

Sound Reproduction

The Acoustics and Psychoacoustics of
Loudspeakers, Rooms and Headphones

Fourth Edition

Floyd E. Toole, with Sean Olive and Todd Welti

Contents

ACKNOWLEDGMENTS	xvii
ABOUT THE AUTHORS	xix
Introduction to the Fourth Edition.....	1
FLOYD TOOLE	
1 An Overview of the Research	7
FLOYD TOOLE	
1.1 The Scientific Method Applied to Audio.....	7
1.2 Fortuitous Events Lead to a Career	9
1.3 More Chance Factors Steer the Research	11
1.3.1 The Listening Test That Changed My Career	12
1.4 Subjective Evaluations Matter, and How They Are Done Matters More.....	14
1.5 A Review of Some Measurement Options	20
1.5.1 Resonances Are Important.....	20
1.5.2 Non-linear Distortions	21
1.5.3 Frequency Response Is Important— But What Is It?	22
1.5.4 Room Equalization/Calibration Adds Confusion	23
1.6 Listening in and Through Rooms.....	24
1.6.1 Should We Measure the Output of Loudspeakers or the Input to the Ears?	26
1.7 Circles of Confusion Within the Recording Industry	27
References	30
2 A New Standard for Loudspeaker Measurements	31
FLOYD TOOLE	
2.1 Examining the Music Source of the Day: LPs.....	33
2.2 The Research Aids Manufacturers and a Broadcaster	34
2.3 Informative Technical Measurements: Major Progress.....	36
2.3.1 Early Results Were Very Revealing	38
2.4 Learning About the Loudspeaker/Room System.....	41
2.5 A View of the Loudspeaker Industry in the 1980s	45
2.5.1 International Interactions.....	46
2.6 Turning Points in Research and Careers	47
2.7 The “Spinorama” Emerges	49

2.8	Introducing the Research Team.....	53
2.8.1	Sean Olive.....	54
2.8.2	Todd Welti.....	54
2.8.3	Allan Devantier.....	55
2.9	Measurements Have Changed the Loudspeaker Industry.....	56
2.9.1	A Real-World Problem for Loudspeaker Users.....	59
2.10	A Career Draws to a Close.....	63
	References	63
3	Perspectives on Sound Production, Recording and Reproduction.....	65
	FLOYD TOOLE	
3.1	Sound Production.....	65
3.2	Sound Reproduction: The Audio Industry	66
3.2.1	Microphones—The First Transducers.....	68
3.2.2	Reproduction Venues	69
3.3	Can We Reproduce “Reality”? Binaural Techniques.....	71
3.3.1	Head Related Transfer Functions: HRTFs	72
3.3.2	Anecdotal Observations of Adaptation at Work	74
3.3.3	Adding Credible Visuals Makes a Difference	77
3.3.4	Binaural Crosstalk-Cancelled Loudspeaker Presentations	77
3.4	Reproducing the “Perceptual Essence” of Live Performances	80
3.5	Recording Control and Mastering Rooms—Where “Live” Performances Occur.....	82
3.5.1	“Monitor” Loudspeakers Are Not Necessarily “Good” Loudspeakers.....	86
3.5.2	An Acoustic Digression in Pro Audio	88
3.6	The Closed Loop of Cinema Sound	90
3.7	Summary	94
	References	94
4	Sound Reproduction: Part One—Mono to Stereo	97
	FLOYD TOOLE	
4.1	The Principal Perceptual Variables of Reproduced Sound	97
4.1.1	Musical Instruments, Microphones and Rooms	100
4.2	The Monophonic Origins.....	101
4.3	Stereo Adds a Channel and Becomes the Standard	103

4.3.1	The System of Stereo—How It Works	105
4.3.2	A Phantom Image Problem	108
4.3.3	Loudspeakers as Stereo Image Stabilizers	111
4.4	Evaluating Sound Quality and Imaging in Stereo and Mono	113
4.5	Adding More Channels: A Multichannel Effect	123
	References	124
5	Loudspeakers, Rooms, Recordings and Adaptation: Key Factors in What and How We Hear	127
	FLOYD TOOLE	
5.1	One Room, Two Sound Fields—The Transition Frequency.....	128
5.2	Timbral and Spatial Effects Attributable to Rooms	130
5.3	Resonances Need to Be Heard—Or Not—It Depends	130
5.3.1	Measuring and Hearing Resonances.....	132
5.3.2	Finding and Fixing Resonances: Different Methods—Different Results	138
5.4	Room Effects, Listening Methods and Adaptation: An Important Experiment	142
5.5	A Retrospective Examination of These Experimental Results.....	144
5.5.1	The Tested Loudspeakers.....	144
5.5.2	The Rooms and Loudspeaker/Room Interactions.....	146
5.5.3	Program.....	149
5.5.4	The Experimental Method.....	149
5.6	Adaptation Happens Quickly in Everyday Life	150
5.7	More Channels, More Pleasure and More Confusion	151
5.8	Multiple “Rooms” Modify Perceptions	154
5.8.1	Speculation.....	156
5.8.2	Implications for Car Audio	157
5.8.3	Implications for Headphone Listening.....	158
5.8.4	Implications for Low-Frequency Room Resonances.....	159
5.9	Conclusion.....	159
	References	160
6	The Perception and Measurement of Reflections	163
	FLOYD TOOLE	
6.1	A Single Reflection: The Precedence Effect and More	163
6.1.1	One Reflection—Several Audible Effects.....	167
6.1.2	A Real-World View of the Precedence Effect	169
6.1.3	Reflections From Different Directions	171

6.2	A Reflection in the Presence of Other Reflections	172
6.2.1	The “Family” of Curves in a Normal Room.....	173
6.3	Effects on Real and Phantom Images	174
6.4	Results With Music and Other Sounds	175
6.5	Reflecting, Absorbing and Diffusing Surfaces	177
6.5.1	Absorbing High Frequencies Is Not Enough	178
6.5.2	Reflections From Smooth vs. Irregular Surfaces	178
6.6	Interpreting the Measured Evidence of Reflections.....	181
6.6.1	Comb Filtering.....	181
6.6.2	Energy-Time Curves.....	184
	References	187
7	Space: A Motivator for More Channels.....	189
	FLOYD TOOLE	
7.1	Space Is Fundamental: Reflections Are Important.....	189
7.1.1	Perceptually Preferred Amounts of Reflected Sound.....	190
7.1.2	Perceptually Preferred Directions for Reflections.....	192
7.1.3	Perceptions of Space and Sound Quality Compared	196
7.2	How Many Channels Do We Need for Envelopment?	199
7.3	Elevation: The Missing Dimension	205
	References	208
8	Audio Formats: Part Two—Multichannel Audio.....	211
	FLOYD TOOLE	
8.1	Quadraphonics: Stereo Times Two—A Flawed Idea	211
8.1.1	Dolby Adapts the Technology to a Better Purpose	213
8.2	Discrete Multichannel Arrives	213
8.2.1	The Basic Functions Required of Multichannel Systems	214
8.2.2	The Subwoofer Channel: LFE and Bass Management	217
8.3	How Many Channels, Where and What For?.....	219
8.3.1	Immersive Audio Arrives	219
8.4	Multichannel Audio System Options	221
8.4.1	Channel Numbering Schemes	221
8.4.2	The Basics of System Layout.....	221
8.4.3	Dolby Atmos Music	223
8.5	Selecting the Appropriate Loudspeakers.....	224
8.5.1	Loudspeaker Directivity Requirements	225

8.5.2	Selecting Front, Left, Center and Right Loudspeakers	228
8.5.3	Selecting Surround Loudspeakers.....	231
8.5.4	A “Physics” Problem With Side Surrounds	234
8.5.5	Acoustical Treatments Can Help or Hinder.....	237
8.5.6	Domestic Room Systems vs. Custom Home Theaters.....	238
8.6	The Present and Possible Future of Multichannel Audio	240
8.6.1	Upmixing, Downmixing and Rendering.....	241
8.6.2	A Radical Upmixing Alternative: Create Your Own Concert Hall.....	242
8.6.3	Immersive Music Mixing Is Still Evolving.....	242
8.6.4	There Is More to Come: Next Generation Audio	243
	References	244
9	The Perceptual and Physical Dimensions of Sound	245
	FLOYD TOOLE	
9.1	The Frequency Domain.....	245
9.2	The Amplitude Domain.....	247
9.2.1	Absolute and Relative Sound Levels.....	247
9.2.2	Different Interpretations of Sound Pressure Levels.....	248
9.3	Amplitude and Frequency Together: Frequency Response.....	249
9.4	Amplitude and Frequency Together: Equal-Loudness Contours.....	253
9.4.1	Loudness Controls: Do They Work?.....	255
9.4.2	Loudness, Tone and Tilt Controls—A Summary	258
9.5	The Boundaries of What We Can Hear.....	260
9.5.1	What Is Acceptable Background Noise?.....	262
9.6	Linear Distortions: Amplitude, Phase and Polarity.....	263
9.6.1	Spectral Deviations From Flat and Smooth: Resonances.....	264
9.6.2	Resonances Viewed in Amplitude, Frequency and Time: Waterfalls.....	265
9.6.3	Critical Bands, ERBNs and the “Resolution” of the Hearing System.....	267
9.6.4	The Audibility of Phase Shift and Group Delay.....	269
9.6.5	Phase Shift at Low Frequencies—A Special Case	271

9.6.6	The Audibility of Absolute Polarity—Which Way Is “Up”?	272
9.7	Non-linear Distortion	272
9.8	Dynamic Range and Power Compression	275
9.9	Wavelength: The Key to Understanding Much in Audio	277
9.9.1	The Effects on Loudspeaker Directivity and Sound Quality	278
9.9.2	Acoustical Resonances in Rooms and Enclosures	280
9.9.3	Understanding Resistive and Membrane Absorbers	282
9.9.4	Diffusers and Other Sound-Scattering Devices	283
	References	284
10	Subjective Measurements: Turning Opinion Into Fact	287
	FLOYD TOOLE	
10.1	Seeing Is Believing: An Audio Placebo Effect?	289
10.1.1	Why Blind Listening Is Necessary	290
10.1.2	Hearing Ability and Listening Performance	293
10.2	Loudspeaker Reviewing Is a Challenge Few Can Meet	299
10.3	Designing Listening Tests	300
10.3.1	Is Stress a Factor? Relax	300
10.3.2	Stereo vs. Monophonic Listening	301
10.3.3	The Listening Room	302
10.3.4	Solutions for the Loudspeaker Position Problem	303
10.3.5	Solutions for Multiple Listener Tests	306
10.3.6	Making the Test Blind and Double-Blind	306
10.3.7	Binaural Record/Replay Loudspeaker Comparisons	307
10.3.8	Equal-Loudness Testing at a Known Loudness Level	308
10.3.9	Choosing Program Material	310
10.3.10	Electrical and Electronic Decisions	312
10.3.11	Listener Choice and Training	317
10.3.12	Cultural and National Biases	318
10.4	Loudness and Sound Level Measurements	319
10.5	Is It Preference or Accuracy That Is Evaluated?	323
	References	324

11	Closing the Loop: Predicting Listener Preferences From Measurements	329
	FLOYD TOOLE	
11.1	The Olive Experiments—Part One.....	332
11.2	The Olive Experiments—Part Two.....	334
11.3	The Olive Experiments—Part Three	335
11.4	Summary.....	338
	References	339
12	Room Acoustics and Acoustical Devices	341
	FLOYD TOOLE	
12.1	Reverberation Time	341
12.1.1	Measuring Reverberation Time	344
12.1.2	Calculating Reverberation Time	345
12.1.3	Is There a More Useful Metric for Our Purposes?	346
12.1.4	Diffusion in Small Rooms	347
12.2	Sound Propagation Basics	348
12.2.1	Point Sources.....	348
12.2.2	Near and Far Fields Influence How We Do Measurements	350
12.2.3	Line Sources	352
12.2.4	How Various Sources Interact With a Floor.....	353
12.2.5	Are Floor Reflections Special?.....	356
12.3	Propagation in Rooms With and Without Reflections	357
12.3.1	Classic Concert Hall Acoustics	357
12.3.2	Sound Propagation in Typical Listening Rooms.....	359
12.3.3	The Meaning of Steady-State Room Curves.....	360
12.3.4	One Loudspeaker in Many Rooms	364
12.3.5	The “Harman” Room Curve Is a Result, Not a Target	367
12.3.6	Personal Preferences for Spectral Balance.....	369
12.3.7	High Frequencies: Air Absorption and Screen Loss	370
12.4	Absorbers, Bass “Traps” and Diffusers	372
12.4.1	Porous/Resistance Absorbers.....	373
12.4.2	Diaphragmatic/Membrane Absorbers: Bass “Traps”	377
12.4.3	Geometric-Shape Diffusers	378
12.4.4	Engineered-Surface Diffusers.....	380
12.5	Loudspeakers and Rooms Determine “Translation”	382

12.5.1	A Perspective on the “Translation” of Recordings.....	383
12.5.2	Close Listening Is Useful, But . . .	384
12.5.3	Translation Viewed From the Reproduction End.....	385
12.5.4	Translation Recommendations.....	386
12.5.5	An Interesting Experiment: Blackbird Studio C.....	388
12.6	The Acoustical Treatment of Listening Rooms.....	390
12.6.1	Estimating Reverberation Time.....	393
	References.....	394
13	Acoustics: Adjacent-Boundary Effects.....	397
	FLOYD TOOLE	
13.1	The Effects of Solid Angles on Sound Radiated by Point Sources.....	397
13.2	Classic Adjacent-Boundary Effects.....	400
13.3	Alleviating Adjacent-Boundary Effects.....	401
13.3.1	Positioning the Woofer.....	401
13.3.2	Equalization.....	402
13.4	Loudspeaker Mounting Options and Effects.....	403
13.4.1	An Example of Adjacent-Boundary Interference.....	407
13.5	Boundary-Friendly Loudspeaker Designs.....	408
13.6	Listeners Also Have Boundaries.....	410
	References.....	412
14	Below the Transition Frequency: Optimizing the Experience.....	413
	TODD WELTI AND FLOYD TOOLE	
14.1	Objectives and Assumptions.....	413
14.2	The Basics of Room Resonances and Standing Waves.....	414
14.3	A More Complete Understanding.....	417
14.3.1	Modal Coupling Factors.....	419
14.3.2	Modal Resonances.....	420
14.3.3	Simplifying a Complex Situation.....	421
14.3.4	Tools for Modal Manipulation—A Preview.....	423
14.4	Generalized Optimization of Room Dimensions—Does an “Ideal” Room Exist?.....	424
14.4.1	Necessary Assumptions.....	425
14.4.2	Are Non-rectangular Rooms the Answer?.....	426
14.5	Solutions for the Real World.....	426
14.5.1	Deliver Energy to the Modes and Dissipate Some of That Energy With Absorbers.....	429

14.5.2	Deliver Energy to the Modes and Reduce the Coupling of That Energy to the Listener by Optimizing the Listening Location	434
14.5.3	Reduce the Energy Delivered to a Bothersome Mode by Optimizing the Loudspeaker/Subwoofer Location.....	436
14.5.4	Reduce the Energy Delivered to Bothersome Modes by Using Combined Coupling of Two Sources to Mode.....	438
14.5.5	Use Standardized Subwoofer Configurations for Generalized Multiple Subwoofer Mode Manipulation—Basic	441
14.5.6	Use Standardized Subwoofer Configurations for Generalized Multiple Subwoofer Mode Manipulation—Advanced.....	444
14.5.7	Manipulate Modes Using Multiple Subwoofers and Computer Optimized Signal Processing—Rectangular Rooms	448
14.5.8	Manipulate Modes Using Multiple Subwoofers and Computer Optimized Signal Processing—All Rooms.....	451
14.5.9	Final Equalization at Low Frequencies: Global Correction of System Response Without Modal Modification	455
14.5.10	Revisiting Room Resonances in Time and Space	457
14.5.11	Do We Hear the Spectral Bump, the Temporal Ringing or Both?	461
14.5.12	Stereo Bass: Little Ado About Even Less	464
14.5.13	Bass Management Makes It All Possible.....	465
14.6	Summary and Discussion	466
	References	467
15	Headphones: The Perception and Measurement of Their Sound Quality.....	469
	SEAN OLIVE	
15.1	The Psychoacoustics of Headphones	469
15.1.1	Spatial Impressions.....	469
15.1.2	Timbral Impressions	470
15.1.3	Reduced Sensitivity to Resonances.....	471
15.1.4	Lack of Tactile Experience in Headphones.....	471
15.1.5	Immersive Audio Over Loudspeakers vs. Binaural Headphones.....	472

15.1.6	Single Stimulus Comparisons, Auditory Memory and Adaptation.....	472
15.1.7	Summary	473
15.2	Headphones: The Primary Devices Through Which We Listen to Reproduced Sound.....	473
15.3	Types of Headphones	474
15.3.1	Headphones With Headbands.....	476
15.3.2	Headphones Without Headbands.....	477
15.3.3	Headphone Type and Hearing Loss	477
15.4	Headphone Test Fixtures	478
15.4.1	Type 3.3 Ear Simulator.....	480
15.4.2	Type 4.3 Ear Simulator.....	480
15.4.3	Head and Torso Simulators	480
15.4.4	Headphone Measurement Challenges.....	480
15.4.5	Effect of Test Fixture on Headphone Measurements.....	481
15.4.6	Comparing Headphones Measured on Humans vs. Test Fixtures	484
15.4.7	Reproducibility of Headphone Measurements on Humans.....	486
15.4.8	The Hyperion Project.....	487
15.4.9	Measuring ANC Performance and Transparency in Headphones.....	488
15.5	A History of Preferred Headphone Calibrations: Free, Diffuse and Semi-reflective Fields.....	489
15.5.1	Free-Field Calibration.....	490
15.5.2	Diffuse-Field Calibration.....	490
15.5.3	The Semi-reflective Field (SRF) Calibration	491
15.6	The Harman Research (2012–2024).....	492
15.6.1	Headphone Listening Test Methods: Physical Substitution	492
15.6.2	The Virtual Headphone Method	493
15.6.3	The Harman Headphone Target Curve	494
15.6.4	Testing Harman Target Curve Against Three Highly Regarded Headphones	496
15.6.5	Listeners' Preferred Levels of Bass and Treble.....	497
15.6.6	Benchmarking the Harman Target Against 31 Models.....	499
15.6.7	Segmentation of Listeners Based on Preferred Headphone Sound Profile	499
15.6.8	Predicting Listener Headphone Preferences Based on Objective Measurements	501

15.6.9	Harman IE Headphone Target for B&K 5128	503
15.6.10	Proper Application of the Harman Research.....	506
15.7	No Correlation Between Price and Frequency Response or Predicted Sound Quality	507
15.8	Harman Target Tested Against Other Proposed Targets	509
15.8.1	Sonarworks.....	509
15.8.2	Knowles IE Headphone Target Curve.....	510
15.8.3	SoundGuys.....	511
15.8.4	Rtings.....	512
15.8.5	SenseLab Study.....	513
15.8.6	Headphones.com: Preference Bounds and DF Calibration	515
15.9	The Three Faces of Harman Targets.....	516
15.10	Headphones for Spatial Audio.....	518
15.10.1	Growth in Immersive Audio	518
15.10.2	Is There a Different Headphone Target for Spatial Audio?.....	518
15.11	Topics for Future Research	519
15.12	Conclusions	520
	References	521
16	Hearing Loss and Hearing Conservation.....	527
	FLOYD TOOLE	
16.1	Occupational Noise Exposure Limits.....	529
16.1.1	What Can Audio Professionals Do for Protection?.....	530
16.2	Non-occupational Noise Exposure	531
16.3	Hidden Hearing Losses.....	531
16.4	What Is Enjoyment? It Might Depend on Speech Clarity.....	532
16.5	Obsession Can Be a Good Thing.....	535
	References	535
17	Summary and Conclusions.....	537
	FLOYD TOOLE	
17.1	Interpreting Anechoic Data	538
17.2	Looking Back 60 Years.....	541
17.3	Where Are We Now?	545
	INDEX.....	549