

# **Contents**

---

<b>Abstract</b>	<b>iii</b>
<b>Resumen</b>	<b>v</b>
<b>Resum</b>	<b>vii</b>
<b>List of Figures</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	3
1.2 Objectives . . . . .	5
1.3 Organization of the thesis . . . . .	6
<b>2 Background</b>	<b>9</b>
2.1 Principles of spatial hearing . . . . .	10
2.1.1 Interaural Differences . . . . .	11
2.1.2 Spectral cues . . . . .	12
2.1.3 Distance cues . . . . .	12
2.1.4 Dynamic cues . . . . .	13
2.2 Spatial sound systems classification . . . . .	14
2.2.1 Based on amplitude panning . . . . .	14
2.2.2 Based on binaural reconstruction . . . . .	15
2.2.3 Based on acoustic field synthesis . . . . .	16
2.3 Panning with loudspeakers . . . . .	17
2.3.1 The phantom effect . . . . .	18
2.3.2 Stereophony and multichannel sound . . . . .	18
2.3.3 Vector Base Amplitude Panning VBAP . . . . .	21
2.4 Binaural sound . . . . .	23
2.4.1 The HRTF . . . . .	24
2.4.2 Problems of binaural sound . . . . .	25
2.4.3 HRTF individualization techniques . . . . .	27
2.4.4 Headphones equalization . . . . .	30
2.4.5 Conversion to binaural . . . . .	31
2.5 Wave-Field Synthesis principles . . . . .	33

<b>I Headphones and binaural systems</b>	<b>37</b>
<b>3 Effects of Headphones in perception</b>	<b>39</b>
3.1 Perception of quality and immersion . . . . .	41
3.1.1 Introduction and motivation . . . . .	41
3.1.2 Measurements and Virtual Headphone Simulation .	43
3.1.3 Test 1. Sensitivity Disparity between Left-Right Transducers . . . . .	51
3.1.4 Test 2. Frequency Response on Quality and Spatial Impressions . . . . .	55
3.1.5 Test 3. Non-Linear Distortion . . . . .	59
3.1.6 Test 4. Frequency Response on Binaural Azimuth Localization . . . . .	61
3.1.7 Conclusions . . . . .	66
3.2 Perception of non-linear distortion caused by equalization .	68
3.2.1 Introduction and motivation . . . . .	68
3.2.2 Measurements, equalization and non-linear distortion simulation . . . . .	69
3.2.3 Perceptual test . . . . .	73
3.2.4 Conclusions and future work . . . . .	75
<b>4 HRTF measurements</b>	<b>77</b>
4.1 Introduction and motivation . . . . .	77
4.2 Constructed HRTF measurement system . . . . .	81
4.2.1 Room conditioning . . . . .	81
4.2.2 The speaker set-up and hardware . . . . .	83
4.2.3 Measurement software. Exponential sweep and Multiple exponential sweep method . . . . .	86
4.2.4 Procedure protocol and measurement checking . . .	90
4.2.5 SOFA format . . . . .	92
4.3 Post-processing of the measurements . . . . .	94
4.3.1 Level and loudspeaker response correction . . . . .	94
4.3.2 Removal of reflections by Frequency Dependant Windowing . . . . .	95
4.3.3 Lowest-frequencies reconstruction . . . . .	97
4.4 Proposed method to remove low-frequency reflections by Plane Wave Decomposition . . . . .	100
4.4.1 Problem formulation and background . . . . .	101
4.4.2 General description of the proposed method . . . . .	105

---

4.4.3	Validation of the method with real measurements . . . . .	111
4.5	Supplementary headphones measurements and compensation filters . . . . .	118
4.6	Conclusions and future work . . . . .	122
<b>5</b>	<b>HRTF individualization tools</b>	<b>125</b>
5.1	HRTF magnitude parametric modeling . . . . .	127
5.1.1	Introduction and motivation . . . . .	127
5.1.2	Individual HRIR measure and preprocessing . . . . .	130
5.1.3	Parametric model description . . . . .	134
5.1.4	Test description . . . . .	136
5.1.5	Analysis of the results . . . . .	139
5.1.6	Conclusions and future work . . . . .	142
5.2	ITD scaling . . . . .	144
5.2.1	Introduction and motivation . . . . .	144
5.2.2	BRIR measurements and extraction of objective variables . . . . .	146
5.2.3	ITD manipulation . . . . .	152
5.2.4	Test description . . . . .	152
5.2.5	Outlier responses treatment . . . . .	157
5.2.6	Analysis of the results . . . . .	158
5.2.7	Prediction of individual ITD scaling factor by polynomial equations . . . . .	163
5.2.8	Conclusions and future work . . . . .	168
<b>II</b>	<b>Loudspeaker based systems</b>	<b>171</b>
<b>6</b>	<b>Distance perception comparison between WFS and VBAP</b>	<b>173</b>
6.1	Introduction and motivation . . . . .	173
6.2	Test description . . . . .	175
6.3	Analysis of the results . . . . .	179
6.4	Conclusions . . . . .	184
<b>7</b>	<b>Perceptual spatial acuity of spectrally divided sound sources</b>	<b>187</b>
7.1	Introduction and motivation . . . . .	187
7.1.1	Coloration effects in loudspeaker reproduction . . . . .	188
7.1.2	Concurrent Minimal Audible Angle (CMAA) . . . . .	189
7.1.3	Work motivation . . . . .	190

---

7.2	Experimental approach . . . . .	191
7.3	Test 1. Left/Right distinction . . . . .	192
7.4	Test 2. Angle of arrival . . . . .	196
7.5	Test 3. Source width . . . . .	198
7.6	Conclusions and applications . . . . .	202
<b>8</b>	<b>Conclusions and future work</b>	<b>205</b>
8.1	Conclusions and contributions to knowledge . . . . .	205
8.2	Future work . . . . .	211
8.3	List of publications . . . . .	213
	<b>Bibliography</b>	<b>217</b>