

# Table of contents

Cover page	i
Contact information	ii
Abstract	iii
Inscription	v
Preface	vi
Invictus	ix
Table of contents	x
List of symbols	xvi
List of abbreviations	xxi
<b>1 INTRODUCTION</b>	<b>1</b>
<b>1.1 Spatial sound — three dimensional sound</b>	<b>1</b>
<b>1.2 Utilization of spatial hearing</b>	<b>2</b>
<b>1.3 Research objectives and paradigms</b>	<b>3</b>
<b>1.4 Outline of study</b>	<b>4</b>
<b>2 SPATIAL HEARING</b>	<b>5</b>
<b>2.1 Auditory system</b>	<b>5</b>
2.1.1 External ear	6
2.1.2 Middle ear	6
2.1.3 Inner ear	7
2.1.4 Auditory nervous system	7
<b>2.2 System of coordinates</b>	<b>8</b>
<b>2.3 Sound localization</b>	<b>9</b>
<b>2.4 Homosensory theories, models and cues of spatial hearing</b>	<b>9</b>
2.4.1 Interaural time difference	10
2.4.2 Interaural level difference	12
2.4.3 Torus (cone) of confusion	12
2.4.4 Ear canal	13
2.4.5 Pinnae and pinnae cavities	13
2.4.6 Torso and head	17
2.4.7 Distance perception	17
2.4.8 Early reflections	17
2.4.9 Binaural auditory models for complex signals	18
<b>2.5 Multisensory support for spatial hearing</b>	<b>18</b>
2.5.1 Motional effects	19
2.5.2 Vision	19
2.5.3 Tactile and vestibular senses	20
<b>2.6 Cross-modal induction in spatial hearing</b>	<b>20</b>
2.6.1 Ventriloquism effect	20
2.6.2 McGurk effect	20
2.6.3 Effects of attention	21

<b>3</b>	<b>HRTF ACQUISITION AND PROCESSING</b>	<b>22</b>
<b>3.1</b>	<b>Head-related transfer function: free-field transfer function</b>	<b>22</b>
3.1.1	Free-field transmission model	23
3.1.2	Microphone placement along auditory canal	24
3.1.3	HRTF compensation	24
3.1.4	Individual HRTF equalization: headphone-to-ear transfer function	25
3.1.5	Generalized HRTFs: free-field and diffuse-field equalization	26
<b>3.2</b>	<b>HRTF measurement and auditory experimentation systems</b>	<b>26</b>
3.2.1	Experimentation environment	27
3.2.2	System constructions	27
3.2.3	System electromechanics	28
3.2.4	System electronics	30
3.2.5	Test subject positioning	32
3.2.6	HRIR measurements	33
<b>3.3</b>	<b>Digital signal processing of HRTFs</b>	<b>33</b>
3.3.1	Windowing	34
3.3.2	Auditory resolution in binaural hearing?	34
3.3.3	Minimum-phase reconstruction	35
3.3.4	ITD estimation from measured HRTFs	35
3.3.5	System compensation of measured HRIRs	36
<b>4</b>	<b>HRTF AND PTF REPEATABILITY</b>	<b>37</b>
<b>4.1</b>	<b>Attributes affecting HRTF variability and repeatability</b>	<b>37</b>
4.1.1	Acoustic disturbances	38
4.1.2	Physical inconveniences	38
4.1.3	Measurement errors	39
4.1.4	Perceptually justified means of analysis	40
<b>4.2</b>	<b>Fundamental quality: effect of experiment system and surroundings</b>	<b>40</b>
4.2.1	Quality of measurement system: measurement repeatability	41
4.2.2	Long-term stability of measurement system	44
4.2.3	Effect of measurement chair and simulated torso	47
4.2.4	Robustness of system compensation method	48
4.2.5	Summary	50
<b>4.3</b>	<b>Ideal quality: repeatability of dummy head HRTFs</b>	<b>50</b>
4.3.1	Properties of Cortex MK II manikin	50
4.3.2	Measurement techniques and set-up	51
4.3.3	Robustness of measurement method	51
4.3.4	Dual effect on microphone position variation	52
4.3.5	Effects of microphone displacement and variation in occlusion of artificial meatus	54
4.3.6	Summary	55
<b>4.4</b>	<b>Repeatability of careful real head measurements</b>	<b>55</b>
4.4.1	Effect of microphone displacement	58
4.4.2	Effect of varying degree of concha occlusion	60
4.4.3	Effect of ear plug type	61
4.4.4	Summary	61

<b>4.5</b>	<b>Repeatability of practical real head measurements</b>	<b>64</b>
4.5.1	Fit of ear plug	64
4.5.2	Measurement method and procedure	65
4.5.3	Course of analysis	66
4.5.4	Effect of repetition: microphone insertion consistency	67
4.5.5	Effect of ear plug	68
4.5.6	Effect of experimenter	73
4.5.7	Total deviation: global HRTF quality	73
4.5.8	Discussion and comparison to literature	74
<b>4.6</b>	<b>Headphone-to-ear transfer function measurement repeatability and variability</b>	<b>76</b>
4.6.1	Headphone to ear coupling	76
4.6.2	Attributes affecting PTF uncertainty	77
4.6.3	Consecutive measurement repeatability applying dummy head	78
4.6.4	Insert-headphone-to-artificial-ear-canal repeatability	78
4.6.5	Significance of ear canal cross-section at low-frequencies?	81
4.6.6	Intra-subject variability and within-trial repeatability	81
4.6.7	Generic PTF repeatability and variability	83
4.6.8	Performance criteria for headphones	86
4.6.9	Summary and comparison to previous studies	88
<b>5</b>	<b>HRTF VARIABILITY VS. IDIOSYNCRASY</b>	<b>90</b>
<b>5.1</b>	<b>Inter-subject variability vs. generic acoustical phenomena</b>	<b>90</b>
5.1.1	Single direction: maximal head shadow	91
5.1.2	Time domain reflections in median plane	92
5.1.3	Median plane resonance structures	93
5.1.4	Horizontal plane HRTF characteristics	94
5.1.5	Frontal plane characteristics	100
5.1.6	Interaural time difference	102
5.1.7	Empirical comparison of analytical HRTF and ITD models	102
5.1.8	Summary and comparison to literature	105
<b>5.2</b>	<b>Prominence of HRTF idiosyncrasy</b>	<b>107</b>
5.2.1	Individual behavior: repeatability vs. idiosyncrasy	107
5.2.2	HRTF equalization	109
5.2.3	Effect of measurement distance	114
<b>5.3</b>	<b>HRTF robustness: effects of postural changes of subject and head</b>	<b>118</b>
5.3.1	Positioning accuracy of test subject	118
5.3.2	Tilted head	119
5.3.3	Pivoted head	123
5.3.4	Rotated subject vs. head	125
5.3.5	Head movements	128
5.3.6	Effects on interaural time difference	130
5.3.7	Comparison to literature: reflections and diffractions inside concha	132
5.3.8	Summary	133
<b>5.4</b>	<b>HRTF personality: effect of outward appearance — hair/style, spectacles, garments and headpieces</b>	<b>135</b>
5.4.1	Measurement surroundings and method	135
5.4.2	Measurement conditions	136
5.4.3	Effect of hair	137

5.4.4	Effect of hairstyle	141
5.4.5	Effect of spectacles	149
5.4.6	Effect of clothes	151
5.4.7	Effect of headpieces	154
5.4.8	Combinatory effects: outward attributes composed in HRTFs	158
5.4.9	Effect of anatomical changes	159
5.4.10	Summary and comparison to literature	161
<b>6</b>	<b>COMPUTATIONAL HRTF EVALUATION</b>	<b>163</b>
<b>6.1</b>	<b>Detection of measurement errors and inaccuracies</b>	<b>163</b>
6.1.1	Reversed channels	164
6.1.2	Electrical errors	164
6.1.3	Estimation and equalization for bilateral asymmetry in anatomy, meatus/concha occlusion and microphone placement	164
6.1.4	Estimation of static and dynamic changes in head posture based on symmetry assumptions	166
6.1.5	Estimation of data deterioration based on template matching	170
<b>6.2</b>	<b>Quantitative HRTF analysis: inspection of deviance</b>	<b>171</b>
6.2.1	Estimation of deviant measurements	172
6.2.2	Evaluation of HRTF database	173
<b>6.3</b>	<b>Quantitative estimation of HRTF idiosyncrasy</b>	<b>175</b>
6.3.1	Hrtf matching calculus	175
6.3.2	Implications to sound localization behavior	179
<b>6.4</b>	<b>Summary</b>	<b>179</b>
<b>7</b>	<b>PERCEPTUAL HRTF EVALUATION</b>	<b>182</b>
<b>7.1</b>	<b>Objectives for listening tests</b>	<b>182</b>
7.1.1	Utilization of naïve subjects + one trained subject	184
7.1.2	Hearing skills of test persons	185
<b>7.2</b>	<b>Common experimentation equipment and methods</b>	<b>186</b>
7.2.1	Creation of real source positions	186
7.2.2	Crystal ball	187
7.2.3	Keypad	188
7.2.4	Targeting lights	188
7.2.5	Unides ADU1a audio stimulator	189
<b>7.3</b>	<b>Analyses of sound localization experiments</b>	<b>189</b>
7.3.1	Definition of localization error	189
7.3.2	Common treatment of judgment confusions	190
7.3.3	Developed methods for treating judgment confusions	191
7.3.4	Visualization approaches of sound localization data: scatter plots	194
7.3.5	Previous methods of statistical analyses	195
7.3.6	Treatment of judgment reversals	197
7.3.7	Spatial pre-processing	197
7.3.8	Treatment of erroneous and inside-the-head localization data	198
7.3.9	Statistical factor analyses	199
<b>7.4</b>	<b>Experiments 1 – 2: localization of real and individualized virtual sources</b>	<b>201</b>
7.4.1	Experiment 1 procedure	202

7.4.2	Experiment 2 procedure	203
7.4.3	Working hypotheses for statistical analyses	203
7.4.4	Typical localization performances in Experiment 1	204
7.4.5	Typical localization performances in Experiment 2	205
7.4.6	Statistical analyses of full target space	206
7.4.7	Statistical analyses of quadrant space	216
7.4.8	Matters affecting absolute localization accuracy: problems in comparisons between experiments	217
7.4.9	Externalization of sound sources	219
7.4.10	Comparison to previous works	219
7.4.11	Summary	225
<b>7.5</b>	<b>Experiment 3: effect of microphone position and reproduction equipment</b>	<b>227</b>
7.5.1	Experiment 3 conditions and procedure	227
7.5.2	Working hypotheses for statistical analyses	228
7.5.3	Scatter plots from chosen subjects	229
7.5.4	Statistical analyses of full target space	230
7.5.5	Statistical analyses of quadrant space	238
7.5.6	Inside-the-head localization	240
7.5.7	Comparison to previous works and Experiment 2	240
7.5.8	Summary	244
<b>7.6</b>	<b>Experiment 4: effect of outward appearance and HRTF recording position</b>	<b>245</b>
7.6.1	Working hypotheses for statistical analyses	245
7.6.2	Scatter plots from chosen subjects	246
7.6.3	Statistical analyses of full target space	247
7.6.4	Statistical analyses of quadrant space	251
7.6.5	Inside-the-head localization	255
7.6.6	Individual performance: effect of background and experience	256
7.6.7	Comparison to previous experiments	256
7.6.8	Summary	260
<b>7.7</b>	<b>Experiment 5: evaluation of HRTF idiosyncrasy</b>	<b>261</b>
7.7.1	Working hypotheses for statistical analyses	261
7.7.2	Scatter plots from all subjects	262
7.7.3	Statistical analyses of full target space	264
7.7.4	Statistical analyses of quadrant space	272
7.7.5	Inside-the-head localization	274
7.7.6	Individual performance and comparison to previous experiments	274
7.7.7	Summary	277
<b>7.8</b>	<b>Experiment 6: localization blur of virtual sources</b>	<b>280</b>
7.8.1	Experiment procedure	280
7.8.2	Working hypotheses for statistical analyses	281
7.8.3	Scatter plots from all subjects	282
7.8.4	Statistical analyses of full target space	284
7.8.5	Statistical analyses of quadrant space	290
7.8.6	Externalization of sound sources	292
7.8.7	Individual performance and comparison to previous experiments: special characteristics of sound localization by naïve subjects	293
7.8.8	Summary	295

<b>7.9</b>	<b>Experiment 7: effect of binaural recording position near the blocked pinna</b>	<b>298</b>
7.9.1	Experiment procedure and conditions	298
7.9.2	Working hypotheses for statistical analyses	299
7.9.3	Scatter plots from all subjects	300
7.9.4	Statistical analyses of full target space	306
7.9.5	Statistical analyses of quadrant space	307
7.9.6	Inside-the-head localization	308
7.9.7	Individual performance and comparison to previous experiments	308
7.9.8	Summary and comparison to literature	309
<b>7.10</b>	<b>Meta-analyses of Experiments 1 – 7</b>	<b>310</b>
7.10.1	Meta-analyses A: free-field localization	315
7.10.2	Meta-analyses B: localization of individual far-field virtual sources	315
7.10.3	Between-experiment analyses C and D: localization of far-field non-individual virtual sources — existence of ‘golden’ HRTFs?	316
7.10.4	Between-experiment analyses E – G: localization of near- vs. far-field virtual sources — idiosyncratic HRTF distance effect?	317
7.10.5	Summary	320
<b>7.11</b>	<b>Experiment AV-1: spatial segregation in McGurk effect applying virtual auditory stimuli</b>	<b>322</b>
7.11.1	Experiment method and procedure	322
7.11.2	Population performance	323
7.11.3	Statistical analyses of results	324
7.11.4	Comparison to previous studies	324
<b>7.12</b>	<b>Experiment AV-2: effects of congruency on localization of audiovisual 3-D speech sounds</b>	<b>324</b>
7.12.1	Experiment method and procedure	326
7.12.2	Population performance	326
7.12.3	Statistical analyses of results	326
7.12.4	Summary and comparison to previous experiments	330
<b>7.13</b>	<b>Experiment N: human cortical representation of virtual auditory space</b>	<b>331</b>
7.13.1	Virtual auditory stimuli	331
7.13.2	Neuromagnetic recordings	332
7.13.3	Results	334
7.13.4	Discussion	334
<b>7.14</b>	<b>Perceptual salience of localization cues and implications to cortical processing</b>	<b>336</b>
7.14.1	Dynamic (motional) cues — morphological processing in the auditory cortex	336
7.14.2	Static cues — associative processing in the auditory cortex	336
<b>8</b>	<b>CONCLUSIONS</b>	<b>338</b>
<b>8.1</b>	<b>Main results</b>	<b>338</b>
A)	Empirical HRTF repeatability, variability and idiosyncrasy analysis	338
B)	Computational HRTF evaluation	340
C2)	Subjective HRTF evaluation	341
C3)	Cross-modal interaction between vision and spatial hearing, applying non-individual virtual speech sounds	343
C4)	Human auditory processing and cortical representation of virtual auditory space	344
	<b>REFERENCES</b>	<b>345</b>
	<b>APPENDIX A</b>	<b>358</b>