, the topmost box indicates that speaking style affects the value of long-lag VOTs. Longer VOTs for voiceless stops are produced in more formal speaking styles, sometimes referred to as citation form or "clear" speech (Krause & Braida, 2004; Smiljanić & Bradlow, 2005). Casual speech styles yield shorter VOTs. The difference between formal and casual speaking styles is likely to involve a difference in speaking rate. Formal speaking styles typically have slower rates than casual styles (Picheny et al., 1986).

A special case of VOT modification for voiceless stops is indicated by the "sCV" box above the short-lag range. "sCV" stands for prestressed s + stop clusters, in words such as "stop," "skate," "speech," "astounding." Voiceless stops in s + stop clusters have short-lag

cochlea is oriented in the head as if the tip is pointing along the horizontal axis. The back half of the cochlea is shown in this view. On either side of the center of the slice, two “triplets” of ducts are seen, one triplet at the base (labeled “basal turn” in the figure), the other just above it (labeled “middle turn”). The top triplet of ducts is at the apical turn of the cochlea, at the very tip of which the two outside ducts—the scala vestibuli and scala tympani—are connected. The center “core” section of the cut is called the modiolus (not labeled in Figure 13–16). The turns of the bony cochlea wrap around this center core as they spiral to the apex. The modiolus contains the nerve fibers that innervate the hair cells. It also contains ganglion cells where fibers emerging from the cochlea make their first synapse before continuing to the internal auditory meatus as the auditory part of the auditory-vestibular nerve.

From base to tip, the modiolus sends out two bony shelves toward the outer edges of the spiraling cochlea. These shelves are called the spiral lamina, whose bony extensions serve as the divider between the two outer ducts—the scala vestibuli and scala tympani (labeled

only for the basal turns in Figure 13–16). The spiral lamina does not extend to the lateral, bony border of the cochlea. Rather, as described below, membranes extending from the end of the bony lamina to the inside of the lateral border of the cochlea create the third duct sitting between the scala vestibuli and scala tympani. This third duct is called the scala media, or alternately the cochlear duct. All three ducts are filled with fluid.

The second way to appreciate the structure of the cochlea is by studying a zoomed view of the ducts in the cochlea. The zoomed view of the bony cochlea in Figure 13–17 is from its basal turn. From top to bottom the ducts are the scala vestibuli, scala media, and scala tympani. At the beginning of the basal turn of the scala vestibuli, near the section shown in the figure, is the oval window. The termination of the basal turn of the scala tympani is the round window. The two membranes that extend from shelves of the spiral lamina to the outer edge of the cochlea, and enclose the scala media, are called Reissner’s membrane (dividing the scala vestibuli from the scala media) and the basilar membrane (dividing the scala tympani from the scala

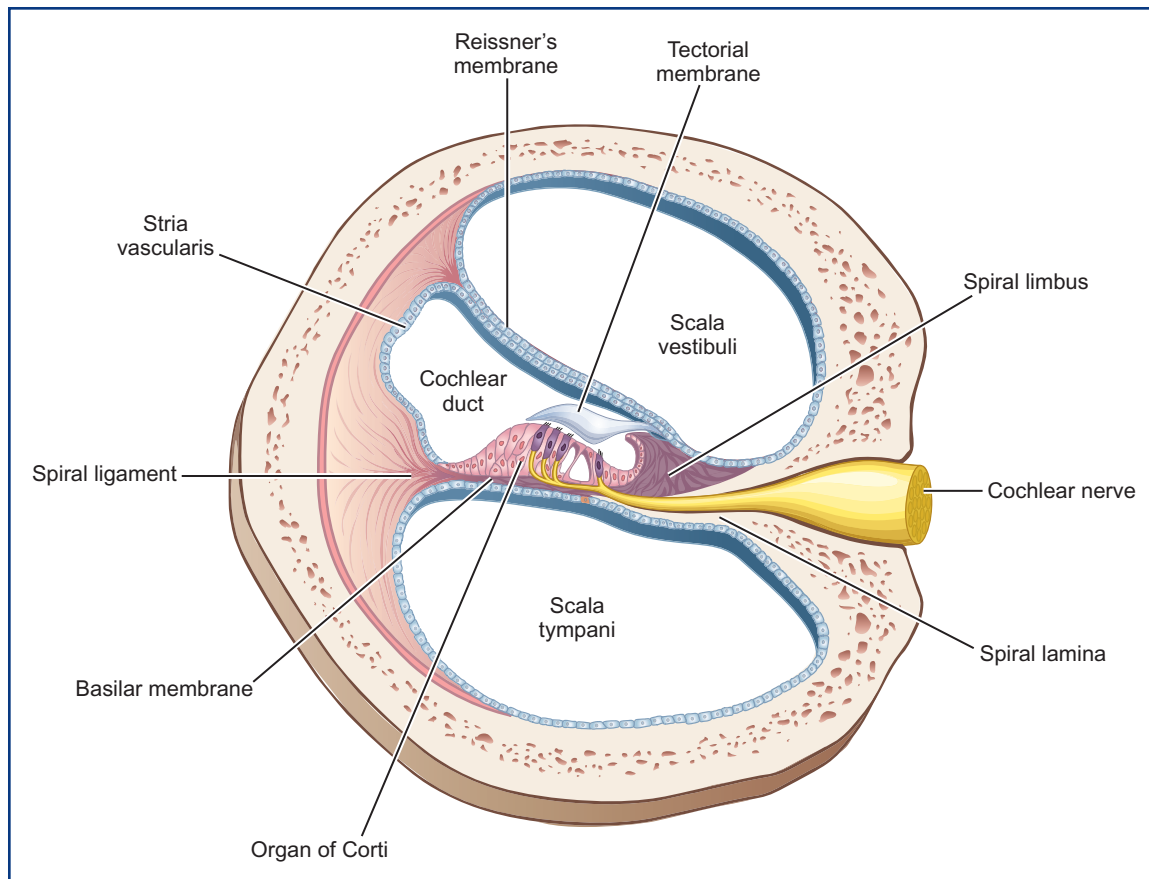


Figure 13-17. Zoom view of cochlear scalae from the basal turn of the cochlea.

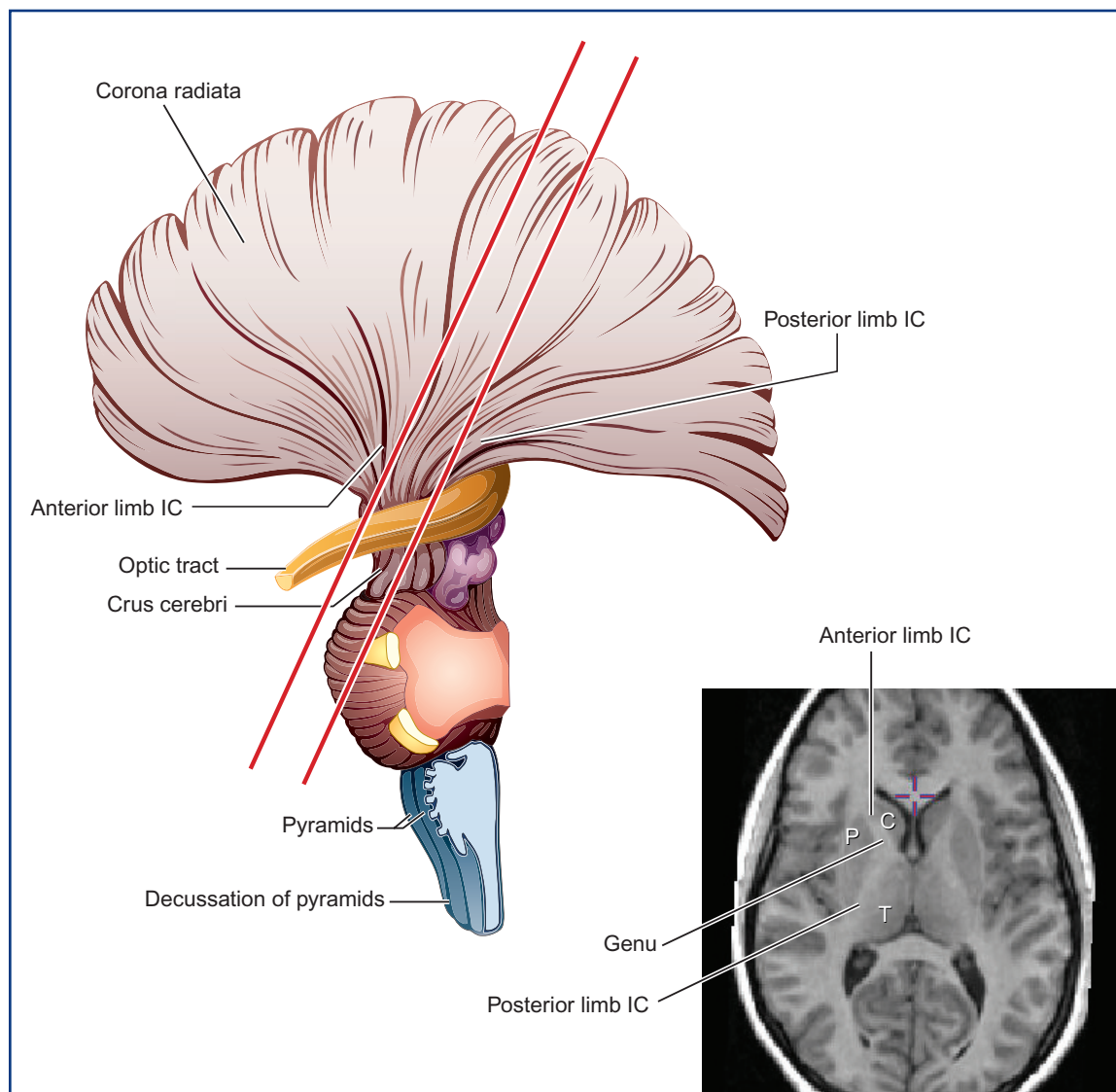


Figure 15-12. *Upper left*, view of fibers of the corona radiata descending in the cerebral hemispheres and gathering into a narrow bundle called the internal capsule (IC), which passes between several subcortical nuclei en route to the brainstem. *Lower right*, horizontal section of cerebral hemispheres showing the “boomerang” shape of the internal capsule. The anterior and posterior limbs plus the genu of the internal capsule are labeled. C = caudate nucleus; P = putamen; T = thalamus.

to reveal the fibers of the corona radiata and internal capsule. Even though the internal capsule is the tightly gathered merger of the many fibers of the corona radiata, the internal capsule has an anterior, middle, and posterior part (IC = internal capsule in Figure 15-12, upper image). The precise location of a coronal slice therefore determines which part of the internal capsule is displayed. Like so many other parts of the brain, the internal capsule is not a random jumble of fibers, but is arranged systematically based on the cortical origin of the fibers. In a horizontal (axial) slice (inset, lower right of Figure 15-12; the anterior part of the brain is

toward the top of the image) the internal capsule in each hemisphere has a boomerang shape with the “angle” of the boomerang most medial and the two arms extending away from this angle anterolaterally and posterolaterally. To provide a rough idea of the systematic arrangement of fibers within the internal capsule, most corticobulbar fibers associated with control of facial, jaw, tongue, velopharyngeal, and laryngeal muscles run through a compact bundle close to or within the angle (called the genu) of the internal capsule. Fibers descending to motor neurons in the spinal cord are mostly located in the posterior arm (called the

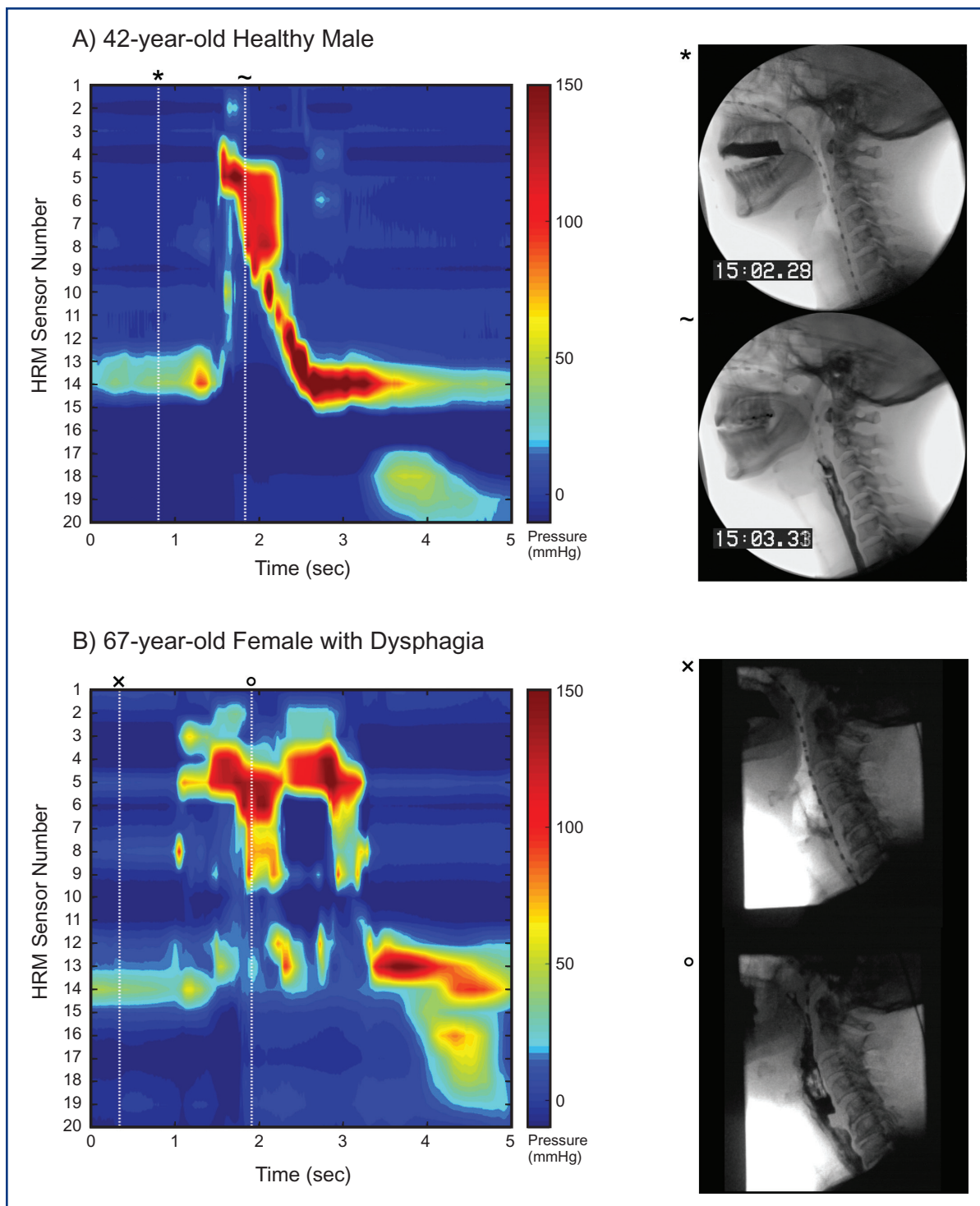


Figure 16-12. Simultaneous videofluoroscopy and pharyngeal high-resolution manometry of a 10 cc thin barium swallow from a 42-year-old healthy man (**A**) and a 67-year-old woman with dysphagia (**B**). High-resolution manometry sensors appear as black rectangles on the videofluoroscopy stills. Videofluoroscopy still images correspond to the time indicated by the vertical lines on the manometry plot with the same symbol at the top. In the data from the healthy man, pressures in the pharynx are low at rest (sensors 4-12: dark blue), whereas pressure is higher in the upper esophageal sphincter (sensors 13-14: light blue/green). During swallowing, the pharynx constricts, creating high pressures (orange/red) at the same time the upper esophageal sphincter relaxes (dark blue). The data from the woman with dysphagia reveals that she swallowed twice to clear the bolus, as indicated by the gap in the pressure wave (sensors 10-11: dark blue). Also note the area of elevated pressure in the upper esophageal sphincter (sensor 13: light blue/green) during opening. Courtesy of Timothy McCulloch, MD, and Corinne Jones, PhD, CCC-SLP.

Preclinical Speech Science Workbook

Preclinical Speech Science Workbook

THIRD EDITION

Jeannette D. Hoit
Gary Weismer





5521 Ruffin Road
San Diego, CA 92123

e-mail: info@pluralpublishing.com
website: <http://www.pluralpublishing.com>

Copyright © 2020 by Plural Publishing, Inc.

Typeset in 12/14 Palatino by Flanagan's Publishing Services, Inc.
Printed in South Korea through Four Colour Print Group

All rights, including that of translation, reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, recording, or otherwise, including photocopying, recording, taping, Web distribution, or information storage and retrieval systems without the prior written consent of the publisher.

For permission to use material from this text, contact us by
Telephone: (866) 758-7251
Fax: (888) 758-7255
e-mail: permissions@pluralpublishing.com

Every attempt has been made to contact the copyright holders for material originally printed in another source. If any have been inadvertently overlooked, the publishers will gladly make the necessary arrangements at the first opportunity.

Library of Congress Cataloging-in-Publication Data:

ISBN-13: 978-1-63550-063-9
ISBN-10: 1-63550-063-X

Contents

PREFACE	vii
Questions	1
1 Introduction	1
2 Breathing and Speech Production	5
3 Laryngeal Function and Speech Production	37
4 Velopharyngeal-Nasal Function and Speech Production	67
5 Pharyngeal-Oral Function and Speech Production	95
6 Speech Physiology Measurement and Analysis	119
7 Acoustics	145
8 Acoustic Theory of Vowel Production	163
9 Theory of Consonant Acoustics	177
10 Speech Acoustic Measurement and Analysis	185
11 Acoustic Phonetics Data	199
12 Speech Perception	217
13 Anatomy and Physiology of the Auditory System	225
14 Auditory Psychophysics	239
15 Neural Structures and Mechanisms for Speech, Language, and Hearing	251
16 Swallowing	265

Answers	277
1 Introduction	278
2 Breathing and Speech Production	279
3 Laryngeal Function and Speech Production	291
4 Velopharyngeal-Nasal Function and Speech Production	301
5 Pharyngeal-Oral Function and Speech Production	311
6 Speech Physiology Measurement and Analysis	322
7 Acoustics	330
8 Acoustic Theory of Vowel Production	343
9 Theory of Consonant Acoustics	354
10 Speech Acoustic Measurement and Analysis	363
11 Acoustic Phonetics Data	376
12 Speech Perception	391
13 Anatomy and Physiology of the Auditory System	400
14 Auditory Psychophysics	411
15 Neural Structures and Mechanisms for Speech, Language, and Hearing	418
16 Swallowing	429
REFERENCES	435

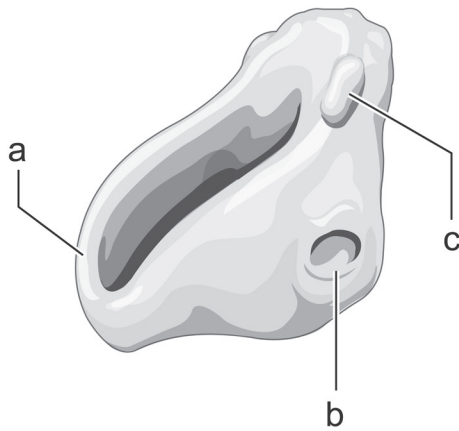
Preface

The *Preclinical Speech Science Workbook, Third Edition* is a natural companion to the *Preclinical Speech Science, Third Edition* textbook. It has been carefully designed to help students reinforce, integrate, apply, and go beyond the material presented in the textbook.

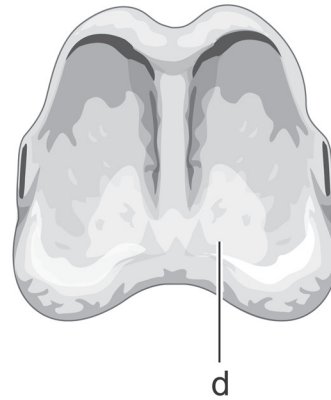
The workbook contains a wide variety of activities. These include anatomic labeling, measuring physiologic and acoustic data, interpreting graphs, calculating quantitative problems, answering thought questions about material presented in the textbook, and conducting simple experiments (without the use of special equipment). The solutions to all these activities are provided at the back of the workbook; however, we strongly encourage students to work through each activity independently and refer to the solutions only when completely satisfied with their answers. This will provide the best learning experience and will help students make the transition from passive learners to active participants in their development toward becoming speech-language pathologists, audiologists, and clinical scientists.

3-3. Label the parts of the cricoid cartilage indicated in the figures.

Side oblique view



Back view



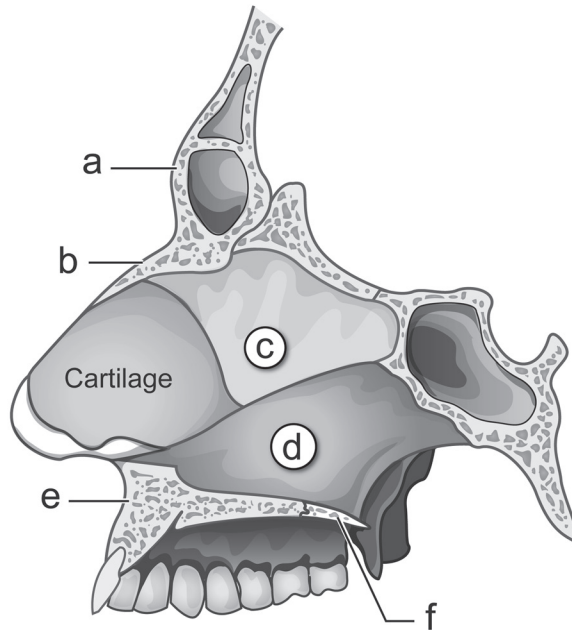
a _____

c _____

b _____

d _____

4-6. Label the bones indicated in the figure.



a _____ d _____
 b _____ e _____
 c _____ f _____

(a) The two nasal cavities are separated from one another by the nasal _____, which is made up of [Check one]

_____ tendons and ligaments.

_____ a matrix of soft tissue.

_____ muscle.

_____ cartilage and bone.

(b) The hard palate is made up of the _____ bone and the _____ bone.

6-21. The velopharyngeal orifice area can be estimated by a method developed by Warren and DuBois (1964; see Figure 6-15 in your textbook). Estimate the velopharyngeal orifice area using the formula and the values given below for oral pressure (P_1 , in dynes/cm²), nasal pressure (P_2 , in dynes/cm²), and nasal flow (in cubic centimeters per second, cc/s). The formula is:

$$\text{Velopharyngeal port area} = \frac{k \sqrt{\frac{\text{Nasal airflow}}{2 (\text{Air pressure differential}) \cdot \text{Density of air}}}}$$

Note that dynes/cm² is a unit of measure for pressure that is much smaller than cmH₂O (specifically, 1 cmH₂O \approx 980 dynes/cm², so 1 dyne/cm² \approx 0.001 cmH₂O). Also, note that k is a constant that adjusts for the fact that airflow is often turbulent during speech production, rather than laminar (smooth). The suggested value for k is 0.65, density of air \approx .001 (g/cm³), and the air pressure differential = $P_1 - P_2$.

Velopharyngeal orifice area is expressed in square centimeters (cm²). Calculate the velopharyngeal orifice area from the oral pressure, nasal pressure, and nasal flow values given below.

Oral Pressure (P_1 ; dynes/cm ²)	Nasal pressure (P_2 ; dynes/cm ²)	Nasal Flow (cc/s)	Velopharyngeal Orifice Area (cm ²)
100	80	200	_____
100	0	0	_____
100	20	30	_____

Indicate which of the calculated values above best describes the velopharyngeal orifice area for:

Sustained vowel with normal voice quality _____

Sustained vowel with hypernasal voice quality _____

Sustained /m/ _____

13-30. When is the electrical potential of the hair cells of the organ of Corti and of the crista ampullaris changed?

13-31. The parts of the vestibular system that sense position of the head in the front-to-back and side-to-side dimensions are the _____ and _____, respectively. These two structures are part of the organ called the _____.

13-32. The core of the cochlea is called the _____, which contains _____ originating at the base of the hair cells as well as the group of cell bodies called the _____.

13-33. The membranes that separate the three cochlear ducts are _____ and _____.

13-34. In three sentences or less, describe the organ of Corti.
