

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Hypothesis and objectives . . . . .	2
1.1.1	BFV analysis in different navigation conditions . . . . .	4
1.1.2	BFV analysis in different immersive conditions . . . . .	6
1.1.3	BFV analysis during a visual perception task . . . . .	7
1.1.4	BFV analysis during motor tasks . . . . .	8
1.2	Structure . . . . .	8
<b>2</b>	<b>Presence</b>	<b>15</b>
2.1	Concept of presence . . . . .	15
2.2	Dimensions of presence . . . . .	16
2.3	Causes and consequences of presence . . . . .	18
2.3.1	Causes of presence . . . . .	18
2.3.2	Consequences of presence . . . . .	19
2.4	Relationship of presence with other factors of the VE experience . . . . .	19
2.4.1	Presence and performance . . . . .	20
2.4.2	Presence and emotional state . . . . .	20
2.4.2.1	Fear of heights . . . . .	21
2.4.2.2	VR Mood Induction Procedures . . . . .	22
2.4.2.3	Other kinds of emotional VE . . . . .	23
2.4.3	Presence and technology . . . . .	24
2.4.3.1	Stereoscopy . . . . .	25
2.4.3.2	Type of display . . . . .	26

2.4.3.3	Field of view . . . . .	29
2.4.3.4	Other visual aspects . . . . .	30
2.4.3.5	Other sensorial inputs . . . . .	31
2.4.3.6	Interaction . . . . .	32
2.5	Presence measurement . . . . .	34
2.5.1	Subjective measures . . . . .	35
2.5.2	Objective measures . . . . .	38
2.5.2.1	Behavioral measures . . . . .	38
2.5.2.2	Peripheral physiological measures . . . . .	40
2.5.2.3	Neurological measures . . . . .	44
2.5.3	Breaks in presence (BIPs) . . . . .	49
<b>3</b>	<b>Transcranial Doppler Monitoring</b>	<b>51</b>
3.1	Doppler Ultrasound . . . . .	51
3.1.1	Doppler Effect . . . . .	51
3.1.1.1	Introduction . . . . .	51
3.1.1.2	Emission focus in movement . . . . .	52
3.1.1.3	Observer in movement . . . . .	54
3.1.2	Doppler Ultrasound principles . . . . .	54
3.1.2.1	Blood cell velocity . . . . .	54
3.1.2.2	Insonation angle . . . . .	56
3.1.2.3	Spectral analysis . . . . .	59
3.1.2.4	Ultrasound Doppler techniques . . . . .	60
3.2	Transcranial Doppler Ultrasound . . . . .	62
3.2.1	TCD unit and probes . . . . .	62
3.2.2	Windows . . . . .	63
3.2.3	Blood flow velocity measures . . . . .	64
3.2.4	Blood flow velocity and cerebral blood flow . . . . .	67
3.2.5	Cortical areas supplied by the cerebral vessels. . . . .	69
3.2.5.1	Middle cerebral arteries . . . . .	70
3.2.5.2	Anterior cerebral arteries . . . . .	71
3.2.5.3	Posterior cerebral arteries . . . . .	72
3.2.6	TCD advantages and disadvantages . . . . .	72
3.3	TCD in psychophysiological studies . . . . .	73
3.3.1	Visual perception tasks . . . . .	73

3.3.2	Language . . . . .	76
3.3.3	Motor tasks . . . . .	77
3.3.4	Emotions . . . . .	79
3.3.5	Vigilance and attention tasks . . . . .	80
3.3.6	Video games . . . . .	81
3.3.7	Other tasks . . . . .	82
3.4	Blood flow velocity signal analysis . . . . .	83
3.4.1	BFV signal analysis in functional studies . . . . .	83
3.4.1.1	One execution of the experimental task . . . . .	84
3.4.1.2	Repetitive executions of the experimental task . . . . .	86
3.4.2	Other analyses of the BFW signal . . . . .	89
3.4.2.1	Spectral analysis . . . . .	89
3.4.2.2	Non-linear analysis . . . . .	91
<b>4</b>	<b>Methods</b>	<b>95</b>
4.1	BFV analysis in different navigation conditions . . . . .	95
4.1.1	Participants . . . . .	96
4.1.2	Apparatus . . . . .	96
4.1.3	Virtual reality setting . . . . .	96
4.1.4	Software . . . . .	100
4.1.5	Procedure . . . . .	102
4.1.5.1	Preliminary phase . . . . .	102
4.1.5.2	Exposure to the VE . . . . .	106
4.1.5.3	Training stage . . . . .	106
4.1.5.4	Free navigation condition . . . . .	107
4.1.5.5	Automatic navigation condition . . . . .	108
4.1.5.6	BIPs . . . . .	108
4.1.5.7	Presence questionnaires . . . . .	110
4.1.6	Data analysis . . . . .	110
4.1.6.1	Comparison of SUS questionnaire responses between the free navigation condition and the automatic navigation condition . . . . .	111
4.1.6.2	Comparison of BFW between repose periods and VE exposure periods . . . . .	112

4.1.6.3	Correlation between SUS responses and BFV values during the different navigation conditions . . . . .	113
4.1.6.4	Comparison of BFV variations in the free navigation condition and the automatic navigation condition . . . . .	114
4.1.6.5	Analysis of BFV signal when BIPs occur .	114
4.2	BFV analysis in different immersive conditions . . . . .	116
4.2.1	Participants . . . . .	117
4.2.2	Apparatus . . . . .	117
4.2.3	Virtual reality setting . . . . .	117
4.2.4	Software . . . . .	117
4.2.5	Procedure . . . . .	118
4.2.6	Data Analysis . . . . .	118
4.2.6.1	SUS-questionnaires analysis . . . . .	119
4.2.6.2	Comparison of BFV variations in the free navigation condition and the automatic navigation condition . . . . .	120
4.3	BFV analysis during a visual perception task . . . . .	120
4.3.1	Participants . . . . .	120
4.3.2	Apparatus . . . . .	121
4.3.3	Procedure . . . . .	121
4.3.3.1	Preliminary phase . . . . .	121
4.3.3.2	Visual stimulation . . . . .	121
4.3.3.3	Final stage . . . . .	122
4.3.4	BFV signal analysis . . . . .	122
4.3.4.1	Data normalization . . . . .	123
4.3.4.2	Spectral analysis . . . . .	123
4.3.4.3	Low-frequency estimation . . . . .	124
4.3.4.4	Calculus of BFV parameters . . . . .	125
4.3.5	Statistical analysis . . . . .	126
4.4	BFV analysis during motor tasks . . . . .	126
4.4.1	Participants . . . . .	126
4.4.2	Apparatus . . . . .	126
4.4.3	Procedure . . . . .	127

4.4.3.1	Preliminary phase . . . . .	127
4.4.3.2	Motor tasks . . . . .	128
4.4.3.3	Final stage . . . . .	128
4.4.4	Registering and pre-processing BFV signals . . . . .	129
4.4.4.1	BFV signal features . . . . .	129
4.4.4.2	Pre-processing . . . . .	130
4.4.5	Non-linear Analysis of BFV signals . . . . .	132
4.4.5.1	Introduction . . . . .	132
4.4.5.2	Surrogates method . . . . .	133
4.4.5.3	Multiscale entropy . . . . .	134
4.4.5.4	Correlation dimension . . . . .	141
4.4.5.5	Fractal dimension using the Katz method .	147
4.4.5.6	Maximum Lyapunov exponent . . . . .	148
4.4.6	Statistical Analysis . . . . .	150
<b>5</b>	<b>Results</b>	<b>153</b>
5.1	BFV analysis in different navigation conditions . . . . .	153
5.1.1	Comparison of SUS questionnaire responses between the free navigation condition and the automatic navigation condition . . . . .	154
5.1.2	Comparison of BFV between repose periods and VE exposure periods . . . . .	155
5.1.2.1	MCA-L results . . . . .	158
5.1.2.2	MCA-R results . . . . .	159
5.1.2.3	ACA-L results . . . . .	160
5.1.2.4	ACA-R results . . . . .	161
5.1.2.5	Global results . . . . .	162
5.1.3	Correlation between SUS responses and BFV values during the different navigation conditions . . . . .	163
5.1.4	Comparison of BFV variations in the free navigation condition and the automatic navigation condition .	165
5.1.5	Analysis of BFV signal when BIPs occur . . . . .	166
5.1.5.1	Evolution of the BFV signal during BIPs .	167
5.1.5.2	Evolution of the BFV signal during recoveries from BIPs . . . . .	171

5.2	BFV analysis in different immersive conditions . . . . .	174
5.2.1	SUS questionnaire analysis . . . . .	174
5.2.2	Comparison of Bfv variations in the free navigation condition and the automatic navigation condition . .	177
5.3	BFV analysis during a visual perception task . . . . .	179
5.3.1	Spectral Estimation . . . . .	180
5.3.2	Low-frequency estimation . . . . .	182
5.3.3	Bfv parameters . . . . .	183
5.4	BFV Analysis during motor tasks . . . . .	186
5.4.1	Surrogates . . . . .	186
5.4.2	Multiscale entropy . . . . .	189
5.4.2.1	Descriptive statistics . . . . .	189
5.4.2.2	Comparison between the different experimental conditions . . . . .	194
5.4.3	Correlation dimension . . . . .	199
5.4.3.1	Descriptive statistics . . . . .	201
5.4.3.2	Comparison between the different experimental conditions . . . . .	201
5.4.4	Fractal dimension using the Katz method . . . . .	203
5.4.4.1	Descriptive statistics . . . . .	203
5.4.4.2	Comparison between the different experimental conditions . . . . .	203
5.4.5	Maximum Lyapunov exponent . . . . .	204
5.4.5.1	Descriptive statistics . . . . .	204
5.4.5.2	Comparison between the different experimental conditions . . . . .	204
<b>6</b>	<b>Discussion</b>	<b>207</b>
6.1	General comments . . . . .	207
6.1.1	Comparison of TCD with other brain imaging techniques . . . . .	207
6.1.2	Comments about the experimental design of the different studies . . . . .	209
6.1.2.1	Physiological measurements . . . . .	209
6.1.2.2	Position of the subjects during the experience	210

6.2	BFV analysis in different navigation conditions . . . . .	210
6.2.1	Vessel selection . . . . .	210
6.2.2	Presence Questionnaires . . . . .	211
6.2.3	Selected features for BFV analysis . . . . .	211
6.2.4	Comparison of BFV between repose periods and VE exposure periods . . . . .	212
6.2.5	Comparison of BFV variations in the free navigation condition and the automatic navigation condition .	214
6.2.6	Analysis of BFV signal when BIPs occur . . . . .	215
6.2.6.1	Responses during BIPs . . . . .	215
6.2.6.2	Responses during recovery periods . . . . .	217
6.3	BFV analysis in different immersive conditions . . . . .	218
6.3.1	Effects of navigation . . . . .	219
6.3.1.1	SUS questionnaires . . . . .	219
6.3.1.2	BFV percentage variations . . . . .	219
6.3.2	Effects of Immersion . . . . .	220
6.3.2.1	SUS questionnaires . . . . .	220
6.3.2.2	BFV percentage variations . . . . .	220
6.3.3	Effects of navigation x immersion . . . . .	220
6.3.3.1	SUS questionnaires . . . . .	220
6.3.3.2	BFV percentage variations . . . . .	221
6.3.4	Global comments about immersion and navigation .	222
6.4	BFV analysis during a visual perception task . . . . .	222
6.4.1	General comments . . . . .	222
6.4.2	Vessel selection . . . . .	223
6.4.3	BFV features analysis . . . . .	223
6.4.4	Final comments . . . . .	225
6.5	BFV analysis during motor tasks . . . . .	226
6.5.1	General comments . . . . .	226
6.5.2	Vessel selection . . . . .	226
6.5.3	Non-linearity of the Doppler BFV signal . . . . .	227
6.5.4	Selection of non-linear features for the analysis .	227
6.5.5	Discussion about MSE results . . . . .	229
6.5.6	Discussion about other non-linear measures . . . . .	232
6.5.6.1	Correlation dimension . . . . .	232

6.5.6.2	Fractal dimension using Katz method . . . . .	232
6.5.6.3	Maximum Lyapunov Exponent . . . . .	233
6.5.7	Final comments . . . . .	233
<b>7</b>	<b>Conclusions</b>	<b>235</b>
7.1	Contributions of the present PhD Thesis . . . . .	235
7.1.1	Virtual Therapy . . . . .	236
7.1.2	Augmented Cognition . . . . .	237
7.2	Publications . . . . .	238
7.2.1	Publications in journals included in the JCR Science Edition . . . . .	238
7.2.2	Publications in other journals . . . . .	239
7.2.3	Book chapters - Conference proceedings . . . . .	240
7.2.4	Other conferences . . . . .	241
7.3	Future work . . . . .	242
<b>A</b>	<b>List of acronyms</b>	<b>245</b>
<b>B</b>	<b>SUS Questionnaires</b>	<b>247</b>
<b>C</b>	<b>BFV analysis in different navigation conditions. Analysis of Normality</b>	<b>249</b>
<b>D</b>	<b>BFV analysis in different immersive conditions. Analysis of Normality</b>	<b>255</b>
<b>E</b>	<b>BFV Analysis during a Visual Perception Task. Analysis of Normality</b>	<b>257</b>
<b>F</b>	<b>BFV Analysis during Motor Tasks. Analysis of Normality</b>	<b>259</b>