Embodied learning in immersive virtual reality: the role of sensory-motor affordances in shaping conceptual and procedural understandings

Omar Ceja Salgado

Thesis presented for the degree of

Doctor of Philosophy

in the field of

Education and Immersive Technologies

Supervised by:

Prof Sara Price

Dr Mutlu Cukurova

University College London

UCL: Institute of Education
Department of Culture, Communication and Media

May 2022

Declaration

I, Omar Ceja Salgado, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated accordingly.

Word count: 84,337 (excluding cover page, declaration statement, acknowledgements, table of contents, list of figures and tables, references, and appendices)

Abstract

Immersive virtual reality technology (iVR) has been the subject of study in research laboratories for decades. The introduction of the Google Cardboard platform and the Oculus Rift headset brought about significant consumer adoption and renewed interest in its potential use in different domains including education and training. Over the past seven years, the iVR landscape has rapidly evolved and the term now encompasses a range of hardware that can offer significantly different experiences, thus raising issues when it comes to the selection, fit, implementation, and efficacy of these technologies as tools for instruction.

This research looks at secondary school students learning with immersive virtual reality technologies and hypothesises that the sensory-motor affordances of an iVR system can shape the way students make sense of conceptual and procedural knowledge. This thesis explores notions around movement and embodied interaction between two types of distinct iVR systems and examines the effects of those affordances in relation to: (a) the ways in which enabling locomotion, movement, touch, and gestural interaction can influence students' sense of presence, body ownership, and agency; and (b) the effect that these sensory-motor affordances can have on students' measured learning in a science learning context.

A mixed methods design was employed for the empirical work. This involved secondary school interventions in which 27 participants performed chemistry experiments in two virtual laboratories: Labster and HoloLAB Champions.

Findings stemming from the analysis of recordings, interviews, questionnaires, and tests indicate that the sensory-motor affordances of an iVR system play an important role in eliciting perceptual states such as the sense of presence, agency, and hand ownership. Furthermore, the conjunction of these was observed to play at least a partial role in supporting conceptual and procedural understandings, as demonstrated by the way participants used gestures to discuss them. It was found that such gestures instantiated the kinetic, tactile-kinaesthetic properties of their interactions with the iVR environments.

KEYWORDS: immersive virtual reality, embodied cognition, iVR-assisted education, embodied interaction, natural gestural interaction, HCI, presence, agency, body ownership.

Impact statement

This research builds upon previous studies looking at immersive virtual reality technologies and how these can influence perceptual states and learning outcomes (see Papachristos, Vrellis and Mikropoulos, 2017; Schwartz and Steptoe, 2018; Calvert and Abadia, 2020). The empirical findings in this research will be of interest to schools and practitioners looking to implement iVR technology for instructional use; developers of educational iVR experiences who want to inform their designs around active engagement and embodied interaction; and other researchers interested in advancing our understanding of how embodied interaction can be central to supporting conceptual and procedural understandings in educational immersive virtual environments.

This work contributes to existing knowledge in several respects: (a) it describes the interrelationship between the sensory-motor affordances of an iVR system and the kinds of experiences that these can enable; (b) it elucidates the ways in which hardware and sensory-motor affordances contribute to support perceptual states, namely the sense of presence, agency, and hand ownership; (c) it reconceptualises the notion of embodiment in the context of low- and high-end iVR systems; (d) it demonstrates how gestures made during speech provide a window into the ways embodied interaction can shape participants' understandings of concepts and procedures; (e) it also demonstrates how such gestures instantiate the kinetic, tactile-kinaesthetic properties of the mechanisms used for interaction in the iVR experiences; and (f) it lays out some of the ground work towards the development of a taxonomy of embodied cognition in immersive virtual reality which includes the degree of embodiment, the sense of presence, and the sense of embodiment.

For practitioners and schools, this research provides insights into how the selection of immersive virtual reality systems should be driven by instructional aims. This involves the challenges associated with using these types of technologies. Among such challenges, time, cost, expertise, and access to experience are the most prominent.

For developers of educational iVR experiences, this work provides valuable insights concerning the design of spaces involving active engagement, direct manipulation, and touch.

It also highlights the importance of fostering exploration, trial and error, and the simulation of mistakes and their effects, as well as the need to embed scaffolding techniques as part of the experiences' guidance or support system.

Lastly, for researchers, this study advances current understandings around sensory-motor engagement and embodied interaction in immersive virtual reality and highlights potential avenues for exploration going forward in the field of iVR-assisted education.

Acknowledgements

This research has been made possible with the support of the government of the United Mexican States through the National Council of Science and Technology (CONACYT) and the co-sponsorship of University College London.

Reconocimientos

Este trabajo de investigación se ha realizado con el apoyo del gobierno de los Estados Unidos Mexicanos a través del Consejo Nacional de Ciencia y Tecnología (CONACYT) y el copatrocinio de University College London.

First and foremost, I would like to thank all my fellow researchers, academics, and student participants who gave their time to take part in the pilot studies, interviews, and interventions to make this research possible.

My sincerest gratitude to my supervisors Prof Sara Price and Dr Mutlu Cukurova for their guidance and invaluable advice and feedback over the past four years. You were an integral part in the development of this research, but most importantly my professional development as a researcher.

For the provision of essential hardware and software to conduct this research, special thanks are due to Valve Corporation for the Valve Index prototype controllers which were a key component for the study of interaction; to Labster for entrusting me with unlimited access to their virtual laboratories to conduct my study; and to Schell Games for allowing me to use HoloLAB Champions in the empirical study.

I also would like to thank Johnny Manning and Manning's Tutors for the support in recruiting schools for my research study. Similarly, I would like to express my gratitude to the schools that were involved in the research and the people who contributed to making sure the study could be conducted in a timely and organised manner. In particular, I would like to thank Mr Liam McGillicuddy (Headteacher), Mr Matthew Howe (Head of Faculty of Science), and Mrs Mairi Vodden (Careers Administrator) from Bishopshalt School; Ms Leann Swaine (Headteacher), Mr Stuart Owen (Head of Faculty of Science), and Mr John Jones (Teacher) from East Barnet School; Mr. Richard Tillett (Principal), and Dr Paul Davies (Assistant Head Teaching and Learning) from Queen's College, London; and last, but not least, Dr Robert Davies (Lead Teacher of Chemistry), and Ms Marina Mavrou (Second i/c of Science) from Kensington Aldridge Academy.

Last, but not least, I would like to thank my family and friends, particularly my cousin Betty, my brother Juan Carlos, my dad Bernardino, and my friends Gary Rutley, Dr Jason Go, Aidan Dillon, Dr Richard MacKinnon, and Frank de Jongh Swemer. Thank you all for the laughs, the great moments, the companionship, and the constant support and encouragement. I want to give special recognition to Fily for believing in me, for the useful advice, for pushing me to keep going, and for always being there for me. This thesis is dedicated to you all and to the memory of my mom, Yolanda.

Table of contents

Declaration **2**

Abstract **3**

Impact statement **4**

Acknowledgements **6**

Table of contents **8**

List of figures and tables **15**

Acronyms and initialisms **21**

Nomenclature **24**

Chapter 1 : Introduction **37**

Chapter overview 37

Chapter 2 : Background and literature Review **45**

Chapter overview 45

2.1 What is immersive virtual reality? 46

2.1.1 Brief historical account of immersive virtual reality. 47

2.1.2 Typology of virtual reality technology. 49

2.1.3 Core features of immersive virtual reality systems. 54

2.2 Uses of immersive virtual reality. 59

2.3 Research on embodiment and iVR technology. 68

2.3.1 Gesture. 71

Chapter summary 78

Chapter 3 : Theoretical framework **79**

Chapter overview 79

3.1 The significance of perception and action in immersive virtual reality environments. .. 80

3.2 Embodied cognition in immersive virtual reality. 82
3.2.1 Embodied interaction 85
3.3 Gesture and gestural interaction. 88
3.4 Immersion. 92
3.4.1 The sense of presence. 94
3.5 The sense of embodiment. 95
3.5.1 The illusion of self-location. 96
3.5.2 The illusion of body ownership. 97
3.5.3 The illusion of agency 97
Chapter summary 99
Chapter 4 : Methodology 100
Chapter overview 100
4.1 Methodological approach. 101
4.2 The design of the school interventions. 103
4.2.1 Study conditions. 103
4.2.2 Study groups and pathways for participation. 105
4.2.3 Recruitment and eligibility of participants. 107
4.2.4 The apparatus and virtual environments. 109
4.2.5 Protocol for data collection. 117
4.3 Methods of data collection. 119
4.3.1 Testing. 119
4.3.2 Questionnaire. 122
4.3.3 Semi-structured interviews. 124
4.3.4 Screencasting and video recordings. 125
4.4 Methods of data analysis. 125
4.5 Reliability, validity, and replicability of the study. 126
4.6 Ethical dimensions. 127

Chapter summary 129

Chapter 5 : The features and affordances of iVR technology 130

Chapter overview 130

5.1 Defining the features of virtual reality hardware. 131

5.1.1 Audio-visual features. 131

5.1.2 Kinetic tactile-kinaesthetic features. 134

5.2 Defining the affordances of immersive virtual reality HMDs. 137

5.2.1 The sense of presence 139

5.2.2 The sense of embodiment. 143

5.2.3 Movement. 145

5.3 Gestural congruency. 147

Chapter summary 153

Chapter 6 : Comparing learning gains between study conditions 155

Chapter overview 155

6.1 Comparing findings from pre-, post-, and delayed tests in the low-end and high-end iVR conditions across experimental groups. 158

6.2 Exploring relationships with gender, year of schooling and number of elapsed days for the delayed test 162

6.3 Learning through immersive virtual reality environments. 165

6.3.1 Learning by doing. 165

6.3.2 Risks and consequences of behaviour. 167

6.3.3 Making mistakes and scaffolding learning. 168

6.3.4 Collaboration. 169

Chapter summary 171

Chapter 7 : Exploring the experience of presence 173

Chapter overview 173

7.1 Comparing experiences of presence as measured by the iVRPQ 174

7.2 Visuo-proprioceptive congruency between the real and the virtual. 182

7.3 The VE becoming the dominant reality. 187
7.4 The VE meeting expectations. 191
Chapter summary 198
Chapter 8 : Exploring the perceptions of hand ownership and agency 200
Chapter overview 200
8.1 Constrained active engagement. 201
8.2 Mediating interaction. 203
8.2.1 The impact of interaction on the perception of hand ownership. 207
8.2.2 Experiencing agency through embodied interactions. 211
Chapter summary 216
Chapter 9 : Looking at conceptual and procedural understandings 217
Chapter overview 217
9.1 The body and spatial awareness 220
9.2 Subverting expectations about interaction 224
9.2.1 Behavioural change 228
9.3 Kinetic, tactile-kinaesthetic properties of procedural and conceptual understandings 231
Chapter summary 236
Chapter 10 : General discussion of findings 238
Chapter overview 238
10.1 Preliminary work and pilot studies 239
10.1.1 The features of immersive virtual reality technology. 239
10.1.2 The sensory-motor affordances of immersive virtual reality technology. 240
10.1.3 Mapping gestural movements to conceptual and procedural content. 241
10.2 Main empirical study. 242
10.2.1 Learning gains between study conditions. 242
10.2.2 Comparing experiences of presence between study conditions. 245
10.2.3 Systematising the notion of presence in immersive virtual reality 248

10.2.4 Comparing experiences of hand ownership, and agency between study conditions. 250

10.2.5 Systematising the notions of hand ownership and agency 253

10.2.6 Looking at embodied interaction and its role in shaping conceptual and procedural understandings in science. 255

10.2.7 Systematising the notion of embodiment 257

Chapter 11 : Conclusion 261

Chapter overview 261

11.1 Concluding remarks 262

11.2 Contribution and impact 265

11.3 Limitations of the study. 266

11.4 Future avenues of enquiry. 267

References 269

Appendix A : Ethics and informed consent 290

Appendix overview 290

A.1 Information brochure and privacy notice 291

A.2 Participant and parental consent forms. 294

A.3 Approved ethics application. 296

Appendix B : Evaluation of iVR software 297

Appendix overview 297

B.1 Evaluation matrix of immersive virtual reality experiences. 298

B.2 Descriptive matrix of Labster (Pipetting: Mastering the Technique). 307

B.3 Descriptive matrix of HoloLAB Champions (Chemiluminescence) 310

Appendix C : Methods of data collection and analysis 315

Appendix overview 315

C.1 Semi-structured interview schedule. 318

C.1.1 Low-end iVR condition 318

C.1.2 High-end iVR condition. 319

C.2 Coding framework for interviews. 320
C.3 Tests for low-end iVR condition. 325
C.3.1 Form A pre-test / Form B post-test. 325
C.3.2 Form A post-test / Form B pre-test. 327
C.3.3 Delayed test. 329
C.4 Tests for high-end iVR condition. 332
C.4.1 Form A pre-test / Form B post-test. 332
C.4.2 Form A post-test / Form B pre-test. 334
C.4.3 Delayed test. 336
C.5 Immersive virtual reality presence questionnaire (iVRPQ). 339
C.5.1 Inter-item correlation matrix of presence questionnaire. 342
C.5.2 Measures of central tendency of items responses. 343
C.5.3 Tests verifying assumptions for Mann-Whitney U test to compare mean presence scores between conditions and across experimental groups. 344
C.6 Q-Q plots showing the distribution of mean test scores across experimental groups. 346
C.6.1 Q-Q plot showing the distribution of pre-test scores in the within-subject group for the low-end iVR condition. 347
C.6.2 Q-Q plot showing the distribution pre-test scores in the between-groups group for the low-end iVR condition. 347
C.6.3 Q-Q plot showing the distribution of post-test scores in the within-subject group for the low-end iVR condition. 347
C.6.4 Q-Q plot showing the distribution post-test scores in the between-groups group for the low-end iVR condition. 348
C.6.5 Q-Q plot showing the distribution of delayed test scores in the within-subject group for the low-end iVR condition. 348
C.6.6 Q-Q plot showing the distribution delayed test scores in the between-groups group for the low-end iVR condition. 348

C.6.7 Q-Q plot showing the distribution of pre-test scores in the within-subject group for the high-end iVR condition. 349

C.6.8 Q-Q plot showing the distribution pre-test scores in the between-groups group for the high-end iVR condition. 349

C.6.9 Q-Q plot showing the distribution of post-test scores in the within-subject group for the high-end iVR condition. 349

C.6.10 Q-Q plot showing the distribution post-test scores in the between-groups group for the high-end iVR condition. 350

C.6.11 Q-Q plot showing the distribution of delayed test scores in the within-subject group for the high-end iVR condition. 350

C.6.12 Q-Q plot showing the distribution delayed test scores in the between-groups group for the high-end iVR condition. 350

Appendix D : Illustrative animated GIFs........ 351

Appendix overview 351

List of figures and tables

Figures:

All figures marked with an (*) portray gestures or postures that participants performed during interventions. As these are not always clearly illustrated through still images, animated gifs have been created capturing movement. These can be found in Appendix D with the same figure number and title.

Figure 2.1. Simplified representation of a “virtuality continuum” (Milgram and Kishino, 1994, p. 3). 50

Figure 2.2. Typology of virtual reality technology. 52

Figure 2.3. Six-dimensional motion sensing over six degrees of freedom (Nelson, 2013). ... 55

Figure 2.4. Specification of low-end, 3DoF iVR headsets. 56

Figure 2.5. Specification of high-end, 6DoF iVR headsets. 57

Figure 3.1. A continuum of gesture types (Krauss, Chen, and Chawla, 1996, p. 392). 90

Figure 4.1. Methodological approach for the empirical study. 102

Figure 4.2. Organisation of participation pathways for each study condition according to experimental group. 106

Figure 4.3. Google Daydream View 2 headset with remote controller (Google LLC, 2017). 110

Figure 4.4. Composite image showing the HTC Vive headset with SteamVR tracking base stations (HTC Corporation, 2016) and Valve Index controllers (Valve Corporation, 2019). 111

Figure 4.5. Screen capture of the Pipetting Simulation in Labster (Labster, 2018). 115

Figure 4.6. Screen capture of the Chemiluminescence experience in HoloLAB Champions (Schell Games, 2018). 116

Figure 4.7. Protocol followed for every intervention. 118

Figure 5.1*. Screen capture illustrating the surrounding virtual environments in Labster (2018) and HoloLAB Champions (Schell Games, 2018). 140

Figure 5.2. Visual cues signalling interactable objects within Labster (2018) and HoloLAB Champions (Schell Games, 2018). 141

Figure 5.3*. Screen capture illustrating plausibility illusion or experienced realism in Labster (2018) and HoloLAB Champions (Schell Games, 2018). 142

Figure 5.4*. Screen capture illustrating the kinaesthetic mechanisms used to elicit and support active engagement in Labster (2018) and HoloLAB Champions (Schell Games, 2018). 142

Figure 5.5. Screen capture illustrating the sense of embodiment in Labster (2018) and HoloLAB Champions (Schell Games, 2018). 144

Figure 5.6*. Locomotion in HoloLAB Champions (Schell Games, 2018). 146

Figure 5.7*. Screen capture illustrating the use of the Valve Index controllers in HoloLAB Champions (Schell Games, 2018). 147

Figure 5.8*. Illustration of embodied congruency of gestures in Labster (2018). 148

Figure 5.9*. Illustration of embodied congruency of gestures in HoloLAB Champions (Schell Games, 2018). 149

Figure 6.1. Mean test score changes over time in the study condition across experimental groups. 162

Figure 6.2. Scatter plot showing the correlation between delayed-test mean scores and year of schooling for Labster in the low-end iVR condition. 163

Figure 6.3. Scatter plot showing the correlation between pre-test mean scores and year of schooling for the high-end iVR condition. 163

Figure 6.4. Scatter plot showing the correlation between post-test mean scores and year of schooling for the high-end iVR condition. 164

Figure 6.5. Scatter plot showing the correlation between delayed mean test scores and year of schooling for the high-end iVR condition. 165

Figure 6.6. Composite image showing gestural congruency across recordings of body language during interview, the visual of the VE, and the physical performance........ 166

Figure 7.1. Scatterplot comparing presence mean scores between study conditions. 175

Figure 7.2. Distribution of presence scores for the low-end iVR condition across experimental groups. 177

Figure 7.3. Distribution of presence scores for the high-end iVR condition across experimental groups. 177

Figure 7.4. Distribution of presence mean scores across study conditions in Pathway 1 (within-subject design)........ 178

Figure 7.5. Distribution of presence mean scores across study conditions in Pathway 2 (within-subject design)........ 179

Figure 7.6. Distribution of presence scores across study conditions following a between-groups design. 180

Figure 7.7. Distribution of presence scores for the high-end iVR condition across interventions (excluding responses from condition as a first intervention). 180

Figure 7.8. Distribution of presence scores for the low-end iVR condition across interventions (excluding responses from condition as a first intervention). 181

Figure 7.9. Comparison of frequencies for item 1 of the presence questionnaire. 184

Figure 7.10. Comparison of frequencies for item 4 of the presence questionnaire. 184

Figure 7.11. Comparison of frequencies for item 6 of the presence questionnaire. 186

Figure 7.12. Comparison of frequencies for item 7 of the presence questionnaire. 189

Figure 7.13. Comparison of frequencies for item 8 of the presence questionnaire. 191

Figure 7.14. Comparison of frequencies for item 11 of the presence questionnaire. 192

Figure 7.15. Comparison of frequencies for item 12 of the presence questionnaire. 193

Figure 7.16. Comparison of frequencies for item 5 of the presence questionnaire. 193

Figure 7.17. Comparison of frequencies for item 13 of the presence questionnaire. 195

Figure 8.1. Visual of virtual controller when touching and object (left) vs. holding it (right) (Schell Games, 2018). 210

Figure 9.1*. Participant 13 describes the congruency of movements in HoloLAB Champions (Schell Games, 2018). 220

Figure 9.2*. Participant 17 discusses interaction in Labster (2018). 221

Figure 9.3*. Participant 17 discusses the use of pipettes in Labster (2018)........................ 222

Figure 9.4*. Participant 18 demonstrates the use of a pipette in Labster (2018)................. 223

Figure 9.5*. Participant 06 describes tactile feeling whilst holding the controllers in HoloLAB Champions (Schell Games, 2018). 223

Figure 9.6*. Participant 04 describes a break in her sense of proprioception in HoloLAB Champions (Schell Games, 2018). 224

Figure 9.7*. Participant 06 describes expectations of touch in HoloLAB Champions (Schell Games, 2018). 225

Figure 9.8*. Participant 24 demonstrates her proximity to manipulatives in HoloLAB Champions (Schell Games, 2018). 226

Figure 9.9*. Participant 13 illustrates consequences of careless behaviour in HoloLAB Champions (Schell Games, 2018). 227

Figure 9.10*. Participant 13 spills a substance in HoloLAB Champions (Schell Games, 2018). 227

Figure 9.11*. Participant 13 throwing a scoop across the laboratory in HoloLAB Champions (Schell Games, 2018). 228

Figure 9.12*. Participant 13 describes the realism of interaction in HoloLAB Champions (Schell Games, 2018). ... 228

Figure 9.13*. Participant 13 transfers and spills a substance in HoloLAB Champions (Schell Games, 2018). ... 229

Figure 9.14*. Participant 13 discusses how he adjusted to the conditions of HoloLAB Champions (Schell Games, 2018). ... 229

Figure 9.15*. Participant 13 comparing volumes in cylinders in HoloLAB Champions (Schell Games, 2018). ... 230

Figure 9.16*. Participant 13 describes changes in body posture to engage with manipulatives in HoloLAB Champions (Schell Games, 2018). ... 230

Figure 9.17*. Participant 13 picks up a scoop from the floor in HoloLAB Champions (Schell Games, 2018). ... 230

Figure 9.18*. Participant 04 conceptualising measuring mass in HoloLAB Champions (Schell Games, 2018). ... 232

Figure 9.19*. Participant 08 explains what a serial dilution is in Labster (2018). ... 233

Figure 9.20*. Participant 06 explains what a meniscus is in HoloLAB Champions (Schell Games, 2018). ... 234

Figure 9.21*. Participant 14 explains how a sample gets contaminated in Labster (2018). 234

Figure 9.22*. Participant 04 explains how to measure liquid substances in HoloLAB Champions (Schell Games, 2018). ... 235

Figure 10.1. Dimensions of the sense of presence in immersive virtual reality environments. ... 248

Figure 10.2. Dimensions of the sense of embodiment in immersive virtual reality environments. ... 253

Figure 10.3. Dimensions of the sense of embodiment in immersive virtual reality environments. ... 257

Tables:

Table 3.1. Central concepts to the notion of embodied cognition and embodied interaction. 86

Table 4.1. Support for variables of study between study conditions. 104

Table 4.2. Eligibility criteria for student participants. 107

Table 4.3. Final random allocation of participants to pathways. 108

Table 4.4. Description of iVR systems used in each study condition. 109

Table 4.5. Comparative of iVR experiences used in the empirical study. 113

Table 4.6. Summary of questions employed in both interventions. 121

Table 5.1. Audio-visual and processing features of virtual reality hardware. 133

Table 5.2. Kinetic tactile-kinaesthetic features of virtual reality hardware. 135

Table 5.3. Mapping of gestural interactions in Labster. 150

Table 5.4. Mapping of gestural interactions in HoloLAB Champions. 151

Table 6.1. Distribution of test forms. 157

Table 6.2. Descriptive statistics from study conditions across experimental groups. 159

Table 7.1. Representation of participants by year of schooling, age, and gender. 174

Table 9.1. Coding scheme of video recording from interviews. 219

Table 10.1. Magnitude of the sense of presence in immersive virtual reality environments.250

Table 10.2. Magnitude of the sense of embodiment in immersive virtual reality environments. 254

Table 10.3. Degrees of embodiment of immersive virtual reality systems. 259

Table 10.4. Descriptor of the degrees of embodiment of an immersive virtual reality system.259

Acronyms and initialisms

The following is a list of all the acronyms and initialisms used throughout this thesis.

1PP – First person perspective.

3D – Three dimensional.

3PP – Third person perspective.

AE – Augmented embodiment.

AMOLED – Active-matrix organic light-emitting diode.

AR – Augmented reality technology.

AV – Augmented virtuality.

BERA – British Education Research Association.

BID – Body image disturbance.

CAD – Computer-aided design

CAVE – Cave Automatic Virtual Environment.

CBT – Cognitive-behavioural treatment.

CPU – Central processing unit.

DE – Direct embodiment.

DoF – Degrees of freedom of movement.

ESRC – Economic and Social Research Council.

FoV – Field of view.

GDPR – General Data Protection Regulation.

GPU – Graphics processing unit.

HCI – Human computer interaction.

HiVR	–	High-end immersive virtual reality condition (also high-end iVR).
IAT	–	Implicit association test.
ID	–	Unique identification number.
IPD	–	Inter-pupillary distance or pupillary distance (**PD**).
IPQ	–	iGroup Presence Questionnaire.
IR	–	Infrared radiation.
iVR	–	Immersive virtual reality technology.
iVRPQ	–	Immersive virtual reality presence questionnaire.
LCD	–	Liquid-crystal display.
LED	–	Light-emitting diode. LCD, OLED, or AMOLED
LiVR	–	Low-end immersive virtual reality condition (also low-end iVR).
MR	–	Mixed reality technology.
NiVR	–	Non-immersive virtual reality technology.
NPC	–	Non-playable character.
OLED	–	Organic light emitting diode.
PI	–	Place illusion.
PPI	–	Pixels per inch.
PQ	–	Witmer-Singer Presence Questionnaire.
Psi	–	Plausibility illusion.
PTSD	–	Post-traumatic stress disorder.
QUAL	–	Qualitative (research tradition or strand of data in the research).
QUAN	–	Quantitative (research tradition or strand of data in the research).
SE	–	Surrogate embodiment.
SoE	–	Sense of embodiment.

SUS	–	Slater-Usoh-Steed Questionnaire.
STEAM	–	Science, Technology, Engineering, Arts, and Maths.
UI	–	User interface.
VE	–	Virtual environment.
VR	–	Virtual reality technology.
XR	–	Extended or alternative reality technology.

Nomenclature

The following is a list of terms that are frequently used throughout the thesis and whose definition might be ambiguous or not immediately clear. Whenever these terms are found in the following pages, they are signalled with an asterisk (*) to indicate that a definition can be found in this section.

A

Affordances – are defined as the "possibilities for action that a particular object permits a particular agent" (Dawson, 2014, p. 62); that is, the inherent and, therefore, invariant qualities of an object, space, or medium that can be perceived by an individual as an opportunity for enaction (Gibson, 1977, 2014). In the case of this research, these could take the form of moving around in the space, looking under things, and interacting with manipulatives in ways that are supported by the VR system and called for by the object itself such as picking up, throwing, tilting, rotating, or grabbing laboratory equipment in a certain manner.

Agency – although the concept of agency will be discussed in more depth in Chapter 8 and Chapter 10, broadly speaking it refers to wilful and self-regulated behaviour, intention, and control over interactions with manipulatives in the virtual environment (Blanke and Metzinger, 2009).

Agent – is an individual capable of physically or virtually acting upon the virtual environment and the objects within it.

Augmented embodiment (AE) – refers to a form of physical engagement with a virtual environment that uses a representational system like an avatar and an augmented feedback system like cameras that translate the user's movements to the avatar (Black et al., 2012).

Augmented reality (technology) (AR) – is a form of mixed reality in the virtuality continuum proposed by Milgram and Kishino (1994) which seamlessly integrates or superimposes some elements of computer-generated imagery on the physical environment, thus complementing or expanding it. It is most commonly delivered through a mobile device screen such as a tablet or smartphone using the integrated camera; however, it can also be experienced through headsets such as Microsoft's HoloLens which use lenses or translucent screens to superimpose holograms over real world objects. The former integrates sensors to recognise gestures as a form of interaction, whereas the latter also supports the use of a single 6DoF-controller.

Avatar – is a word taken from Hinduism that refers to the manifestation of a deity in physical form. The term has been adapted to designate a computer-generated figure that can be embodied by an individual in a virtual world or environment (Sherman and Craig, 2003).

B

Body ownership – concerns the perception of inhabiting a virtual body (see sense of embodiment).

C

Cave Automatic Virtual Environment (CAVE) – is a virtual reality system described as "a cube with display-screen faces surrounding a viewer" (Cruz-Neira et al., 1992, p. 67). Most modern versions involve the use of stereoscopic 3D glasses, a controller, and some form of tracking system to sense and replicate the user's movements in the virtual environment.

Central vision – refers to the central sightline starting from the centre of the retina (the macular). Central vision is responsible for most sight tasks or functions such as reading and recognizing shapes, patterns, and colours (Yun, 2020)

D

Degrees of freedom of movement (DoF) – is a term used to refer to the dimensions or directions in which independent motion can happen in a three-dimensional space and as such have a direct effect on locomotion, the nature of the interactions that can be supported, and by extension, on the degree of agency that can be experienced (Google LLC, 2018b). When referred to as a capability of VR hardware, two types can be found: headsets or controllers offering three-degrees of freedom of movement which only support rotational motion such as moving the head or hand left or right, tilting up or down, and pivoting left and right; and headsets or controllers offering six-degrees of freedom of movement which additionally support positional motion such as moving forward, backward, left, right, up, and down (Barnard, 2019).

Direct embodiment (DE) – refers to a form of engagement with a virtual environment that allows a user to engage with it physically through movement and gesture. (Black et al., 2012).

Distal enaction – refers to behaviour that takes place away from the body of the individual performing it. This is done with the help of a controller used as a pointer to support point-and-click interactions with manipulatives beyond arms' length.

E

Embodied metaphor – is a term used by Bakker, Antle and van den Hoven (2012) to refer to "cognitive structures that are applied unconsciously in learning" (p. 433). According to the authors, these embodied metaphors allow agents to make sense of a physical experience, in terms of another, an embodied schema.

Embodied schemata – is a term used to denote "abstract representations of recurring dynamic patterns of bodily interactions that structure the way we understand the world" (Hurtienne and Israel, 2007, p. 130). These schemata can be comprised of multiple modes and, as a result, do not need to be exclusively represented visually. Furthermore, their strength in capturing sensory and motor experiences relies in the metaphors to which they correlate.

Embodiment or embodied cognition – is a concept used throughout this research to denote any form of physical and perceptual engagement with a virtual environment and the manipulatives that it contains. These physical and perceptual engagement must be oriented to meaning making and derived from action (see also Sense of embodiment).

Enaction – is a term used here to indicate behaviour or active engagement such as bodily interaction with a virtual environment.

Extended or alternative reality (technology) (XR) – is an umbrella term used to designate virtual reality, augmented reality, and mixed reality technologies. The letter "X" is used as a variable or unknown to encapsulate present and future spatial technologies.

F

Fidelity – see the definition for reality below as these terms are often used interchangeably.

Field of view (FoV) – refers to the maximum angular size of the observable environment through the optical system, in this case, the lenses in the headset (Greivenkamp, 2004). Human vision covers a visual field of an estimated 210º horizontal arc when facing forward, whilst most headsets offer a field of view ranging from 94º up to 210º, thus creating the effect of looking at the virtual environment through a window as dark borders can be observed in the periphery when the full angle of human vision is not covered by the screen.

First-person perspective (1PP) – is a term used to refer to the point of view that the user has of the virtual environment. In this case, it is from the perspective of the character or avatar being controlled. In immersive virtual environments, this visually translates to the perception of the users themselves being physically in that virtual space.

G

God rays – also known as crepuscular rays or volumetric light scattering, consist of the refraction of light on the lenses in a headset (Moreau-Mathis, 2014). These resemble rays of light emanating from a bright object and they are only perceptible in dark scenes.

Gestures – will be understood throughout this research in two distinct ways, as a form of non-verbal communication and as the hand movements involved during interaction such as the manipulation of objects in a virtual environment. According to Alibali, Boncoddo, and Hostetter (2014) gestures provide evidence of the embodied nature of cognition because they stem from the simulation of actions and express perceptual states.

H

Haptic feedback – refers to incorporation of touch to input devices, whether graspable, wearable, or touchable (Hutson, 2018). This is most commonly achieved through vibrations transmitted to an agent's hands using controllers or gloves.

High-end immersive virtual reality technology – is a term used in this research to refer to virtual reality headsets that offer the most up to date visual and auditory fidelity and possibilities for locomotion and interaction (the term could also designate other forms of immersive virtual reality such as CAVE systems and display walls). These headsets are normally tethered to a computer, although standalone systems can be found such as Oculus Quest by Facebook and Vive Focus Plus by HTC. Some of the differentiating factors of high-end immersive virtual reality systems are the visual quality they can achieve due to being connected to a powerful computer; the resolution of the screen panels, their refresh rate which ranges from 72 to 144 Hz, and the varied field of view they can offer ranging from 94º to 210º; and the inclusion of some form of tracking system that allows for natural physical motion that can go from just the hands and head, to the whole body.

I

Icon – is a term used to denote one of the three ways in which interpretants of any representation can be generated according to an early account of Pierce's Theory of Signs (Atkin, 2010). Icons reflect qualitative features of such sign or representation, for instance a portrait or photograph.

Immersion – is understood in this research as a property of the hardware defined by the extent to which it can support sensory-motor enaction and evoke a stronger sense of presence (Slater and Wilbur, 1997; Slater, 2009). Slater (2018) posits that more immersive systems are capable of simulating what hardware with a lower degree of immersiveness can do. For instance, a system capable of spatial audio can simulate stereo reproduction, and a system capable of direct interaction can simulate distal manipulation of objects, but in both cases the inverse is not possible.

Immersive virtual reality (iVR) – is a term that is used to describe surrounding, 360°, computer-generated virtual environments. These can be presented through CAVE or display wall systems and, more commonly, headsets (Sherman and Craig, 2003).

Index – is a type of sign described by Pierce's Theory of Signs (Atkin, 2010). An index requires a physical connection or causal sign between it and the object, for instance a smoke can be understood as a sign of fire or something burning.

Inside-out tracking – is a term used to denote immersive virtual reality tracking systems where the sensors/cameras that track movement are placed on the headset facing outward. These tracking systems can be marker-less as is the case with Oculus Quest and all Windows

Mixed Reality headsets (their controllers use outside-in tracking). These kinds of headsets use cameras to scan the room and calculate the location of the headset within the space (Microsoft, 2020b). Alternatively, marker-based tracking systems, such as those implemented on the HTC Vive, Valve Index, and other SteamVR-based headsets, use external markers in the environment such as light or IR laser beams to determine the position of the headset and controllers (Weis, 2018).

Interaction / embodied interaction – is understood in this research as bodily actions such as gestures, postures, and locomotion intended to engage with the environment. As Dourish (2004) defines it, "embodiment is the property of our engagement with the world that allows us to make it meaningful". Consequently, "embodied interaction is the creation, manipulation, and changing of meaning through engaged interaction with artifacts" (p. 126)."

Inter-pupillary distance (IPD) or pupillary distance (PD) – is the distance between eye pupils and it is measured in millimetres.

L

Latency – describes a delay between an action and response. In essence, it consists of the measure in milliseconds of the time it takes for data input to reach its destination and back. In the case of VR, this can concern the replication of physical movements in the space (see Stauffert, Niebling and Latoschik, 2020).

Locomotion – refers to the "ability to move in space" (Di Luca et al., 2021). This involves the displacement of the body from one physical location to another in a controlled manner. Through three planes, forward-backward, left-right, and up-down which constitute degrees of freedom of movement.

Low-end immersive virtual reality technology – is a term used in this research to refer to standalone virtual reality headsets that may offer limited visual and auditory fidelity, no support for locomotion, and reduced possibilities for interaction. The term typically designates mobile based systems such as Gear VR by Samsung, Daydream View by Google, and Google Cardboard-compatible headsets, but it also includes headsets with computing components embedded in the headset itself such as Oculus Go by Facebook. Although these headsets may include high resolution screen panels, they cannot present experiences with high demanding visual quality due to their limited processing and graphic power and their refresh rate which ranges from 60 to 72 Hz, additionally they have a smaller field of view ranging from 96º to 100º, and only support rotational tracking (3 DoF). As a result, the movement of hands and body of users cannot be translated or replicated in the virtual environment, all of which increase the likelihood of experiencing motion sickness.

M

Mid-range immersive virtual reality technology – is a term used in this research to refer to standalone virtual reality headsets that sit between the capabilities of low-end and high-end immersive VR technologies as they support locomotion through the integration of a 6DoF, inside-out tracking system for the headset, but not so for the single controller which only supports 3DoF and is often used as a pointer, thus limiting the possibilities for interaction. Two commercially available headsets fit this designation: *Lenovo's* Mirage Solo, and *HTC's* Vive Focus. Although these headsets may include high resolution screen panels and a standard 110º field of view, they cannot present experiences with high demanding visual quality due to their limited processing and graphic power and 75 Hz refresh rate.

Mixed reality (technology) (MR) – refers to the seamless integration of reality and virtual elements. In the virtuality continuum proposed by Milgram and Kishino (1994), mixed reality includes any possible combination between both realms, which the authors call augmented reality or augmented virtuality depending on the degree and prominence of one over the other. The most common use of the technology is in mobile devices where, through the view of the camera, the physical environment is expanded with digital information or objects that can often be interacted with by touching the screen of the device. Another example is Microsoft's HoloLens which use lenses or translucent screens to superimpose holograms over real world objects. The former integrates sensors to recognise gestures as a form of interaction, whereas the latter also supports the use of a single 6DoF-controller.

Modes of representation – is a term used in Multimodality, an inter-disciplinary research methodology, that "attends systematically to the social interpretation of a wide range of communicational forms that are used for making meaning" (Jewitt and Price, 2012, p. 1). The term refers to the different interrelated forms or modes of representation, be it visual, auditory, or embodied such as gaze, posture, and gestures, that contribute to the construction of meaning in any act of communication.

N

Non-Immersive virtual reality (NiVR) – is a term that is used to describe computer-generated virtual environments that do not surround the user. These are presented through a screen on a desktop computer, tabletop, laptop, or mobile device. These forms of virtual reality have also been known as virtual reality learning environment (VRLE), virtual learning environment (VLE), or simply virtual reality (VR).

O

Off-line cognition – “take[s] place decoupled from any immediate interaction with the environment” (Wilson, 2002, p. 626); that is, it concerns mental representations that are not directly linked to the immediate environment, task, or time of occurrence, as is the case with remembering, engaging in hypotheticals, wishful thinking, and imagined scenarios. It is also commonly used in neuroscience to refer to information processing during resting states or when sensory-motor stimuli are minimal such as during sleep or daydreaming (Wamsley and Stickgold, 2010).

On-line cognition – is that which is rooted in the sensory-motor processing of the immediate environment, task, and time where it takes place; that is, it is context dependent or situated (Wilson, 2002).

Outside-in tracking – is a term used to denote immersive virtual reality tracking systems where the sensors/cameras that track movement of the headset and controllers are placed externally in the environment looking in toward them. These tracking systems can be marker-less as is the case with Microsoft Kinect which uses vision algorithms to superimpose a virtual skeletal mapping on users to track their movements (Microsoft, 2019). On the other hand, marker-based tracking systems, such as the one implemented on the Oculus Rift, use IR markers on the headset and controllers as reference to determine their position and movement (Weis, 2018).

P

Peripheral – is a device that can be connected to a computing system or, more appropriately for this research, VR hardware that can provide input of output communication or other complementary functions (i.e. controllers and wireless adaptors) (Merriam-Webster, no date).

Peripheral vision – refers to vision in the field of sight to the sides of the central line of vision. It is use in the processing of spatial information such as motion and orientation (Yun, 2020)

Place illusion (PI) – refers to the illusion of physically being in a place. Slater and Wilbur (1997) consider this illusion a subjective indicator of presence (see Sense of presence).

Plausibility illusion (Psi) – refers to the illusion that what is being experienced in a virtual environment is truly happening, notwithstanding the conscious awareness that it is a virtual space and, as a result, elicits behaviour that is analogous to what would be expected if the environment were real (Slater, 2009) (see Sense of presence).

Posture – is understood throughout this research as the position assumed by the body when static or during dynamic activity. Postures whilst using VR setups can involve, but are not limited to, leaning forward, bending down, reaching out, turning the torso, and head tilting.

Proprioception / proprioceptive – is a term used to denote a perceptual sense of the body. This sense encompasses joint/limb movement and position, muscle tension, and force or effort (Taylor, 2009). It is through this sense that individuals are able to touch their noses with their eyes closed or perceive movement and the location of their limbs in relation to the space.

Proteus Effect – is a term used to describe a change in attitudes and behaviour caused by a digital representation of the self (Yee and Bailenson, 2007).

Proximal enabler of distal enaction – is a term used throughout this research to refer to hardware such as controllers that can be operated by the user and which make possible interactions with manipulatives positioned beyond reach in the virtual environment.

R

Realism or fidelity – Alexander et al. (2005) define fidelity or reality as “the extent to which the virtual environment emulates the real world” (p. 4). Based on a review of the literature, Alexander et al. (2005) identify three subcategories of the concept: physical fidelity, which concerns the degree to which visuals, audio, and controls of the simulation resemble reality; functional fidelity, which defines the degree to which the simulation resembles real behaviour, tasks, or the operation of things; and psychological fidelity, which refers to the perceptual effects that the simulation can have on an agent.

Room-scale – is a feature of mid-range and high-end immersive virtual reality headsets that allows users to move and walk freely within the confines of a pre-defined physical space. This is made possible due to the integration of a 6DoF tracking system for the headset and, in most cases, the controllers, as well as the implementation of a warning system that alerts the user when the boundaries of the play area are about to be reached, usually by visual cues such as a grid (HTC Corporation, 2020).

S

Screen door effect – is a visual anomaly that consists of being able to perceive the space between pixels on a screen. This is a common visual artefact observed with headsets and it is caused by several factors such as the resolution of the screen, its distance from the users' eyes, and the magnification provided by the lenses in the headset. The resulting appearance resembles a mesh or screen door, hence its name (Cho et al., 2017).

Screen refresh rate – is a term used to refer to the number of times an image on a screen or monitor is updated every second. Although 60Hz is a standard refresh rate for monitors and TVs, virtual reality systems such as headsets take 90Hz as a minimum rate to ensure visuals that are smooth enough not to cause motion sickness on most people. Increased refresh rates result in the smoother transition of images, thus contributing to visual comfort (Hoffman, 2018)

Sense of embodiment (SoE) – is a term used to refer to the perceptual experience of being inside, owning, and controlling a body or a part of it. Kilteni, Groten, and Slater (2012) pose that the sense of embodiment is supported by three subcomponents: the feeling of self-location, of body ownership, and agency. This should not be confused with the notion of embodiment or embodied cognition as is more commonly used in cognitive science.

Sense of presence – is a perceptual illusion of being in a place or being part of the virtual environment, notwithstanding of conscious awareness to the contrary (Slater, 2018). According to Slater and Wilbur (1997), presence is a descriptor of an individual's state with respect to the environment and it is both subjective regarding the illusion of being in the place, and objective regarding the illusion that what is happening in that environment is really taking place and, a result, the individual would behave in a manner that would be expected in an comparable real situation. Whilst the term is often used interchangeably with the word immersion, both notions are considered distinctive from each other in this research.

Sensory-motor (perceptuomotor) – is a term used to refer to the first stage in Piaget's Theory of Cognitive Development (Piaget, 1963). This stage is characterized by the integration of sensory and motor interactions with the environment as a means for children to build mental schemes (learn). For the purpose of this research, the term sensory-motor will be understood as the perceptual or sensory states and bodily interactions afforded by a virtual reality system (the hardware and, by extension, the virtual environments it hosts).

Sensory-motor contingencies (SMCs) – are situations or events where there is potential for sensory stimulation and motor actions to take place (Kaspar et al., 2014).

Simulation – is a term used in the embodied cognition literature to refer to the correlative activation of the area in the brain linked to a previously experienced situation or enaction (Scorolli, 2014). This links to research on mirror and canonical neurons which suggests that the same areas of the brain that are activated when an individual carries out an action become active when the action is passively observed, or when the potential for action with an object is envisioned (Kosslyn, 2005; Martin, 2007; Gallese, 2008; Rizzolatti and Sinigaglia, 2010). This raises questions regarding these neurons' role during other forms of off-line processing such as information recall, dreaming, hypothesising, or reflection and planning. The term simulation can also be used to indicate that these spaces recreate aspects of reality such as processes, procedures, or how certain instruments operate.

Simulation or simulator sickness – also known as **cybersickness**, although not necessarily triggered by motion, it is a form of **motion sickness** characterized by causing discomfort such as drowsiness, disorientation, and nausea. This syndrome is caused by discrepancies between visual and vestibular input; for instance, when the body is not experiencing physical movement, but it is receiving visual signals that it is such as when playing a first-person-perspective videogame (Dużmańska, Strojny and Strojny, 2018).

Surrogate embodiment (SE) – refers to a form of physical engagement with a virtual environment that although initiated and controlled by the user, it is enacted by an avatar. (Black et al., 2012).

Surrounding or immersive virtual environment – is a term used to refer to a virtual environment that is displayed continuously around users giving them 360º horizontal and vertical field of views. Immersive VR technology such as CAVE systems or headsets allow for a first-person perspective of the space, thus increasing the perception of being physically present in it.

Symbol – is one of three types of signs described by Pierce's Theory of Signs (Atkin, 2010). Symbols are abstract and their signification is the result of a general convention, habit, or law, for instance a traffic light, or words in a language.

T

Third person perspective (3PP) – is a term used to refer to the point of view that the user has of the virtual environment. In this case, it is from the theoretical perspective of a third person watching the character or avatar being controlled. Although not commonly used in immersive virtual environments, this translates to the perception of being an entity looking down on a miniature, diorama-like environment, or simply an observer within the scene.

Three dimensional (3D) / Stereoscopic 3D – is a term used to refer to imagery presented in a way that simulates human vision and induce the perception of depth by projecting images for each eye. Although the term is often used interchangeably with the term three dimensional (3D), these differ in that the depth of field is only simulated in the image itself, rather than the illusion being created in the brain through stereo photography (Klein, 2015).

Tunnel vision – is a condition caused by moderate and severe loss of peripheral vision creating the perception that the individual is looking through a tube (Haddrill and Heiting, 2020).

V

Vestibular input – "is the sensation of any change in position, direction, or movement of the head." (Ford-Lanza, 2020) Essentially, vestibular input provides information regarding the presence of movement, its direction and magnitude.

Virtual environment (VE) – is a computer-generated space that attempts to simulate certain aspects of reality (Sherman and Craig, 2003).

Virtual reality system or setup – is a term used to denote the integration of “hardware, software, and content assembled for producing virtual reality experiences.” (Sherman and Craig, 2003, p. 6)

Virtual reality (technology) (VR) – presents a fully computer-generated, three-dimensional environment that attempts to simulate some aspect of reality, engages the user’s senses (i.e. visual, auditory, and touch) and can be explored and interacted, thus creating the illusion of being physically present in it (Sherman and Craig, 2003). Milgram and Kishino (1994) place virtual reality to the end of the virtuality continuum indicating its opposition to reality. Two types of modern virtual reality technology are recognised: immersive, which includes headsets, CAVE systems, and display walls, and non-immersive, which is delivered through the screen of a computer or mobile device.

Virtuality continuum – is a term coined by Milgram and Kishino (1994) to categorize mixed reality visual displays. The continuum places real environments on one end and fully virtual environments on the other. The middle area between the two is called mixed reality and implies certain degree of integration between reality and computer-generated imagery. Depending on how each is balanced, it can be classified as augmented reality, or augmented virtuality.

Visual artefacts – are anomalies in the representation of an image (IGI Global, 2021). With respect to head-mounted displays (HMDs), they consist of distortions or effects caused by the display, or the interaction of light with the lenses (see God rays and Screen door effect).

Chapter 1: Introduction

Chapter overview

This chapter provides a general overview of this doctoral research, a rationale for the main study, and introduces the research questions and aims that guide it.

In its modern sense, virtual reality (VR) is an umbrella term used to denote different types of technologies that place users inside computer-generated environments[1]. When experienced through CAVE systems or headsets, these environments surround the user and can elicit the sense of being physically located in them. Before the advent of computers, however, an equivalent to these types of experiences was possible through panoramic or 360-degree murals like the Siege of Sevastopol and The Battle of Borodino by Franz Roubaud, or The Rotunda by Robert Baker (Virtual reality society, 2017).

With the turn of the twentieth century, first strides were made toward modern-day, computer-assisted, immersive VR experiences. Whilst these experiences depicted some aspect of reality, they were also capable of simulating it. Such strides were marked by the development of the first stereoscopic viewers, namely the View-Master by William Gruber (Clatworthy, 2016), Morton Heilig's Sensorama (1962), and Ivan Sutherland's Sword of Damocles (1968).

Modern immersive virtual reality technologies (iVR) have shown tremendous potential for revolutionising the way people visualise, engage with, and consume media, as well as how they carry out other aspects of every-day life such as communication, shopping, and productivity, to name a few. Companies like Google, Facebook's Oculus, Sony, Microsoft, Samsung, Valve, HTC, Lenovo, and Acer were among the first to offer more accessible iVR headsets to consumers (GlobalData Technology, 2020). The involvement of these companies not only brought more attention and investment to the field, but it also incentivised the commercialization of multiple hardware alternatives from which consumers could choose.

Although gaining in popularity, iVR technologies have not seen widespread adoption (Bolas et al., 2016; Digi Capital, 2018). Gaming and entertainment constitute the main domains where iVR technology has been adopted. However, areas like healthcare, education, training, and manufacturing have also seen increased usage in recent years (Gilbert, 2021). Arguably, this can be attributed to the technology's ability to offer interactive and situated forms of content delivery for therapy and treatment, active learning, skills development, and visualization, respectively.

---

[1] The coining of the term virtual reality is attributed to Jaron Lanier, a former Atari employee. The term derived from his work at VPL Research, one of the first companies to develop VR products in the mid-80s.

Despite clear signs that iVR is beginning to mature as a platform (Lang, 2018), its consumer market remains in a fragmented state caused by the commercialisation of multiple types of iVR systems with variable features (Hruska, 2015; Probst, Pedersen and Dakkak-Arnoux, 2017). In that regard, six main factors have been identified as contributors to such fragmentation and slow pace of adoption:

(a) The development and commercialisation of proprietary hardware by multiple companies.
(b) The initial lack of design and hardware standards.
(c) The high cost of adoption.
(d) The computing requirements for some types of systems.
(e) The physical space needed for the operation of some iVR headsets.
(f) The lack of quality content that can be used for instruction.

Furthermore, the commercialisation of iVR systems with different feature sets has brought into question their suitability to certain domains and use scenarios. In that regard, potential users face the task of choosing among:

(a) Standalone (wireless) or tethered devices.
(b) Systems with different mechanisms of interaction including dedicated controllers, touchpads, gloves, gesture-recognition cameras, joysticks, or sight.
(c) Hardware with 3 degrees of freedom of movement (DoF) that only replicate the rotation of the user’s head and hands, or 6DoF-capable systems that enable a full range of hand and body motion.

Considering that support for interactivity, movement, touch, and the elicitation of a general sense of presence and agency can differ from one virtual reality system to another, it is hypothesised in this thesis that such features have the potential to make iVR environments more engaging and appropriate for instruction via the types of experiences that users can have. Most significantly, however, they could shape the way in which agents make sense of those environments[2]. This implies, for instance, that physical forms of interaction and being

[2] Sense making is understood throughout this research as the ways in which users construct meaning in a virtual environment and understand its rules. This suggests that support for body representations, the simulation and congruent replication of movement, and control over the viewpoint and interaction in a virtual environment will dictate their understanding of it. This includes how participants see the world around them, their own role in it, what can be done, its limitations, and how they can engage in communicative and meaning-making practices such as speech, gesture, and posture.

able to change viewpoint, move the limbs, and walk, as opposed to having a fixed view of the space, can allow users to understand a concept or procedure by grounding it on properties such as the size, directionality, and spatial location of objects in relation to their own position in the virtual environment. Moreover, employing the body to interact with the space in a more natural manner, along with the integration of direct manipulation and touch through haptic feedback technologies, can also help in creating and sustaining the illusions of presence, body ownership, and agency which, as discussed in the literature (Slater, Lotto, et al., 2009; Maister et al., 2015; Shin, 2017; Johnson-Glenberg, 2018), are at the core of these experiences and directly impact perception and action.

Due to the above, gaining a better understanding the features of iVR systems and their affordances could have implications for the design of virtual reality experiences. In that sense, these could be optimised for a particular aim, user, scenario, or discipline. Furthermore, as is of interest in this research, they could inform the learning and teaching practices that involve these types of technologies.

Increased support and adoption of VR has been reported within education (Gilbert, 2021). This coupled with the emergence of different strategies and platforms looking to bring immersive virtual reality technologies into classrooms (see Google LLC, 2018a; Labster, 2018; zSpace, 2018; Avantis Education, 2020; MEL Science, 2020; EON Reality, 2021) justifies the need for further research exploring the potential impact that the features of iVR technologies can have on students' learning.

In their current state, school implementations such as those listed above rely on the large body of literature on non-immersive virtual reality. These studies mainly look at virtual environments like Second Life, and the use of serious games and tablets (see Duncan, Miller and Jiang, 2012; Bonde et al., 2014; Merchant et al., 2014; Makransky et al., 2016; Thisgaard and Makransky, 2017). However, given the significant differences between immersive and non-immersive virtual reality technologies and the types of experiences they support, it is important to approach those findings cautiously. What may be applicable to non-immersive VR technologies and environments (NiVR) may not produce similar outcomes with immersive VR.

Another issue observed among developers of educational iVR experiences and school strategies consists in making such experiences platform agnostic. That is, they are developed and commercialised to be compatible with most iVR systems. For the purpose of building a wider user-base and increasing revenue, this seems like a sensible approach. However, often these experiences are developed based on low-end hardware such as Samsung's Gear VR and Google's Carboard and Daydream View headsets. The issue with this approach is that often these experiences are not modified to take advantage of the capabilities of more advanced technology when they are ported over, thus neglecting the added affordances along with their potential benefits.

As argued by Makransky, Terkildsen, and Mayer (2019), "there is limited and inconclusive research investigating whether the added immersion offered by high-immersion VREs [virtual reality environments] leads to higher levels of presence, and ultimately better learning and transfer outcomes" (p.2). Although this claim concerns the shift of VR technology from computers and tablets to headsets, it also describes the current state of research concerning low- and high-end immersive virtual reality. Although the body of literature comparing non-immersive and immersive VR technologies, as well as low-end and high-end iVR systems continues to grow (see Johnson-Glenberg et al., 2011; Papachristos, Vrellis and Mikropoulos, 2017), more work is required to provide a more holistic picture of the implications of using one type of system over another.

Beyond the notions of presence and immersion (see Dede, 2009; Bailey et al., 2012; Cummings and Bailenson, 2016; Slater, 2018), there is little work exploring and comparing the distinctive features of consumer headsets and the affordances that they enable. Furthermore, it is not currently well understood how the mechanisms that provide "added immersion" to VR experiences can impact students' understanding of the content with which they engage. Arguably, affordances such as movement and natural direct interaction are important for the active involvement of users. Moreover, understanding their impact also has implications for how users make sense of these virtual spaces.

This research builds upon prior work with the overarching aim of analysing and comparing two types of immersive virtual reality systems. In particular, this research examines the interrelationship between the capabilities of those systems and the affordances that they enable. These aspects are explored in relation to their potential impact on how students make sense of the virtual environments and the educational content presented in them. For the empirical work in this research, two types of iVR systems are used, coupled with two separate virtual environments introducing STEM content (see Section 4.2.4). Specifically, these environments, HoloLAB Champions and Labster: Pipetting Simulation, present basic conceptual and procedural knowledge about chemistry in the context of two virtual laboratories.

This research involved two phases. The first concerned the analysis of iVR hardware and software with two specific aims:

- To appraise the ways in which the capabilities of the two types of iVR systems define certain affordances to students and shape the types of experiences that they could host.
- To examine how the contrasting mechanisms for interaction employed in the two immersive virtual laboratories mapped to the procedural and conceptual knowledge that they present to students.

The second phase concerned the main empirical study involving two school interventions. Through these interventions it was possible to explore students' engagement with the iVR technology, observe their behaviour, enquire about their perceptual experiences, and assess their knowledge gains. The specific aims for this work were:

- To examine how students' measured knowledge differed after taking part in the interventions for both study conditions.
- To appraise how free movement and embodied interaction could influence the students' perception of presence, hand ownership, and agency.
- To determine if and how free movement and embodied interaction could shape the students' understanding of the procedural and conceptual knowledge with which they engaged during the interventions.

Derived from the above, the preliminary work was guided by three research questions whose findings are presented in Chapter 5:

(a) What are the features of immersive virtual reality technology?

(b) What sensory-motor affordances can the features of an iVR system enable?

(c) How can embodied interactions be congruently mapped to conceptual and procedural content in an educational virtual reality experience?[3]

[3] Embodied interactions can be mapped to conceptual and procedural content to be learnt via the directionality, magnitude, and shape of gestures and movements that need to be performed in the virtual environments. For instance, performing a twisting motion on the wrist constitutes a more congruent bodily form of interaction to learn about pouring and mixing than performing a pushing motion with a finger. A more detailed account of bodily forms of interaction and the concepts and procedures they are mapped to in the iVR experiences used in this research can be found in Table 5.3 and Table 5.4.

Similarly, the main empirical work for this research was guided by three research questions whose findings are presented in Chapter 6, Chapter 7, Chapter 8, and Chapter 9.

(a) How does students' measured knowledge differ between Low- and high-end immersive virtual reality systems as evidenced by test scores, interviews, and observations?
(b) In what ways can free movement and embodied interaction impact how students experience presence, hand ownership, and agency in low- and high-end iVR systems?
(c) How can free movement and embodied interactions influence students' understanding of the conceptual and procedural content with which they engaged during interventions?

This thesis is organised around eleven chapters. Chapter 2 provides an overview of the field of immersive virtual reality (iVR) including an historical account and a proposed typology of iVR systems. Furthermore, this chapter presents a critical evaluation of seminal work in two areas: (a) the use of immersive virtual reality for education and training, and (b) embodied cognition and gestural interaction in virtual environments.

Chapter 3 develops a theoretical framework concerning central ideas to this research. The first section discusses the notions of perception and action for meaning making and how these relate to an embodied view of cognition. The subsequent sections discuss associated ideas such as how the concept of embodied interaction is understood in the context of immersive virtual reality, the significance of gesture as a mechanism for natural interaction, and the introduction of various perceptual dimensions enabled by the level of immersiveness of an iVR system including the sense of presence and embodiment.

Chapter 4 describes the methodological approach followed for the main empirical study comprising this research. This includes rationales for the mixed methods of data collection and analysis, and overview of the apparatus used during school interventions, an overview of the protocol that was followed, and other aspects such as ethical dimensions and the reliability, validity, and replicability of the study.

Chapter 5 explores three aspects concerning immersive virtual reality hardware, immersive virtual reality experiences, and their interrelationship. These findings address the three research questions which guided the preliminary work and underpinned the main empirical study.

Chapter 6 looks at quantitative data stemming from pre-, post-, and delayed test scores across conditions and study groups. This concerns the school interventions in the main empirical study and aims to look at how measured learning as evidenced by those test scores varies between low- and high-end immersive virtual reality systems.

Chapter 7 and Chapter 8 discuss the findings stemming from the statistical analysis of responses to the presence questionnaire and the thematic analysis of interview data. This concerns the second research question guiding the main empirical study. Chapter 7 focuses on the sense of presence, whilst Chapter 8 attends to the notions of hand ownership and agency, both of which conform the sense of embodiment.

Chapter 9 discusses the findings concerning the third question guiding the empirical work. This involves the analysis of a purposive sample of video recordings stemming from the school interventions and interviews with participants. The main aim of this chapter is to explore how participants made sense of the virtual laboratories used in both study conditions, as well as to examine their understanding of the concepts and procedures with which they engaged during the experiments.

Chapter 10 provides a summary of the findings stemming from the preliminary work and the main empirical study. This chapter ponders the implications of those findings in relation to the field and the use of immersive virtual reality for education.

Chapter 11 presents closing remarks for the thesis including conclusions, limitations of the study, potential avenues for further enquiry, and impact of the findings.

Chapter 2: Background and literature Review

Chapter overview

This chapter aims to provide an appraisal of seminal research in the field of immersive virtual reality, as well as embodied cognition and gesture as a way to situate the research presented in this thesis. Three main sections comprise this chapter:

(1) A discussion on what immersive virtual reality is. This involves a brief historical account of the origins and development of the technology, as well as the introduction of a typology to characterise different consumer systems and illustrate their evolution.

(2) A critical evaluation of seminal and most recent work on the uses of immersive virtual reality technology in different domains with a particular focus on education and training.

(3) A discussion of relevant research concerning embodied cognition and gesture as a mechanism for interaction in immersive virtual reality environments.

2.1 What is immersive virtual reality?

Generally speaking, virtual reality (VR) is a medium of communication that allows users to become mentally immersed in an imagined space (Sherman and Craig, 2003). This conceptualization characterizes virtual reality as a medium that hosts artificial environments and acts as a means of communication. Under such general conception, murals, stereoscopic photos, as well as panorama and cave paintings could be considered analogue forms of virtual reality due to their communicative and representational nature. Furthermore, this also highlights the potential of such analogue forms of VR to mentally immerse users, albeit without perceptually surrounding them (Virtual reality society, 2017).

Although, Sherman and Craig's (2003) definition posits key ideas that describe old and new forms of virtual reality making it more inclusive, its broad nature fails to denote the nuances of modern virtual reality. The advent of the digital age not only marked the shift from analogue to technology-based VR, but it also cemented the inextricable relationship between hardware and software going forward. As a result of this digitalization, advances in computing, graphics processing, and display technology made it possible to develop environments that could more closely simulate reality by integrating sensory-motor contingencies in a more natural way such as using gestures or sensing hand and body movements.

In that regard, the development of computing and visualization hardware has not only impacted how virtual environments have been created and presented over time, but as a result of that, it challenges the very notion of what constitutes a virtual environment, what can be considered virtual reality, and how the concept of immersion impacts those ideas.

Firstly, attending to the perceptual nature of VR as a medium, let us consider the software side of its constitution, the virtual environments (VE). VEs are computer-generated spaces that simulate worlds, whether fictional or real. These spaces "exceed the bounds of physical reality by creating a world in which the physical laws ordinarily governing space, time, mechanics, material properties, etc., no longer hold" (Milgram and Kishino, 1994, p. 2). All of which, as it is argued in Chapter 5, can vary depending on the type of hardware that supports them.

Secondly, attending to the representational nature of VR as a medium, it is important to re-define the term itself, especially considering recent advances in the field. The Cambridge English Dictionary (2021b) defines virtual reality as computer-generated imagery and sound that has the aim of representing or simulating environments or situations in which an agent can take part. This definition integrates three ideas that are central to virtual reality as new medium and which are discussed throughout this research: (1) the interconnected nature between hardware and software; (2) the integration of multiple modes of representation (i.e., visual, auditory, and kinaesthetic) (see Kress, 2014); and (3) the active involvement of agents through interaction.

Lastly, regarding the notion of immersion, not to be confused with the illusion of presence (see Section 3.4.1). This is defined as the perceptual involvement that agents can experience due to the capacity of the hardware to visually and aurally surround them (Cambridge English Dictionary, 2021a). That is, it concerns objective features of a system in support of different modes of representation, to which the kinaesthetic mode is a recent addition. In that sense, an agent will experience more or less perceptual immersion to the degree that the system itself is capable of supporting the different modes involved. For instance, a screen that covers the user's entire field of view will be perceived as more immersive than one that covers it partially, as the former more closely simulates human vision.

Based on the discussion above, the term immersive virtual reality technology is understood throughout this research in two interlinked ways: (1) as a medium of representation and meaning making that engages visual, auditory, and kinaesthetic modes; and (2) as a platform that presents surrounding, interactive, computer-generated experiences in which agents can actively take part through embodied engagement and movement such as gestural interactions and postures.

2.1.1 Brief historical account of immersive virtual reality.

As discussed in the previous section, modern immersive virtual reality is intrinsically bound to hardware. As such, innovations in computing, graphics processing, software development, displays, and input devices have shaped both the technology and the experiences they support. Moreover, the rapid pace of such innovations has created a fragmented market as instantiated by current levels of consumer adoption of different types of systems (Lang, 2021a).

The pioneering work of researchers such as Mort Heilig with his multisensory simulator Sensorama in 1958 and Ivan Sutherland's head-mounted display (HMD), the Sword of Damocles in 1968 marked the beginning of virtual reality as a new medium (Hillis, 1999; Sherman and Craig, 2003; Crecente, 2016). Years later, research such as the one conducted on HMDs by Scott Fisher at NASA, the work of Jaron Lanier[4] on his DataGlove and EyePhones HMD in 1985 and 1989, respectively (Crecente, 2016; Ellis, 2016), as well as Carolina Cruz Neira's (1992) development of the first CAVE system cemented virtual reality as a new field of study.

Such initial work not only provided the underpinnings for the development of immersive (iVR) and non-immersive (NiVR) forms of virtual reality in the years to come, but also enabled the emergence of hardware that combines elements from the real and virtual planes to coexist in the same environments. This is a concept defined by Milgram and Kishino (1994) as mixed reality (MR) in their taxonomy of visual displays.

Despite these technologies being the subject of research since the 1950s, virtual and augmented reality technologies have only been available to consumers for less than a decade. For instance, virtual reality systems had their first incursion outside of laboratories and into arcades in the 1990s with the Virtuality arcade VR system by W-Industries, the Sega VR headset, and Disney's DisneyQuest (Sherman and Craig, 2003). However, VR technology remained too costly for individual consumers and, as demonstrated by Nintendo's commercial failure with the Virtual Boy console in 1995 (Virtual reality society, 2017), these systems were not mature enough for mass adoption. Among other issues, systems like these lacked support for locomotion, could not provide high-resolution visuals or screens capable of high refresh rates to minimize the appearance of visual artefacts and the effects of simulation sickness.

The development of the Oculus Rift HMD prototype by Palmer Lucky in 2010 marked the second attempt to bring virtual reality technology into mainstream use. With the foundation of Oculus VR in 2012 and its subsequent acquisition by Facebook in 2014, the technology started to gain more attention and support, both from other companies and the general public (Crecente, 2016; Virtual reality society, 2017; Poetker, 2019).

Lastly, the launch of the Google Cardboard platform and Samsung's Gear VR headset in 2015 ushered the more widespread adoption of iVR technology that continues to this day. This, along with the release of the Oculus Rift and HTC Vive headsets the following year marked the widespread commercialization of numerous and varied types of head-mounted

[4] Jaron Lanier is credited with coining and popularizing the term virtual reality in the late 1980s (Crecente, 2016)

displays (HMD) which caused the fragmentation of the immersive virtual reality landscape (Virtual reality society, 2017; Poetker, 2019; GlobalData Technology, 2020).

By looking at the different types of VR headsets that have been commercialized to date (Robertson, 2016), it is possible to highlight two main concerns going forward. Firstly, systems, their technical specifications, and the platforms that support them take a more prominent role for developers as their choices have implications for the skills set needed, the types of experiences that can be designed, and the audiences that can be reached, as it is argued in the following sections. Secondly, selecting an iVR system that caters to the needs or interests of a particular user or domain can be challenging. For instance, selecting a system for clients to look at architectural designs or taking virtual tours requires a different kind of hardware than may be needed for training on a virtual simulator or playing video games. Although some systems may be able to accommodate different kinds of use scenarios fitting to multiple domains, others can be more limited, thus making them less fit for certain purposes.

2.1.2 Typology of virtual reality technology.

Presently, the landscape of virtual reality technology more closely resembles the virtuality continuum that Milgram and Kishino (1994) proposed as part of their taxonomy of visual displays (see Figure 2.1). The continuum categorises environments based on how real or artificial they are and to what degree they are augmented by real elements or computer-generated imagery. Despite being proposed nearly three decades ago, this classification still reflects the types of hardware and experiences available to consumers to date.

The continuum presents reality on one end and virtual environments on the other, thus denoting their opposing nature. The central area, designated mixed reality (MR), considers environments that combine elements of both planes. These can take one of two forms: (1) augmented reality (AR)[5], which refers to an environment that is mostly real and augmented with some computer-generated elements; and (2) augmented virtuality (AV), which designates an environment that is mostly artificial or computer-generated with some elements of reality

[5] Common AR devices include smart glasses like Microsoft HoloLens. The technology is also used with mobile devices such as smartphones and tablets where the camera is used to show the real world on the screen and virtual augmentations are superimposed.

brought into it. Together, these types of technologies and environments are covered under the denomination of extended reality (XR) as a field of study.

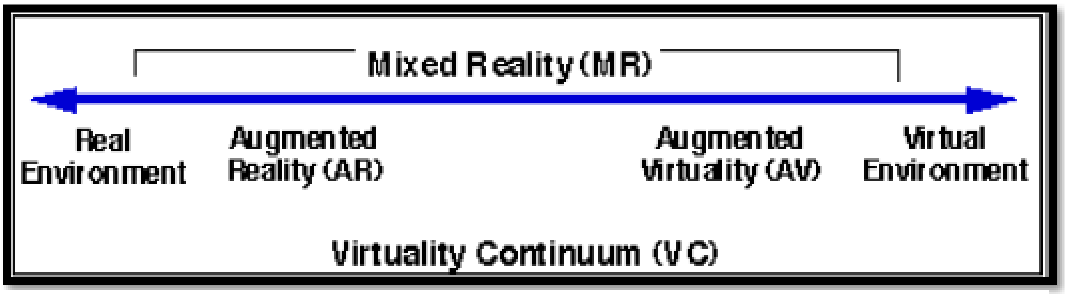


Figure 2.1. *Simplified representation of a "virtuality continuum" (Milgram and Kishino, 1994, p. 3).*

This research is specifically concerned with the use of virtual reality technologies, of which two groups can be distinguished: non-immersive (NiVR) and immersive (iVR). This distinction attends to the capacity of the hardware, or lack thereof, to surround the user in a virtual environment which can elicit the perception of being physically present in it. This is possible by achieving some degree of visual and auditory isolation from reality (Tsyktor, 2019). Of the two types, NiVR is the most prevalent in the literature concerning its use in fields outside of entertainment such as education and training, which can be attributed to three main factors:

(1) Low cost of implementation. Typical hardware comprises personal computers, tablets, or smartphones which users often already own.
(2) Ease of use. These hardware do not require complicated setups the way headsets do. Furthermore, software can be inexpensive and easy to access through established platforms such as Google Play and Apple's App Store.
(3) Expertise of designers and maturity of platforms. These types of experiences resemble traditional videogames (e.g., Second Life) which have been available for decades through well-established platforms. This makes non-immersive experiences simpler to design because developers do not need to learn an entire new medium as is the case with augmented and immersive virtual reality experiences.

Comparatively, immersive forms of virtual reality (iVR) such as headsets, which are the focus of this research, have been commonly regarded as more expensive and complex to use (Jenkins, 2019). Furthermore, the development of iVR experiences requires more advanced expertise to address issues such as the integration of gestural interactions, visual body representations, and modes of locomotion that minimise motion sickness, none of which constitute concerns with non-immersive hardware.

Owing to advances in the design of immersive virtual environments and the refinement of hardware components addressing the issues discussed above, current iVR technology offers a better balance between price, simplicity, and capabilities (Herold, 2014; Jenkins, 2019). For instance, iVR systems like Facebook's Oculus Quest 2 offer more sophisticated hardware than that of mobile-based headsets, whilst being more portable, easy to use, and considerably less expensive than high-end iVR HMDs like Valve Index and the HTC Vive series.

The above does not only denote the ongoing evolution and instability of the immersive virtual reality landscape, but it also highlights, as posited earlier, how fragmented such landscape has become due to the availability of multiple types of headsets with different capabilities (Hruska, 2015; Probst, Pedersen and Dakkak-Arnoux, 2017). Resultingly, separate iVR systems can offer significantly disparate experiences more or less suitable for certain conditions or use scenarios. CAVE systems and vehicle simulators, for instance, require dedicated large spaces and they do not offer the flexibility of headsets in terms of portability. However, they can provide opportunities for collaborative work that headsets currently cannot. Alternatively, mobile-based headsets are not capable of tracking positional movements, nor do they include dedicated controllers for direct interaction like CAVE systems and high-end iVR HMDs.

Figure 2.2 illustrates the stratification of current virtual reality systems based on their characteristics and capabilities. As posited previously, all forms of virtual reality technology can initially be classified into immersive and non-immersive. On the one hand, non-immersive virtual reality systems are characterised by their simplicity of use, low cost, and their maturity and stability of distribution, as illustrated by platforms like Labster (2021) and EON Reality (2021). This allowed for the technology to become a common tool in education and training in the form of simulations, tours, instructional experiences, and games, all of which have been the subject of extensive research (Ferrero and Piuri, 1999; Dalgarno et al., 2009; de Jong, Linn and Zacharia, 2013; Merchant et al., 2014; Fowler, 2015).

Immersive virtual reality systems, on the other hand, can be very different in nature and they can range from vehicle simulators such as those used in industry to train aircraft pilots, to large CAVE systems and, more recently, consumer head-mounted displays. The latter, being the subject of interest in this research, are classified here into three types: (1) headsets based on mobile computing, designated here as low-end iVR; (2) headsets with hybrid feature sets and tracking systems (designated as mid-range iVR); and (3) headsets based on desktop computing with 6DoF tracking systems, referred here as high-end iVR.

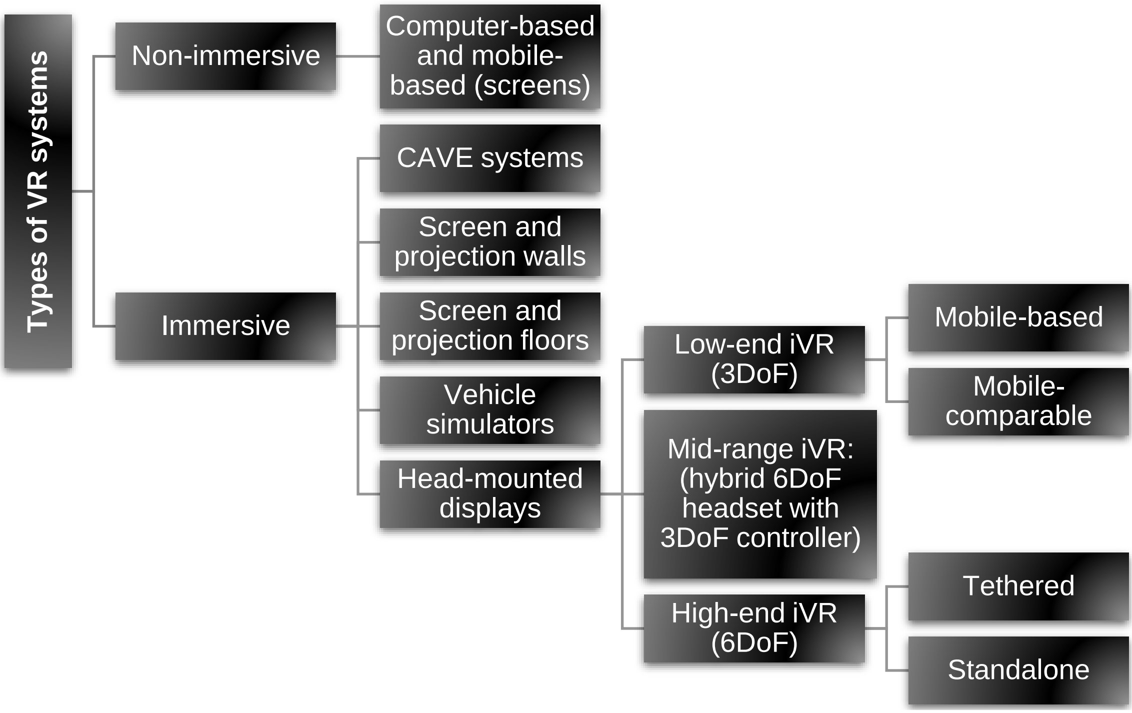


Figure 2.2. Typology of virtual reality technology.

Low-end iVR was popularised by the launch of the Google Cardboard platform (Google LLC, 2014) in 2014, as well as consumer headsets such as Samsung Gear VR in 2015, Google Daydream View in 2016, and Facebook's Oculus Go in 2018. This increased consumer adoption and interest coupled with its low cost and heavy industry support made it possible to bring the technology into the field of education and training. Although compromising on visual quality and support for interaction and movement, these low-end iVR HMDs provide access to immersive visual experiences such as 360° videos (Within, 2020), virtual tours (Google LLC, 2018a; Immersive VR Education, 2018), and virtual STEM lessons like MEL Science (2020).

Despite the announced discontinuation of low-end iVR HMDs like Daydream View[6], Gear VR[7], and Oculus Go[8] between 2019 and 2020, a large percentage of the educational content that can be found online has been designed and is only available for those types of systems. As a result, there is a small, but growing body of literature exploring how these headsets and other immersive technologies can support students' understanding of content and skills development in contrast to non-immersive systems and more traditional forms of education (Gamberini, 2004; Buttussi and Chittaro, 2018; Johnson-Glenberg et al., 2020; Mariscal et al., 2020). Furthermore, education strategies from companies like VRXOne (Munfarid, 2020), RedboxVR (2020), and ClassVR (Avantis Education, 2020) are still focused on bringing low-end iVR HMDs into classrooms, which is why these types of headsets are compared to more advanced systems as part of the empirical work in this research.

The next category, mid-range HMDs, never received any significant support or consumer adoption. Although systems like HTC Vive Focus and Lenovo's Mirage Solo were meant to close the gap between low- and high-end iVR HMDs by incorporating a standalone, 6DoF headset with a 3DoF controller, the rapid pace of development of VR hardware accelerated the shift to standalone systems with fully integrated 6DoF tracking like Oculus Quest and all Windows Mixed Reality HMDs (Qi, 2020).

Lastly, high-end iVR HMDs can be classified into two main types: (1) tethered, which require to be connected to a gaming computer; and (2) standalone, which embed all components in the HMD itself making these systems more portable, convenient, and accessible to consumers. Being more feature rich, high-end iVR systems provide more opportunities for the exploration of visual, auditory, and kinaesthetic modes or representation in virtual environments, hence their use in the empirical work in this research.

It is important to note that although other forms of immersive iVR technology such as vehicle simulators and CAVE systems incorporate several of features found in high-end iVR

---

[6] Google announced the end-of-life of its HMD, Daydream View, in October 2019 (Robertson, 2019), thus stopping hardware and software sales, development, and support for the system.

[7] Samsung declared the termination of its XR services and Gear VR HMD by September 2020 (Hayden, 2020).

[8] Oculus announced the discontinuation of hardware and software sales of Oculus Go by December 2020 and its end-of-life (support) by December 2022 (Hruska, 2020).

HMDs, they have been classified separately from headsets and from each other in the typology (see Figure 2.2) due to their different overall nature. Furthermore, although these could be further defined into subcategories, such classification lies outside of the needs and scope of this research.

2.1.3 Core features of immersive virtual reality systems.

Generally speaking, the most significant differences between low- and high-end iVR HMDs revolve around four main areas (see Section 5.1 for an in-depth analysis of the features of these types of systems):

1. Display technology

Display technology can differ in how it addresses three types of issues. Firstly, the field of view (FoV) which can be altered by balancing the screen size and its distance from the user's eyes. Secondly, the smoothness of a moving image. A smoother image can reduce the likelihood of users experiencing motion sickness and it is affected by the screen refresh rate. And thirdly, the quality of the image. This is particularly evident on screens with a low count of pixels per inch (PPI). Due to the magnification of the lenses inside the headset and the closeness of the screen to the user's eyes, screen panels require a higher density of pixels (higher resolution) to avoid visual artefacts.[9] Additionally, the alignment of the lenses to the user's inter-pupillary distance (IPD) also improves visual clarity, particularly of small text.

2. Graphical, and computing power

The central processing unit (CPU) and dedicated graphics processing unit (GPU) in a VR system or computer running the system are responsible to maintaining a stable framerate and rendering the virtual environment twice, one for each eye independently, thus creating a surrounding stereoscopic 3D view.

3. Input methods

This involves the different mechanisms that the iVR system employs for interaction, which can include gloves, cameras (these can recognise hand gestures or track eye movements),

[9] Examples of such artefacts include the screen door effect and god rays (see Nomenclature).

exoskeletons, body suits, and controllers. In addition to using buttons, controllers may also recognise touch and pressure from individual fingers, thus allowing for gestural interaction.

4. Tracking system

This is responsible for supporting locomotion and other forms of rotational and positional movement of the head/body and hands/fingers. Movement can take place in six different dimensions called degrees of freedom of movement (DoF) (Snyder, 2016; Google LLC, 2018b; Barnard, 2019). Figure 2.3 (Nelson, 2013) illustrates how three of those dimensions translate to rotation (yaw, pitch, and roll), whilst the remaining three represent changes in spatial position (surge, heave, and sway) on the perpendicular axes X, Y, and Z, respectively.

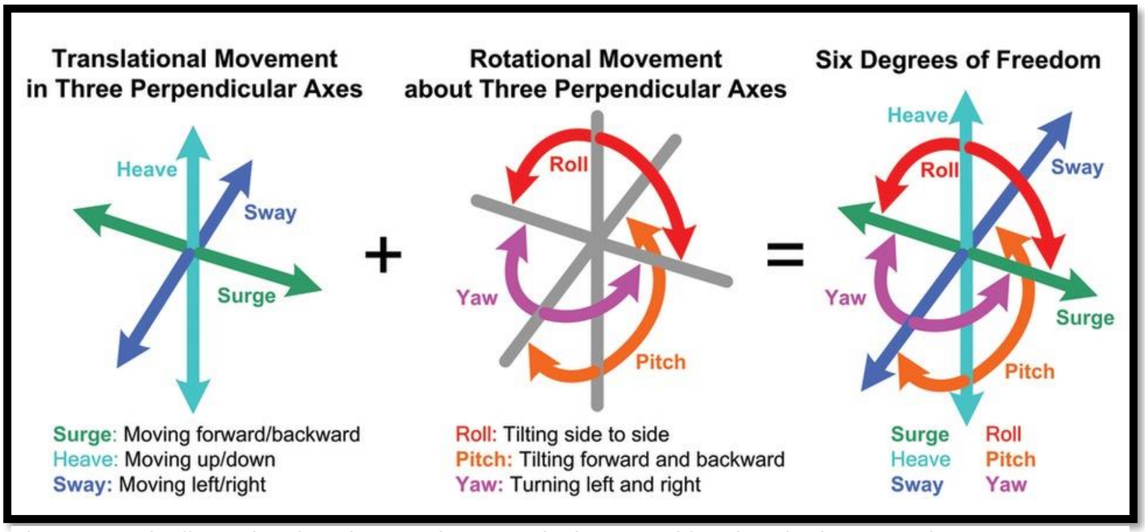


Figure 2.3. Six-dimensional motion sensing over six degrees of freedom (Nelson, 2013).

The incorporation of a tracking system has significant implications for the kind of experiences that can be supported. For instance, thee degrees of freedom of movement (3DoF) tracking systems only register rotational movements in a fixed position (roll, yaw, and pitch) due to their use of an inertial measurement unit (IMU)[10] (Coburn, Freeman and Salmon, 2017). In reference to VR headsets, this typically applies to low-end hardware (see Figure 2.4) and it is limited to the rotation of the head to look around in the virtual environment, as well as the rotation of the user's wrist to move the pointer around the visual field to select manipulatives. Due to this, although users can be afforded control to direct what happens in the virtual environment, this is limited to triggering actions and watching them being performed

[10] The IMU contains a three-axis accelerometer and a three-axis gyroscope that provide the capability to track 3DoF.

automatically, rather than having the ability to carry them out directly. Additionally, the impossibility to track the change in position of the user, limits experiences to seated and standing setups.

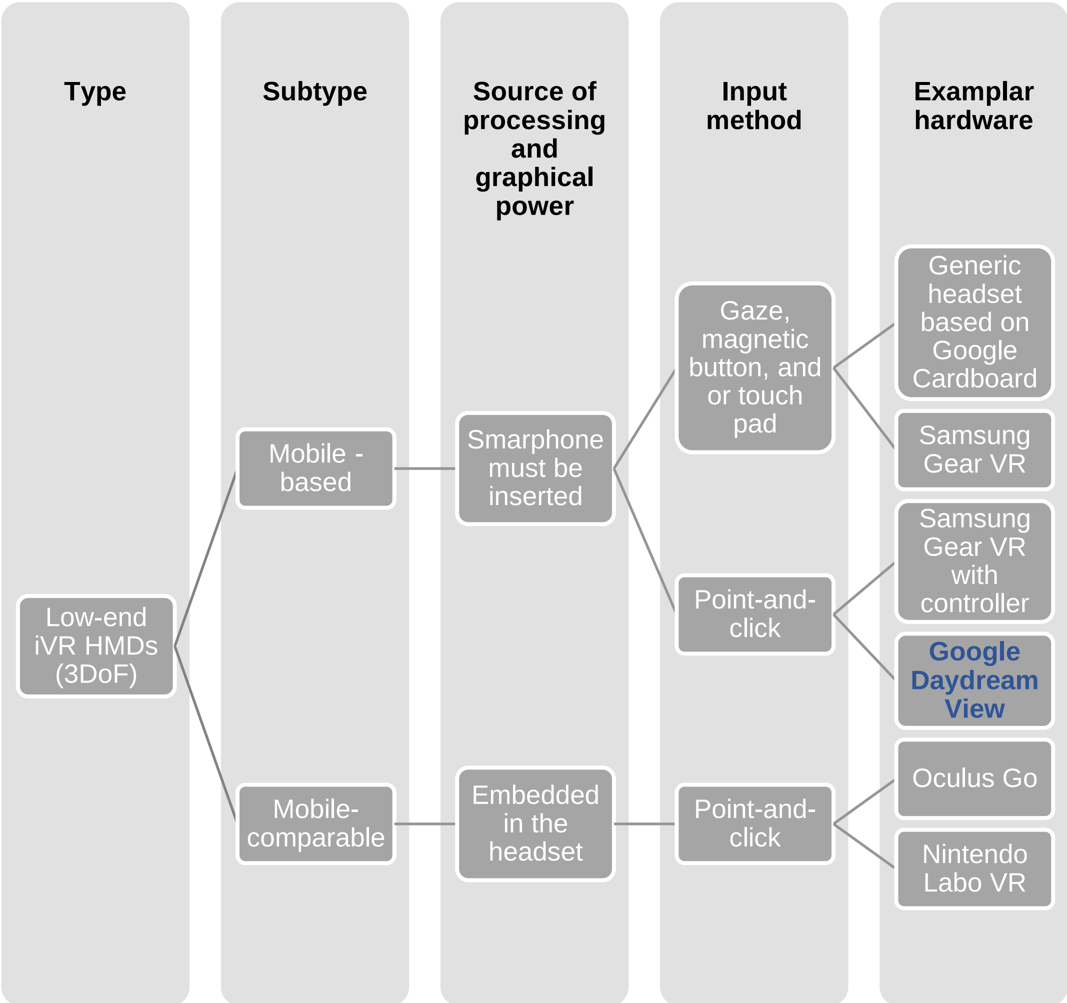


Figure 2.4. Specification of low-end, 3DoF iVR headsets.

Comparatively, six degrees of freedom of movement (6DoF) tracking systems such as those used in high-end iVR HMDs (see Figure 2.5) incorporate three more dimensions of movement (surge, heave, and sway) that allow for a full range of motion, thus supporting standing, seated, and room-scale experiences. This can be achieved through electromagnetic, mechanical, acoustic, or optical methods (Virtual Reality Society, 2017). Most modern consumer HMDs use either an inside-out or outside-in optical method of tracking that not only allows for locomotion (i.e., walking) and interaction through gestures or direct manipulation, but that also enables more subtle forms of motion such as changing the viewpoint, leaning, reaching out, bending down, or hand twisting.

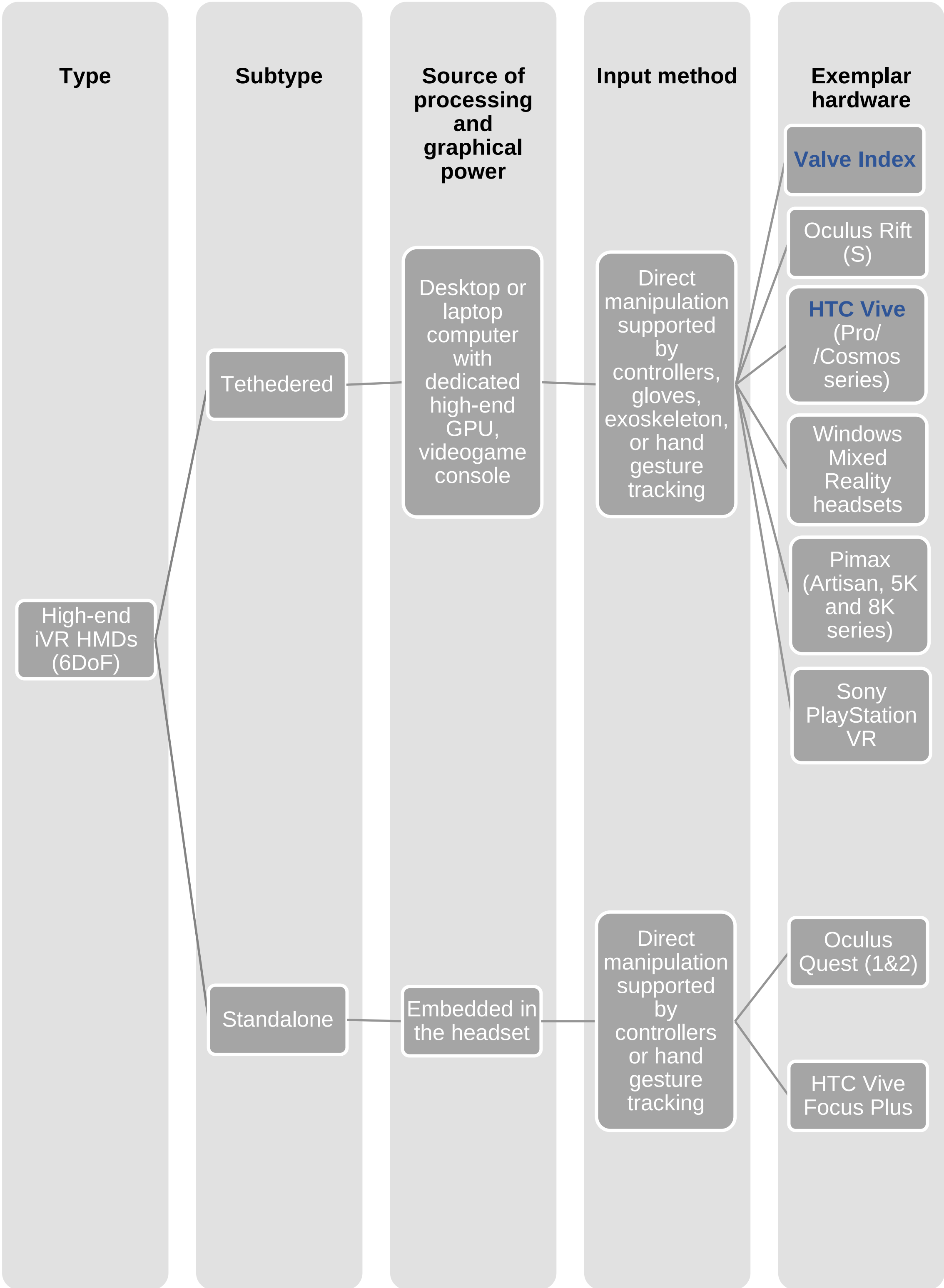


Figure 2.5. Specification of high-end, 6DoF iVR headsets.

Figure 2.4 classifies low-end iVR HMDs based on the 4 differentiators discussed above. These systems can be categorised as mobile based or mobile comparable[11]. The former describes headsets devoid of internal components other than lenses, thus requiring a smartphone to be inserted to serve as the screen, as well as the source of computing and graphical power. The latter describes self-contained headsets that integrate computing and graphical units in the chassis. Both types of low-end iVR HMDs are wireless, which makes them portable. However, because they are only capable of sensing rotational movements, as indicated previously, VR experiences hosted in these systems are designed around seated or standing setups.

Regarding methods for interaction, low-end iVR HMDs typically employ at least one of three types of input methods: (1) Gaze. By rotating the head, a visual reticule can be placed over an interactable object and selections are made by holding the view-point for a few seconds. (2) Magnetic button or touchpad. The former consists of a magnet on the side of the HMD which is operated like a slider to make selections. The latter recognizes finger-brushing motions to move a screen cursor. Selections are made by tapping the touchpad with a finger. (3) Point-and-click. This method uses a remote controller acting like a pointer. This controller typically has a button or touchpad to make selections.

Figure 2.5 classifies high-end iVR HMDs also based on the 4 differentiators discussed above. These systems, as posited in the previous section, can be classified as tethered or standalone. The former consists of headsets that need to be connected to a potent gaming computer, whilst the latter comprise systems that embed all tracking as well as graphical and computing processing components inside the HMD unit.

Both types of high-end iVR HMDs incorporate some form of 6DoF tracking system that allows for the replication of rotational and positional movements of the user's hands and head such as when walking, leaning, or manipulating virtual objects. As a method for interaction, these systems commonly employ dual controllers. However, they can be capable of supporting other types of input devices such as gloves, body suits, exoskeletons, cameras for hand gesture recognition, or purpose-built tools like guns, steering wheels, tools, or medical

[11] The consumer systems listed in Figure 2.4 were commercially available at the start of this research. However, with the exception of Nintendo Labo VR Kit, they have all been discontinued.

equipment, all of which allow for direct manipulation as opposed to the point-and-click method used by low-end iVR systems.

The four differentiators of iVR systems discussed in this section have the same aims regardless of the type of technology used: (1) the display technology is intended to support a surrounding, stereoscopic 3D first-person perspective (1PP) of the virtual environment; (2) the input methods are meant to support interaction with manipulatives, thus providing a sense of agency; (3) the graphical and computing power support the visual quality and performance of the experience; and (4) the tracking system enables kinaesthetic forms of engagement with the virtual environment. Each of those types of systems, however, achieves such aims in different ways, which, as argued in this research, can result in notably dissimilar outcomes. In the case of display technology, for instance, the use of different types of displays such as LCD or LED and their resolution will dictate the presence of visual artefacts such as god rays or the screen-door effect (see Nomenclature), which can hinder visibility and comfort; the size of those screens will impact the user's field of view (see Nomenclature), which has implications the elicitation of a general sense of presence; and the refresh rate of the screens will have a direct effect on any latency and the smoothness of the image (see Nomenclature), which has implications for seamless interaction and minimising simulation sickness (see Section 5.1 and its subsections for an in-depth analysis of how these features of iVR systems impact the types of experiences that they can host).

It is hypothesised in this research that the affordances enabled by those four types of features can be so significant in shaping perception and interaction in immersive virtual environments (see Chapter 7 and Chapter 8, respectively) that they could impact the way users make sense of the content they engage with (see Chapter 9). This can have important implications concerning three main areas: (1) a framework for the design and development of virtual environments for specific purposes or tasks; (2) guidelines for the implementation of iVR HMDs for learning and skills development; and (3) the suitability of certain types of iVR systems to specific domains.

2.2 Uses of immersive virtual reality.

Decades of research coupled with recent increased availability and consumer adoption of virtual reality headsets have fostered the use of different forms of iVR technology in domains like marketing, healthcare, art, design, engineering, education, training, as well as entertainment in the form of videogames, films, 360° videos, experiences, and tours (Jensen and Konradsen, 2018; Suh and Prophet, 2018; Radianti et al., 2020). Implementations in such fields largely look to capitalize on the immersive capabilities and perceptual affordances of immersive systems.

Although the uses of head mounted displays can be as diverse as the domains themselves, it could be argued that the appeal of these immersive technologies relies in the experiential nature of the artificial environments they support where users can engage actively and safely. Such implementations largely revolve around simulation, perception, and interaction, and how these present users with domain-specific affordances that go beyond what is possible through other means.

Some examples of domain-specific affordances include visualization such as the use of 3D models and environments in architecture, engineering, interior design, and real estate. Computer-aided design models (CAD) and technical drawings can be translated into explorable three-dimensional models. Whilst this can act as a money saving measure by eliminating the necessity of a physical model, it can also provide customers who have no knowledge of design with a clearer understanding of the process and spatial perception of a building (Serpa and Eloy, 2020). Additionally, interior designers and real estate agents can showcase a space or provide customers with tours of a development before construction has even started (Ozacar et al., 2017; Deaky and Parv, 2018). Studies like these, however, also highlight the need for fully interactable spaces that can be physically navigated as in the study by Ozacar et al. (2017). In contrast, the study by Serpa and Eloy (2020), required participants to use a mouse to interact with the space, despite involving an HMD capable of direct manipulation of virtual objects. Similarly, the study by Deaky and Parv (2018) demonstrate how the use of photogrammetry can result in highly photorealistic environments, but these have the drawback of not being interactable of navigable.

Another notable domain using iVR technologies is healthcare where therapy and treatment can be carried out by placing patients in environments that are specifically designed for the treatment of an ailment. For instance, some studies have found that post operatory patients reported having experienced less stress and increased tolerance to pain during their engagement with a virtual environment, which was corroborated by respiratory rate, heart rate, and arterial pressure measurements (Loreto-Quijada et al., 2014; Mosso-Vázquez et al., 2014). Similarly, a study involving a paediatric burnt patient reported that using an HMD reduced pain and unpleasantness (Hoffman et al., 2014). Whilst these studies demonstrate novel uses of iVR technology, they also highlight the complexity of ecological implementations as well as the involvement of a larger number of participants as is the case with the study by Hoffman et al. (2014) which follows a single hospital patient.

Concerning psychotherapy and mental health, HMDs have been used due to their capacity to provide surrounding sensory experiences. These experiences engage visual and auditory modes to promote relaxation and address psychological conditions in a safe and controlled environment. Notable cases include:

- Body image disturbance (BID) for which HMDs were found to offer an ecological method of assessment. Participants who were on a diet experienced higher levels of social evaluative concerns through a VR-supported treatment (Mountford, Tchanturia and Valmaggia, 2016). However, the avatar and environment were found to be perceived of low fidelity, with could contribute to the ineffectiveness of the VR treatment.
- Exposure therapy for phobias. The use of a head mounted display showed positive outcomes in reducing fear and anxiety on a patient with an incapacitating fear of spiders (Carlin, Hoffman and Weghorst, 1997). Although this study had the limitation of not involving a trackable mechanism for interaction and movement. This was addressed by involving tactile augmentation, thus highlighting the need for touch and haptic feedback[12] in these types of environments.
- Therapy for social anxiety. Using a head mounted display was found to be more practical and cost-effective for therapists compared to carrying out individual cognitive-behavioural therapy (CBT). According to Bouchard et al. (2017), this form of therapy was also more effective at post-treatment on the primary outcome measure, as well as one of five secondary measures in their study. An important limitation of this study concerns the differences in the scenarios in each condition which can make direct comparisons challenging.
- The treatment of eating disorders. Riva (2005) concluded that body experience disturbances and self-efficacy, both of which have been difficult to address through traditional CBT, can be treated using VR technology. However, technology such as the one used in the study can be difficult to implement and costly.

[12] Although haptic feedback can take many forms (see Blenkinsopp, 2019), in this instance, it concerns the rumble or vibration of the controllers when an object is virtually “touched.”

- The treatment of post-traumatic stress disorder (PTSD). The work of Rizzo et al. (2009) showed positive clinical outcomes as active duty military patients no longer met the diagnostic criteria for PTSD after receiving treatment using a software developed specifically for exposure therapy involving scenarios that simulate war zones. This type of software, however, cannot fully replicate the sensorimotor affordances of a real environment due to the limitations of the hardware.
- Depression. As part of an open trial, it was found that participants experienced reduced self-criticism, and increased self-compassion which indicate the positive effect of interventions to treat depression severity (Falconer et al., 2016). The iVR setup used for this study, however, highlighted the complexity of involving full body motion despite the central role that the body may play in simulations such as these.
- Psychosis and substance abuse. It was found that specially designed VR environments can trigger cravings among patients suffering from substance abuse, thus suggesting their potential for use in treatment. Based on their study, Freeman et al. (2017) concluded that VR cognitive therapy can be more effective than VR exposure to treat patients suffering from delusions and distress. However, this study also demonstrated the need for user experience design that takes advantage of the capabilities of a VR system and caters to the nuances of the treatment.

Despite the discussed limitations around methodological approaches or scope of the studies presented this section, these studies have advanced current understandings in the use of iVR technology if diverse fields, thus highlighting new paths of enquiry. Another field of study where immersive VR technology has been used due to its capacity to elicit perceptual states through sensory experiences is psychology. For instance, a study by Hasler, Spanlang and Slater (2017) showed that white participants' implicit racial bias was diminished after embodying a virtual black body and that identification through mimicry was expressed according to the virtual body's race, rather than the race of the participant. Similarly, Tajadura-Jiménez et al. (2017) looked at embodiment in virtual environments and found that body ownership can be elicited across age groups such as when placing an adult in the body of a child. This impacted the participants' object size estimations by twice as much, thus providing additional evidence that perceptions of body size and age can influence interpretation of sizes and how virtual environments are perceived.

In that regard, Kilteni, Groten and Slater (2012) posit that the illusion of embodying a virtual avatar does not only concern experiencing body ownership, but it is also dependent on achieving a sense of self-location and agency, which are central ideas explored in this research. Whilst this addresses how iVR systems can elicit presence and allow for the exploration of body representations, it also provides important insights into the potential mechanisms that support interaction, as it is discussed further in Chapter 8.

Another notion concerning body ownership is synchrony, which is applied in relation to gestural interaction in this research. Slater et al. (2010) found that visuo-tactile synchrony is not required to generate the illusion of body transfer ownership on male participants embodying a virtual female body. This suggests that perceptual mechanisms can temporarily override knowledge of self-representation, thus positioning immersive virtual reality technology as “a powerful tool in the study of body representation and experience” (Slater et al., 2010, p. 1). This is possible due to the technology’s capacity to manipulate visual input and motion, the latter of which is essential for direct interaction and creating a sense of agency.

Lastly, education and training constitute two domains where iVR HMDs have shown potential to make a significant impact. It has been suggested that virtual reality environments are particularly suited for the simulation of dangerous situations that could pose a risk if performed in reality, or for conditions that are simply impossible to experience through other means (Stavroulia et al., 2019). For instance, students can safely work with chemicals in a virtual laboratory (Dunnagan et al., 2020), they can be placed in the middle of a war zone for a history lesson (Calvert and Abadia, 2020), they can be transported inside a cell or organ to study biology and anatomy (Johnston et al., 2018) or they can make a trip to other planets (Papachristos, Vrellis and Mikropoulos, 2017).

Coupled with the capacity to surround users visually and aurally in virtual environments, some iVR systems can also allow for kinaesthetic engagement to the extent that mechanisms for direct interaction and movement such as grabbing gestures and changing body postures are supported. This constitutes a useful affordance not only in educational experiences that require exploration, visualization, and the performance of procedures, but also in training experiences where developing motor skills and practicing tasks are essential. Examples of this include medical doctors practicing a surgical procedure (Zhou et al., 2018; Osso VR, 2021), and trainees assembling manufacturing equipment (Dodoo et al., 2018), familiarising themselves with industrial processes (Andaluz et al., 2018), or analysing blueprints of a building for a fire drill (Bliss and Tidwell, 1995).

Although greater emphasis has been given to the study of presence in immersive environments for education, other aspects such as gesture, posture, and interaction have remained relatively unexplored in relation to their potential role in supporting learning. Makransky et al. (2019), for instance, looked at virtual environments presented through HMDs and desktop computers. Findings indicate that participants in the former condition experienced increased perception of presence. However, measured learning was lower in that same group. Makransky et al. (2019) attribute this to high levels of extraneous cognitive load and indicate the similarity of their findings to the work of Richards and Taylor (2015) comparing variations in visual representations and that of Moreno and Mayer (2002) which looks at different types of immersive technologies.

Although there is merit to the notion that the use of immersive technologies such as headsets can hinder learning due to cognitive load (Sweller, Ayres and Kalyuga, 2011), it seems problematic to regard presence as the sole predictor of learning in immersive virtual environments considering the multiple modes of representation and engagement that are implicated. Moreover, whilst findings reported by Moreno and Mayer (2002) and Richards and Taylor (2015) suggest lower or comparable levels of measured learning in immersive conditions, the research by Moreno and Mayer (2002) involved an old HMD with no support for interaction, and the research by Richards and Taylor (2015) used a 3D environment that did not require an HDM or any truly immersive technology. As a result, findings such as these are not fully comparable to the work of Makransky et al. (2019).

A similar example can be observed in a study by Papachristos, Vrellis and Mikropoulos (2017) where the authors, much like it is done in this thesis, compared learning outcomes and variables such as presence, satisfaction, usability, and simulator sickness between a low-end and a high-end HMD. Findings indicated no significant difference between the two conditions. An important distinction, however, was that although the selected hardware offered opposing capabilities in their support for interaction, this was not exploited as both conditions used the same virtual environment with minimal point-and-click interaction.

The conditions described above are common among scholarly work exploring the use of virtual reality in education. One of the factors contributing to this can relate to the constant evolution of the technology and how new iterations of hardware enable novel forms of sensory-motor engagement. This has led to three scenarios: (1) the fragmented landscape of consumer VR hardware can cause mischaracterizations of how immersive and non-immersive virtual reality technologies are regarded in the literature, thus making research itself fragmented; (2) the rapid commercialization of new systems can make current versions of hardware and research outdated or no longer relevant to the same extent; and (3) the lack of consideration of the features of different types of VR hardware and their sensory-motor affordances through software can represent important omissions concerning the interpretation of findings.

Given the observations above, findings from empirical studies involving iVR technology for education and training, particularly low-end consumer headsets (see Figure 2.4) and old non-consumer HMDs, ought to be interpreted with caution on the basis of three considerations:

(1) Low-end iVR systems and old, non-consumer HMDs were prone to low graphical performance and visual artefacts. Coupled with bad ergonomics and weight distribution, such artefacts increased the probability of inducing discomfort and motion sickness, which could potentially impact perceptual states such as the illusion of presence. Resultingly, iVR systems regarded as highly immersive in the past, could be considered less immersive now due to their limitations compared to modern hardware.

(2) Low-end consumer headsets and old HMDs typically lacked the capability to track the user’s movements, or they were only able to do it with 3DoF, which impacted their support for kinaesthetic forms of interaction or engagement.

(3) Lastly, those systems either lacked mechanisms for interaction or their implementations only allowed for indirect (surrogate) forms of manipulation of virtual objects such as tapping a finger on a touchpad or using sight or a pointer to make selections. Additionally, gestural interactions, when supported, were not always congruent with the task or content (see Section 2.3.1).

As suggested previously, the rapid development of new types of iVR systems has resulted in educational implementations and research that reflects the fragmented landscape of consumer iVR HMDs. Whilst some newly released hardware may provide parity or minimal advancements such as better visuals, larger field of view, higher refresh-rate, or spatial audio, others may make bigger leaps by altering the way in which sensory-motor engagement is supported. For instance, the use of touch and pressure sensitive controllers, body suits, gloves, or custom-made input devices for training, all represent forms of interaction that significantly depart from point-and-click interaction.

Two major leaps of that nature have taken place with virtual reality technology to date, the shift from non-immersive (e.g., desktop computers and tablets) to immersive hardware (e.g., HMDs and CAVE systems), and that from 3DoF to 6DoF iVR head-mounted displays. These technological shifts have motivated comparative studies in education and training looking to understand differences and opportunities against traditional forms of instruction and other immersive technologies.

Dunnagan et al. (2020), for instance, developed a virtual organic chemistry laboratory to assess its feasibility as a replacement for a traditional laboratory to learn how to use an infrared spectrometer. The experience was designed by sourcing data from teaching assistants whose prelab presentations were recorded to develop a script for the VR experience. The methods of data collection employed involved worksheets, postexposure questionnaires, and a delayed quiz. Although findings indicate participants reported higher satisfaction in the iVR condition over a traditional face-to-face laboratory which was used as a control group (Control, N = 45. Treatment, N = 30), no significant differences in measured learning were found in the short or long term. This, as suggested previously, could be the result of the limitations of the point-and-click interactions supported by the Gear VR headset that this research used. It is important to note that both control and study groups were designed to be similar in content and provide guidance and learning support.

Contrastingly, Pande et al. (2021) carried out a longitudinal study comparing a video-viewing condition and an interactive iVR condition. In this study, Pande et al. (2021) looked at whether and how these two forms of content delivery could affect student learning over time. The study was done in the context of an undergraduate science course exploring topics about environmental biology. These covered photosynthesis, biodiversity, and food webs, all developed by Labster. Data was collected using pre-, post-, and delayed tests and the study followed a quasi-experimental design involving 24 undergraduate students, 13 in the iVR group, and 11 in the video group. Although, similar to the study by Dunnagan et al. (2020), interactions in this research were also based on point-and-click behaviour. Results showed that participants in the iVR condition in this study increased their knowledge test performance over time. These findings highlight the significance of active learning, despite the limited interaction afforded by the hardware used. It is also important to note that this study used a hybrid VR headset that allowed for a full range of movement regarding the body and head, but not the hands.

The discrepancies found between the reported findings by Dunnagan et al. (2020) and Pande et al. (2021) illustrate the possible significance of interaction and active engagement to support learning. Moreover, this may be more impactful than the simple elicitation of perceptual states such as the illusion of presence. An example of this can be found in the work of Calvert and Abadia (2020) who also conducted a study comparing an iVR condition and, in this case, a 360° video-viewing condition. This study was carried out with high school students in Australia (N = 49) and university students in India (N = 30) and looks at student experiences with immersive narratives in a history class about the Kokota campaign. The study involved a purpose-built experience adapted to the modes of delivery and used a post-experience survey enquiring about affective outcomes such as the perception of presence, engagement, and empathy, an online test to assess information recall, and a focus group to elaborate on participant's views on the experiences. The immersive virtual reality environment supported direct interaction and full motion, in contrast to the work of Dunnagan et al. (2020), thus making this a more embodied experience. Findings indicate participants in the iVR condition obtained higher test scores, as well as increased engagement, presence, and empathy than those in the 360° video-viewing condition.

Similarly, Roussou and Slater (2020) explored the use of immersive virtual reality for education. Their mixed methods study looks at the link between interactivity and conceptual learning by having children (N = 50) perform tasks to solve arithmetical fractions problems. The research comprised different conditions going from a non-interactive activity with LEGOs to a fully immersive and interactive VR experience. Quantitative findings indicate that participants who took part in the immersive virtual reality conditions outperformed those in the non-VR condition. However, those results did not provide enough evidence that such learning outcomes could be attributed to interactivity. Based on qualitative analysis, Roussou and Slater (2020) posit that "interactivity aided in promoting skill and problem solving and provided opportunities for contradictions to emerge" (p. 11). However, guidance, rather than interaction, seemed to be more impactful in the resolution of those contradictions, particularly at a conceptual level. These findings highlight the role that interaction can have in developing understandings around a problem that needs solving. Furthermore, it also demonstrates the importance of scaffolding and guidance as, without it, conceptual misconceptions could go unchallenged and doubts unresolved.

Although several other studies have found positive effects concerning knowledge retention (Alhalabi, 2016; Webster, 2016; Krokos, Plaisant and Varshney, 2018; Meyer, Omdahl and Makransky, 2019; Hamilton et al., 2020; Liu et al., 2020; Pellas, Mystakidis and Kazanidis, 2021) and knowledge transfer using iVR HMDs (Butt, Kardong-Edgren and

Ellertson, 2018; Hejtmanek et al., 2020), more needs to be done to develop current understanding of the mechanisms through which immersive technologies like VR can support learning and skills development. In doing so, developers of educational virtual environments and initiatives bringing iVR technology into classrooms will be better supported to carry out evidence-informed designs and instructional implementations.

On that regard, research like the one presented in this thesis can be of interest to practitioners, educational VR developers, and other researchers. In the case of practitioners and schools, for instance, this type of work can inform the selection of immersive virtual reality systems and experiences that have clear educational aims and whose design and mechanisms for interaction align with the needs of the school and of the educational implementation for which it is intended. For developers of educational iVR experiences, this research could provide valuable insights concerning the design of environments and how these could employ embodied and natural forms of interaction that are congruent with educational content. And for researchers, this study advances current knowledge concerning how embodied cognition can take place in immersive virtual reality experiences.

Ultimately, all of the uses of iVR technology discussed in this section instantiate the role that simulation, perception, and interaction have in enabling domain-specific affordances. Such affordances are reflected in the virtual environments that a particular iVR system may support (see Chapter 5), but more importantly, they highlight the prominence of the body when engaging with them. In that regard, the success of iVR-assisted education will not necessarily be dependent on wide adoption or sales, although this could foster the development of more and better-quality educational content. The success of iVR technology for the purpose of education and training will be dependent on how well the technology being used serves the purpose for which it is being brought into the classroom as a tool to support or, in some cases, replace, some aspect of the instructional process in a particular domain or discipline, be it the development of skills, the practice of dangerous tasks, or the integration of perceptually engaging experiences that can make learning more memorable and immersive.

2.3 Research on embodiment and iVR technology.

Due to the perceptual and representational nature of immersive virtual reality technology, the body of the user takes a central role. As Dourish (2004) posits, “embodiment is the property of our engagement with the world that allows us to make it meaningful.” And as such, “embodied interaction is the creation, manipulation, and changing of meaning through engaged interaction with artifacts" (p. 126). This suggests that embodiment in iVR is instantiated through the senses and the way users can appraise an environment from the standpoint of their own anatomy.

Although the notions of embodiment and embodied cognition are discussed more in depth in Section 3.2, the following is an evaluation of scholarly work exploring the role of the body in immersive virtual reality from three perspectives: (1) the illusion of presence in virtual environments; (2) body ownership; and (3) interaction and engagement.

The illusion of being physically present in a virtual environment (see Section 3.4.1) is possible due to the integration of surrounding visual and auditory stimuli. In relation to education, presence has been found to correlate to immediate learning gains. Ratcliffe and Tokarchuk (2020), for instance, looked at motivation, the perception of presence, and mediation effects in iVR environments. The study involved an experiment where participants (N = 24) took part in one of two conditions. The study group integrated embodied and spoken interaction for the memorization of words in the context of a Japanese – English language lesson, and the control group was only limited to spoken interaction. Student performance was assessed via pre-, post-, and delayed tests, and motivation was measured with the MEEGA + educational games experience questionnaire. Reported findings indicate that embodied controls and presence encourage learning in iVR environments; although, their effects erode over time. This of course follows the assumption that an iVR system would be used in isolation without external or internal guidance or the implementation of scaffolded tasks.

In other domains, the study of presence in iVR can span therapeutic uses, the exploration of spatial navigation, virtual travel, and self-representation (see Slater and Sanchez-Vives, 2016). One example of this is the perception of inhabiting an avatar or a virtual representation of the self in a virtual environment (see Section 3.5) which is similarly dependent on sensory stimuli and engagement. Slater and Sanchez-Vives (2014) carried out two experiments involving the use of a virtual environment and motion capture to measure body ownership (N = 36) and racial bias (N = 60). For the second experiment, participants were asked to take a racial bias implicit association test (IAT) (see Greenwald, McGhee and Schwartz, 1998) before and after the intervention. Slater and Sanchez-Vives (2014) propose that "when participants have the illusion of ownership and agency over a virtual or robotic body via multisensory correlations, this has behavioural, attitudinal, and probably also cognitive correlates for the embodied person" (p. 26). This is illustrated in how the perception of body ownership has been found to elicit self-attribution of actions (Banakou and Slater, 2014; Argelaguet et al., 2016), thus providing insights into how the sense of ownership can impact the sense of agency.

Hasler, Spanlang and Slater (2017) also found that eliciting body ownership can reverse racial in-group bias. This was explored by placing white participants (N = 32) in black or white virtual bodies to interact with a virtual human character for 6 minutes. The experiment required that participants engaged with the virtual human character twice. However, each time, the colour of the character's skin was different, once aligning with their own skin colour, and once with the colour of their virtual representation. Findings indicate that participants experienced a strong sense of body ownership irrespective of the skin colour of the avatar. However, results from a IAT showed no changes in implicit racial bias. On the other hand, mimicry with members of the same racial group was found to be malleable. Results showed that the degree of mimicry was greater when the skin colour of the virtual human character matched the skin colour of the avatar participants were inhabiting. As indicated by Hasler, Spanlang and Slater (2017), this "demonstrates the plasticity of racial self-categorizations and the malleability of the racial in-group bias" (p. 12).

The work of Tajadura-Jiménez et al. (2017) show that body ownership can also influence object size perception and self-identification. Based on an experiment where adult participants (N = 34) embodied a virtual child. One condition simply placed participants in the body of a child, whilst in the second condition, their voice was also altered. Based on the results of a post-experience questionnaire and an implicit association test, it was found that participants in the body condition overestimated the size of objects and reported self-attributions, thus demonstrating the malleability of body representations in the brain. It was also found, however, that voice altering had no such effect.

The studies discussed above demonstrate that the engagement that users can have with a virtual environment is body centric not only from a visual and auditory standpoint, but it is also instantiated through the kinaesthetic ways in which exploration and interaction are supported in a virtual environment. These can range from the subtle changes in body posture during exploration, to the hand gestures used during interaction, and the large physical movements performed when walking (see Section 3.3). As argued in Section 2.2, interaction with iVR HMDs can be direct or indirect. The former refers to natural forms of engagement that involve grabbing or pinching gestures, as opposed to button pressing, as well as the ability to affect the VE and manipulate objects with 6DoF. The latter consists of having control over the VE and its manipulatives, although limited to triggering actions, rather than physically performing them. This is what Black et al. (2012) designate surrogate embodiment (SE).

As argued by Jang et al. (2017), there is growing evidence supporting the notion that active engagement and direct manipulation can effectively support learning in contrast to passive viewing of content. In that regard, the work of Johnson-Glenberg et al. (2011) highlights the impact of embodiment and agency on learning in immersive virtual environments and provides evidence that active and embodied engagement can promote immediate knowledge gains (see also Johnson-Glenberg et al., 2020) as well as knowledge retention (see also Johnson-Glenberg et al., 2016). Across two studies, Johnson-Glenberg et al. (2011) compare interaction between SMALLab, an immersive virtual reality experience, and an equivalent desktop simulation. Findings show that although both groups displayed significant learning gains, the use of larger, full body gestures did not seem to have any further impact. These observations of increased learning gains when active engagement and direct manipulation are involved is consistent with other research exploring embodied cognition through VR (see Chittaro and Buttussi, 2015; Ioannou and Ioannou, 2020; Thomas Jha, Price and Motion, 2020).

According to Lindgren et al. (2016), the notion that embodied interaction can support learning or impact the way content is understood relies on the integration of “appropriate cueing mechanisms and representational supports” (p. 183) to ground the new knowledge in real-time sensory-motor experiences. In the case of immersive virtual environments, this is enabled by the simulation of behaviour like gestures that congruently interface with manipulatives in the VE. While the scholarly work discussed in this section considers the centrality of active engagement and agency for learning with iVR, the nature of such embodied interactions remains largely unexplored. As hypothesised in this research, if the meaningfulness and congruency of gestural interactions is relevant to support learning like the literature suggests (Segal, 2011; Johnson-Glenberg, 2018), it must also be of significance whether such interactions are performed directly by the user or through a surrogate.

2.3.1 Gesture.

Interactivity constitutes one of the areas where the inextricable relationship between immersive virtual reality hardware and software is more evident. It is hypothesised in this research that the mechanisms through which interactivity is enabled, and the nature of such interactions can open avenues of enquiry concerning two aspects: (1) how users make sense of the content that they engage with in the VE; and (2) how some immersive technologies can be better suited for certain domains.

Controllers, touchscreens, and cameras for body tracking constitute some of the most common input devices (hardware) that are commonly employed to mediate human computer interaction (HCI) in VR. These do not only enable mechanisms to interface with a virtual environment (software), but they also impact the design of the user interfaces (UI) that make such HCI possible.

On account of such hardware/software dynamic, two approaches can be observed concerning interactivity among non-immersive virtual reality systems:

- Peripherals. Desktop-based systems employ keystrokes, mouse clicks, or button pressing on a joystick for selection, locomotion, triggering an action, manipulation, and all other forms of engagement aimed at altering a virtual environment and the objects within it. As a result, menus, text, and small iconography can be common.
- Touchscreens. Touchscreen-enabled devices like tablets, smartphones, and some laptop computers employ UIs built around gestures. As a result, these types of systems favour large iconography and a visual design language compatible with touch input involving tapping, dragging, or swiping.

The above two approaches significantly contrast to the ways in which immersive forms of virtual reality support interaction. In that regard, three strategies can be observed among current consumer iVR hardware:

- Button-based, tangible input. Devices like HTC Vive and all Windows Mixed Reality HMDs employ dual controllers. Users use buttons, triggers, and trackpads on those controllers to perform actions such as holding or releasing an object or selecting things on a menu.
- Free hand (natural) input. Devices like Microsoft’s Kinect and HoloLens, UltraLeap’s Leap Motion, Intel’s RealSense, and Oculus’s Quest 2, employ cameras that perform hand/finger tracking. Users can execute mid-air natural gestures and gestural metaphors to interact with the virtual environment (See Section 3.3). However, due to the absence of a wearable apparatus, touch or haptic feedback are not present when manipulating objects. Other types of devices that support free hand interaction include

wrists (Lang, 2021b), rings (Hamilton, 2021), and gloves/exoskeletons (HaptX, 2021; MANUS, 2021)[13].

- Touch-based, tangible input. Devices like Oculus Quest 2 and Valve Index employ controllers with touch sensitive surfaces that recognise touch, and in the case of the latter, detect pressure and incorporate a mechanism to strap the controllers to the hands. Similar to free hand interaction, this approach allows users to fully open their hands and perform gestures with their fingers[14] like pinching, pointing, or grabbing, although with the added haptic feedback of controllers[15].

Based on the approaches described above, the nature of interactivity can be described in two ways: (1) Surrogate or indirect interactions. These are enabled through a pointer mechanic (ray casting). Instead of performing an action, users are limited to triggering it by directing a virtual laser pointer at a manipulative in the virtual environment and clicking on a button on the controller to initiate it. The action itself is performed automatically without the user's involvement. In that sense, if a user were required to pick up an object and place it in a different area, their sole involvement would be limited to selecting the object. (2) Direct gestural interactions. Supported by six degrees of freedom of movement, these allow users to approach, pick up, drop, rotate, and manipulate objects in a virtual environment. That is, users are given full somatic control over manipulatives, thus allowing them the agency to choose which objects to interact with, how, and when to do so.

The role of gesture has been extensively explored in domains like cognition (Vilà-Giménez and Prieto, 2021), linguistics (Prieur et al., 2020), verbal instruction (Martinez-Lincoln, Tran and Powell, 2018), and human computer interaction (Vuletic et al., 2019; Yasen and Jusoh, 2019). However, the study of technology-mediated gestural interaction in the context of immersive virtual reality remains relatively unexplored. This may be explained not

[13] Gloves and exoskeletons provide the flexibility of free hand interaction with the added touch haptic feedback of tangibles.

[14] Hand and finger movements can be accurately depicted in the VE due to the implementation of an algorithm that superimposes a skeletal frame over the user's hands, thus predicting movement. An example of this is SteamVR Skeletal Input (Valve Corporation, 2018).

[15] The most common form of haptic feedback found with VR controllers and gloves is vibration. This is known as vibrotactile haptics and it involves the use of small motors that produce vibrations that the agent can interpret as the feeling of touch (see Blenkinsopp, 2019).

only due to the novelty of the field itself, but due to the recentness of consumer technology capable of supporting gesture through direct, free hand or touch-based interaction.

Free hand interaction has been shown to better elicit a sense of presence, whilst being faster, more intuitive, and easier than the button pressing and ray casting (pointer) techniques typically used with controllers (see Raees and Ullah, 2019; Wu et al., 2019). This type of interaction may improve upon other mechanisms or techniques such as button-pressing, keystrokes, and mouse clicks. However, it is not without drawbacks. By involving metaphoric gestures that do not resemble true natural manipulation[16], free hand interaction still involves a set of commands to be learnt. For instance, a pinching gesture performed with both hands whilst moving them away from each other can be a metaphor for zooming-in on an image or for enlarging a virtual object. Although the pinching gesture itself is a natural hand movement, it is not used in this situation in a manner that is congruent with the action or context, thus making it an abstraction whose meaning needs to be learn.

Metaphoric gestures like the one described above are arbitrary and often draw from interfaces and design language from other domains. For instance, in a computer, left clicking on the corner of an image is used to select it and change its size, whilst a closed and open pinching gesture is used on touchscreen mobile devices to perform the same action. As argued by Malizia and Bellucci (2012), prescribed metaphoric gestural interfaces inhibit spontaneity by forcing users into adopting “a static and already defined set of command gestures” (p. 37) which do not necessarily empower them to communicate and engage freely with the computer and the virtual environments.

An example of the above can be observed in a study by Makransky et al. (2019) where participants had to tap on the headset’s touchpad to pick up a pipette. In this case the gesture constitutes a metaphor as there is no congruency between the real (physical) gesture and the virtual simulation. That is, they do not mirror each other in shape, direction, or intensity. This study also had the peculiarity of involving the use of an electroencephalogram to measure participants’ (N = 52) cognitive processing during a science simulation delivered through a VR and a desktop condition, both developed by Labster. Results from a questionnaire, knowledge

[16] Although the use of the term natural to describe gestural interaction could imply that these gestures resemble the way in which humans manipulate objects in real life, it has often been used to simply denote that interfaces “offer a higher degree of freedom and expression power when compared with a mouse-and-keyboard interface” (Malizia and Bellucci, 2012, p. 37).

test, and self-report survey showed that students in the VR condition experienced higher levels of presence, but reduced measured learning compared to the desktop condition. Makransky et al. (2019) conclude that this could be the result of cognitive load as observed in the electroencephalogram's measures.

Similarly, in a study by Schroeder et al. (2017), participants were asked to perform metaphorical gestures such as "Raise arm up, make a 90 degree angle at the elbow" (p. 56). Gestures like this one were recognised by the system's camera as an "open" command and needed to be learnt by participants (N = 75). Resultingly, these gestures showed no congruency between action and simulation. The main aim of this study was to compare interaction methods in a desktop and a VR training experience for university students, one based on gestures, and the other based on voice commands. Results obtained from two questionnaires and a recall test showed no significant differences in perceived presence, usability, or information recall performance. Furthermore, the perception of presence was deemed to be not predictive of learning outcomes, thus suggesting it does not constitute a factor influencing learning in VR.

Attempting to address this issue, elicitation studies have looked to make gestures "more natural" or personalised. Wu et al. (2019), for instance, compared freehand, user-defined gestures with ray casting, and button pressing input techniques in the context of a shopping experience. The research was comprised of two studies involving 60 and 30 participants performing interaction tasks. Findings indicate that personalised (user-defined) gestures allow for more intuitive interaction with less cognitive effort. Wu et al. (2019) attribute this to the isomorphic nature of the gestural system in the free hand condition. This means that, even though gestures may remain metaphoric, faithfully replicating them with the virtual hands can contribute to eliciting a sense of self-attribution, agency, and presence.

Concerning instructional virtual environments, however, there is less clarity regarding the impact of prescribed and personalised gestures, or the potential advantages of gesture over other approaches to interaction. Alkemade, Verbeek and Lukosch (2017) looked at the usability, task load, and performance of two gesture-based VR interfaces for the manipulation of virtual objects in a conceptual design and compared them to a traditional mouse-and-screen-setup. During the intervention, participants were required to perform six to nine tasks in which a geometric figure had to be changed (i.e., moved, scaled, or rotated). Towards the end, participants were asked to answer questionnaires about the experience and interactions, a standardised System Usability Scale (SUS) (Brooke, 1996), and a modified version of NASA's Tax Load Index (TLX) (Hart and Staveland, 1988). Findings showed no significant learning differences between gestural and mouse-and-screen interfaces. This is not to say the gestural interface was unsuccessful. It performed just as well as traditional setups. However, advances in human-computer interaction could improve performance, particularly regarding actions that do not have a physical equivalent and for which metaphoric gestures are required.

Similarly, the work of Planey and Lindgren (2020) looked at interaction in VR. However, this research involved whole-body gestures in a collaborative STEM setting. In this study, 70 undergraduate students were randomly assigned to one of four treatments where they were asked to perform prescribed gestures or invent their own after which they had to answer an engagement and perception survey to support data stemming from video recordings. Results indicate that despite significant learning gains, there seems to be no significant difference between prescribed and personalised gestures. While these findings do not indicate the inefficiency of gesture compared to non-gestural mechanisms for interaction in instructional virtual environments, they may be the result of confounding factors such as the context and manner in which gestures are implemented and the very nature of such gestures, which are of particular interest for this research.

The study of gesture as a mechanism for human-computer interaction has also been explored in relation to speech as a way to develop human-centric interfaces that are more natural (see Williams and Ortega, 2020). Similarly, the relationship between gesture and UIs that are hand-adapted as opposed to eye-centred have been explored. Observations around this indicate that building user interfaces around the hands, rather than the field of view can impact target selection resulting in higher interaction efficiency and lower perceived difficulty and physical exertion (see Lou et al., 2020). Lastly, the role of congruency of interaction in instructional environments has been explored leading to the proposition of design principles involving gesture and hand controls (Johnson-Glenberg, 2018) and the development of a taxonomy of embodied learning (Johnson-Glenberg and Megowan-Romanowicz, 2017).

Ultimately, as posited by Malizia and Bellucci (2012), "the main aim of natural interfaces should be to break down the technology-driven approach to interaction and provide users with gestures they are more used to, taking into account their habits, backgrounds, and cultural aspects" (p. 38). Resultingly, this research looks at both approaches to gesture in iVR systems, surrogate interaction through a ray casting technique and direct interaction through natural gestures, to explore how they could influence the way users make sense of the content they engage with through such interactions.

Chapter summary

The first section of this chapter presented a brief historical account of the development of virtual reality technology. This section had three main aims: (1) to situate head-mounted displays among other types of virtual reality systems; (2) to posit the notion that the landscape of iVR HMDs has become too fragmented, thus calling into question the suitability of iVR technologies across different domains; and (3) to discuss the role of hardware and software when defining what constitutes modern immersive virtual reality.

The second section provided an appraisal of relevant scholarly work exploring the use of iVR HMDs in education and other domains. This highlighted the need for further research looking at the different ways in which iVR systems engage visual, auditory, and kinaesthetic modes and how doing so may enable affordances and perceptuomotor contingencies for learning in virtual environments.

Lastly, the third section drew on the notion that virtual environments provide spaces for perceptuomotor engagement and examines the work that has been done on gestural interaction and the interrelation between embodiment and learning with iVR systems.

Chapter 3: Theoretical framework

Chapter overview

This chapter begins with a discussion on the significance of perception and action in immersive virtual environments and how it relates to the notion of embodied cognition. This provides the theoretical grounding for this research.

Subsequently, it is argued that embodied interaction in immersive virtual reality is underpinned by two affordances of this type of technology: (1) its support for gestural interaction; and (2) its capacity to elicit a sense of presence and of embodiment, both of which are constituted by more specialised perceptual states including the illusion of agency, body ownership, and the plausibility of the environment.

3.1 The significance of perception and action in immersive virtual reality environments.

Gibbs (2005) defines perception as “the ability to derive meaning from sensory experience in order to guide adaptive behaviour” (p. 42). Based on this conception, it can be presumed that (1) an individual’s experience of the world is situated through perception (Dawson, 2014) and that (2) perception is intrinsically related to action (Stolz, 2015).

Concerning the first of those assumptions, the mere reality of having a body provides sensory-motor faculties that can shape perception and, as a result, impact the way humans engage and make sense of their surroundings. This is defined by Sheets-Johnstone (2000) as a “fundamental kinetic tactile-kinaesthetic reality of human life” (p. 344). On that basis, having eyes, opposable thumbs, being able to move, and having a sense of smell, taste, hearing, and touch all shape how humans act upon their immediate environment, as well as how such environment is understood as providing opportunities for action[17]. For instance, a chair can be viewed as an object to sit due to the capacity and intent of an individual to engage in such behaviour. Similarly, assessing the ripeness of fruit based on its colour and smell is predicated on the ability to perceive such sensory stimuli.

It can be argued that perception is relative to every observer and that this can be influenced by their body, the way in which they can use that body to engage with the environment, and their intents and needs. For instance, a visually impaired person could have a perceptually different appreciation of an object’s shape and spatial position from that of someone without such impairment; children could have a different perception of the size of objects due to the perspective that their body size provides; and a short person could perceive a stool not only as a piece of furniture to sit on, but as a steppingstone to reach high areas.

Barsalou (2008) asserts that perception underpins an individual’s capacity to engage with its surroundings and to create mental representations for future retrieval. In that regard, perception takes a particularly important role with immersive forms of digital media such as 360-degree videos, augmented reality spaces, and surrounding virtual reality environments for two main reasons. Firstly, because these types of technologies rely on active engagement and

[17] This what Gibson (1977) defines as an affordance (see Section 5.2).

the stimulation of the senses (i.e., sight, hearing, and touch) to elicit bodily states such as the sense of presence, self-location, body ownership, and agency, all of which constitute the distinct affordances of immersive virtual reality (see Section 5.2); and secondly, because these immersive technologies allow for the dynamic multimodal representation and simulation of some aspect of reality (Sherman and Craig, 2003). In that sense, immersive technologies have the potential to alter perceptions of the self and of the virtual environment, thus impacting the meaning-making practices and mental representations constructed within them.

Concerning the second assumption made from Gibbs's (2005) definition of perception, Riener and Stefanucci (2014) posit that there is an ongoing debate with respect to the nature of the relationship between perception and action. Perception has been described in the literature as (1) being oriented towards servicing action (Goodale and Milner, 1992), (2) being a distinct function separate from action (Pylyshyn, 1999), (3) as a bodily skill in itself (Noë, 2004), and (4) as being inextricably related to action (Gibson, 2014).

The main point of contention among such views relies not only in the nature of the relationship between both functions, but in the distinction that is made between them. For instance, the positions of Goodale and Milner (1992), Pylyshyn (1999), and Noë (2004) recognise a separation between mind and body, whilst Gibson (2014) regards perception and action as body dependent and constrained by the environment.

The above mirrors the debate between traditional cognitivism and alternative perspectives in cognitive science such as extended, enactive, grounded, and embodied cognition. Traditional theories of cognition assume a computational view of the mind in which "knowledge resides in a semantic memory system separate from the brain's modal systems of perception […], action […], and introspection […]" (Barsalou, 2008, p. 618). In contrast, alternative perspectives of cognition recognise the role of perception in the construction of symbolic mental representations and re-examine the interrelationship between body, mind, and environment (Shapiro, 2012; Hatfield, 2014).

Due to the way immersive virtual reality environments integrate multiple modes of representation (see Kress, 2014) and provide opportunities for congruent and meaningful kinetic, tactile-kinaesthetic engagement (see Chapter 9), this research rejects the computational description of the mind and ascribes to an embodied view of cognition (see Section 3.2 for a discussion on embodied cognition vs computational theories of the mind). From this perspective, perception and action are considered inextricably coupled and play a central role in cognition (Borghi and Caruana, 2015). Moreover, it is recognised that representations are grounded in modality-specific systems in the brain, rather than transduced into amodal descriptions (Barsalou et al., 2003).

3.2 Embodied cognition in immersive virtual reality.

Embodied and grounded approaches to cognition emerged in response to two theoretical criticisms aimed at representational and computational theories of the mind (Borghi and Caruana, 2015; Matheson and Barsalou, 2018). The first of these criticisms concerns the notion that perception and action are separate functions which, as argued in the previous section, creates a body/mind divide.

The second criticism consists in the view that representations of the world are anchored in amodal, abstract symbol systems in the mind. This poses what is known as the symbol grounding problem (Harnad, 1990) in which the interpretation of arbitrary, abstract symbols can only be done through other symbols of the same nature, thus creating a system where cognition cannot take place. Embodied and grounded views of cognition propose to address this impossibility by defining the role of action, body, and situated experience in cognitive operations. For instance, Goldstone, Landy and Son (2008) observed that cognitive operations in fields such as mathematics and science, which were thought to involve purely abstract/symbolic reasoning, also integrate perceptual processes.

The criticisms described above have become the two core tenets of embodied and grounded approaches to cognition: (1) the notion that cognition is shaped by sensory-motor engagement; and (2) the rejection of the computational mind, which conceives representations as amodal. As argued by Matheson and Barsalou (2018), despite these unifying themes, it is impossible to refer to a single cohesive theory of embodied cognition because some of the main propositions have emerged from multiple disciplines like linguistics (Lakoff and Johnson, 1999), cognitive science (Varela, Rosch and Thompson, 2017), psychology (Barsalou, 1999), and philosophy (Clark, 2008) to name a few.

Stemming from enactivism, for instance, is the notion that sensory-motor and affective processes are inextricably related (Di Paolo, Rohde and De Jaegher, 2010; Gallagher and Lindgren, 2015). As Di Paolo and Thomson (2015) note, “the link between the body and cognition is […] constitutive and not merely causal” (p. 76). Based on this, if the body is considered crucial to how the world is experienced, it could be capable of shaping interaction and meaning-making.

Another example concerns the centrality of the body in phenomenology for which being embodied involves having a sense of ownership and agency (Merleau-Ponty, 2012; Gallagher, 2015). The former describes the “intrinsic ownness” of an experience, what makes it unique to a particular agent, whilst the latter is concerned with the identification of the self as the origin of behaviour (see Section 3.5). As Anderson (2003) argues, it’s not just a matter of “having, and acting through, some physical instantiation, but recognizing that the particular shape and nature of one’s physical, temporal and social immersion is what makes meaningful experience possible” (p. 124).

Other ideas include: (1) the primacy of action stemming from the American pragmatist tradition; (2) Gibson’s (2014) ecological approach to perception and his theory of affordances; and (3) evidence of a link between perception and action stemming from research on mirror and canonical neurons through which it was found that motor areas in the brain become active not only when an agent performs an action, but also when observing the same action being performed by another agent (Kosslyn, 2005; Martin, 2007; Gallese, 2008; Rizzolatti and Sinigaglia, 2010).

Due to the diverse emergence of ideas from various disciplines, there have been attempts to create taxonomies to deal with the different research approaches on embodied and grounded cognition. Wilson (2002), for instance, has identified six common claims regarding cognition: (1) it is situated, which highlights the role of perception and action; (2) it is timed-pressured, which recognises how real-time interaction constrains cognition; (3) the notion that cognitive work is off-loaded onto the environment such as when indexing information using colours or shapes to be remembered later; (4) the environment can be considered an element of the cognitive system, thus seeing the mind as distributed outside of the body; (5) cognition is for action, which refers to the idea that cognition serves adaptive activity; and (6) the notion that off-line cognition is body based in the sense that it draws from the same perceptual and motor mechanisms used when in a physical environment.

Comparatively, Shapiro (2012) defined three types of hypothesis that broadly summarise the work done addressing the relationship between perception and action through embodied cognition: (1) the conceptualization hypothesis considering the ways in which the body enables or constrains how an agent makes sense of the environment (see Lakoff and

Johnson, 1999); (2) the constitution hypothesis considering the integration of the body and the environment in cognitive processing, thus making the link more than causal (see O'Regan and Noë, 2001); and (3) the replacement hypothesis which argues that actions are mediated by sensory-motor contingencies, thus rejecting the notion of symbolic representations altogether (see Wilson and Golonka, 2013).

There is a growing body of research exploring how embodied and grounded cognition can take place in immersive virtual environments (Johnson-Glenberg et al., 2016, 2020; Lindgren et al., 2016; Jang et al., 2017; Johnson-Glenberg, 2018; Ratcliffe and Tokarchuk, 2020). However, some of the ideas discussed above have not been explored more broadly. For instance, it is still not fully understood how the different mechanisms for interaction used by an iVR system can shape perception and action and influence the way agents make sense of a virtual environment.

Furthermore, the interrelation between body, action, and situated experience/environment has not been looked at more deeply beyond the elicitation of the sense of presence and body ownership (Slater, 2009; Slater, Perez-Marcos, et al., 2009; Kilteni et al., 2015; Schroeder et al., 2017). Lindgren et al. (2016), for instance, argue that physically engaging students with the content to be understood can help in anchoring the concepts upon which to build knowledge. Such claims suggest that embodied interaction in immersive virtual environments could have a significant effect on knowledge retention. This is consistent with reported findings by Johnson-Glenberg et al. (2016) who observed that, whilst there was no significant difference at the post experience test point, participants in the highly embodied condition of their study remembered more at the 1-week delayed testing point than those in the low embodied conditions. However, more work needs to be done to get a better understanding of the ways in which situated experience and action can ground knowledge by engaging the body as a means of representation and meaning making.

This research assumes the view that cognitive states are stored in the memory as snapshots originating from the body's "modalities" such as sound, touch, and sight (Bailey, Bailenson and Casasanto, 2016). This aligns with Shapiro's (2012) constitution hypothesis as described above and it is best illustrated by what Casasanto (2014) deems as the body specificity hypothesis. This hypothesis states that "people with different kinds of bodies, who interact with their physical environments in systematically different ways, form correspondingly different mental representations, even in abstract domains" (Casasanto, 2009, p. 365). While this does not presuppose that the body, mind, and environment constitute a single cognitive unit, it does suggest that their interrelation is essential, at least for the embodied stance on cognition that is taken in this research.

3.2.1 Embodied interaction

The previous section provided an overview of the field of embodied cognition and discussed how some of its fundamental ideas have emerged from different disciplines. As stated above, this research uses some of those notions as a framework to explore the implications of the use of immersive virtual reality systems in education. However, this highlights the need to consider the nature of the sensory and motor engagement that an agent is afforded in a virtual environment, thus defining what it means to be embodied.

Matheson and Barsalou (2018) argue that due to the multidisciplinary origin of the ideas underpinning embodied cognition, there is no single overarching notion of embodiment. On that basis, such conceptualization should attend to the hypothesis being explored, rather than a particular theoretical proposal.

Embodiment can be understood as “the property of our engagement with the world that allows us to make it meaningful” (Dourish, 2004, p. 126). In the context of this research, such a world is virtual and the nature of the engagement with it can be defined by two conditions: (1) the perceptual and motor capabilities of the agent’s body; and (2) the affordances of the technology in relation to how virtual environments support visual, auditory, kinetic, and tactile-kinaesthetic modes of representation and engagement.

Derived from the above, it can be said that conceptualising embodiment and interaction in immersive virtual environments involves not only perception and action, but the pairing of two realities through the body’s sensory system, “a mix of the virtual and physical, intangible and tangible, reality and fantasy” (Price et al., 2009, p. 6). Thus, embodied interaction consists in “the creation manipulation, and sharing of meaning through engaged interaction with artifacts” (Dourish, 2004, p. 126) and it can range from body postures, to whole body movement like locomotion, and hand gestures, be it to interface with the system, or to directly perform a task.

Being mediated by technology, embodied interaction in immersive virtual reality is enabled and bound by three fundamental affordances of these types of systems: (1) movement as instantiated though locomotion, body postures, and hand gestural interaction, (2) the elicitation of the sense of presence as a perceptual response to the immersiveness of a system, and (3) the sense of embodiment with its respective dimensions, self-location, agency.

Movement as a form of interaction with a virtual environment constitutes an affordance directly enabled by the capacity of a system to track a user's body in all axes. In doing so, the virtual environment can replicate body changes in rotation and position such as when walking, performing gestures, and changing postures. The sense of presence and the sense of embodiment, on the other hand, constitute perceptual responses to audio-visual, kinetic, tactile, and proprioceptive stimuli users are exposed to whilst in a virtual environment. The former concerns the perception of being physically placed in an environment, while the latter refers to the perception of inhabiting and owning a virtual body or avatar. Table 3.1 lists the different concepts related to the notion of embodied cognition and the embodied forms of interaction which are central to this research. These concepts and their dimensions are discussed in more depth in the following sections.

Table 3.1. Central concepts to the notion of embodied cognition and embodied interaction

Movement	**What is it?**	
	Broadly speaking, movement refers to a change in position and place (Cambridge English Dictionary, 2022). In the case of this research, those changes concern the user's hands, limbs, and body. As a result, there are three types of movements that support embodied interaction: locomotion, body posture, and hand gestures.	
	Instantiations	
	Locomotion	This consists in the ability for controlled positional movement such as when walking or moving from one position to another in a space (Di Luca et al., 2021).
	Body posture	This concerns the position assumed by the body when static or during dynamic activity. Postures include leaning forward, bending down, reaching out, turning the torso, or tilting the head.
	Hand gestures	These refer to hand movements performed with the aim of interacting with the virtual environment such as in the manipulation of objects.

Immersion	**What is it?**	
	Immersion is generally defined as the extent to which an iVR system can support sensorimotor enaction and evoke perceptual states such as the sense of presence or body ownership (Slater and Wilbur, 1997; Slater, 2009). Two postures can be observed in the literature, immersion as a property of a system and as a perceptual response. These are treated as complementary dimensions in this research.	
	Dimensions	
	Objective property	As an objective and measurable property of a system, immersion is defined by the capacity of hardware to support different sensory input, isolate users from external audio-visual stimuli, and surround them by a virtual world (Slater, 1999).
	Subjective response	As a subjective response, immersion consists in the psychological state resulting from feeling surrounded by an environment and receiving different stimuli (Witmer and Singer, 1998). Given the use of the term in this research, this way of understanding immersion positions it as an overarching psychological state that encompasses different perceptions such as the sense of presence, self-location, body ownership, and agency.
Sense of presence	**What is it?**	
	The sense of presence consists in the perceptual illusion of being in a place or virtual environment, notwithstanding of the conscious awareness of its artificiality (Slater, 2018). It is achieved through three dimensions: the consistency of the illusion of place, its plausibility, and the how agents assimilate, or process breaks in the illusion.	
	Dimensions	
	Place illusion or consistency	This refers to the perception or illusion of physically being located in a virtual environment (Slater and Wilbur, 1997).
	Plausibility illusion	This refers to the illusion that what is being experienced in a virtual environment is truly happening despite knowledge to the contrary (Slater, 2009).
	Assimilation	It consists in the process through which agents assume the plausibility and reality of a virtual environment even when external stimuli cause inconsistencies that may break them.
Sense of embodiment	**What is it?**	
	This perceptual state is defined as the experience of being inside, owning, and controlling a body or a part of it and it involves three dimensions: self-location, body ownership, and agency (Kilteni, Groten and Slater, 2012).	
	Dimensions	
	Self-location	Self-location refers to the idea that one is physically located in a space (the body) which acts as the reference frame for

		any stimuli that is registered (Kilteni, Groten and Slater, 2012; Argelaguet et al., 2016)
	Body ownership	The feeling of body ownership consists in the illusion of one's body being the source or origin of experience (Slater et al., 2010)
	Agency	The perception of agency consists in the wilful motor control that agents experience over their body; that is, the experience that one is the source of a certain action (Gallagher, 2015; Argelaguet et al., 2016)

3.3 Gesture and gestural interaction.

Nathan (2008) argues that "one of the ways that cognition is seen as embodied is through the close relation of hand gestures with thinking and communication" (p. 375). Such relation is where the relevance of gesture resides to this research as studies have shown that embodied action and gestures can effectively support learning (Segal, 2011; Johnson-Glenberg et al., 2014; Vazquez et al., 2018).

Becvar, Hollan and Hutchins (2007) posit that gesture has been conceptualised in the literature in different ways including the notions that (1) gestures are derived from the engagement with objects, (2) they depict the performance of actions, and (3) they constitute communicative actions which can be bound to speech. This section presents a discussion concerning two of those perspectives attending to how they can support learning: the notion of gesture as a mechanism for human computer interaction (HCI) which derives from sensory-motor engagement (Black et al., 2012), and gesture as action accompanying speech, thus acting as a window into an agent's thoughts (Goldin-Meadow, 1999, 2009).

Concerning the first perspective, gestures can be used as a way to interface with virtual environments. This is made possible through peripherals that track the agent's movements for the system to react to or replicate. In that regard, Saffer (2009) defines gesture as "any physical movement that a digital system can sense and respond to without the aid of a traditional pointing device such as a mouse or stylus" (p. 2). Although such devices are no longer used with commercial VR systems, peripherals like controllers, joysticks, gloves, touchscreens, touchpads, and cameras are integral to enable gestural interaction with current technology.

As argued by Segal (2011), gesture as a mechanism to interface with technology must be congruently mapped to content. This is a notion previously defined by Tversky, Morrison and Betrancourt (2002) as the congruence principle. Gestural congruency is particularly significant in educational uses of iVR technology where both the physical movement and the visual representation of it must be congruently mapped (Johnson-Glenberg, 2019).

Alibali, Boncoddo and Hostetter (2014) state that “when speakers express ideas that they mentally represent in simulations of actions and perceptual states, they naturally produce gestures, and these gestures manifest the embodied nature of those ideas” (p. 152). Consequently, “if gestures are simulated actions that result from spatial representation and mental imagery” (Black et al., 2012, p. 7), it could be argued that the nature of the gestures agents perform in a virtual environment could influence the way they make sense of it, which constitutes the main hypothesis explored in this research.

In that regard, Alkemade, Verbeek and Lukosch (2017) observed that a simple freehand interface using symbolic gestures performed comparatively the same as a traditional mouse and screen interface. However, recent iVR systems have become more sophisticated and support more natural forms of freehand interaction which justifies the need for further exploration of gesture in immersive virtual reality for education.

By way of context, non-immersive virtual reality systems support the direct manipulation of objects. However, as they typically use touchscreens, they require agents to use their fingers to perform gestures like tapping, dragging/sliding, scrolling, swiping/flicking, pinching, stretching, and rotating, thus triggering actions mapped to them (Wroblewski, 2010).

Comparatively, immersive virtual reality systems support both the indirect and direct manipulation of objects. Based on the analysis of different systems (see Section 5.1), this has been observed to take different forms. Low-end systems typically use a remote controller with buttons. In this case, gesturing is limited to point-and-click behaviour and tasks are not directly performed by the agent but carried out automatically by virtual hands. Comparatively, high-end systems support the direct manipulation of objects, although this is enabled in two ways depending on the mechanism employed:

(1) Hand motion. Through this approach, controllers are used as tools that mediate interaction. Agents move their hands to perform motions like picking up, dropping, pressing, pushing, and lifting. Although hand movements are fully tracked and replicated in the virtual environment, individual finger movements cannot be discerned, thus constraining actions to button pressing and static virtual hand representations.

(2) Freehand interaction. This is mediated by gloves, controllers, or cameras that track the movement of the hands and individual fingers of an agent. Two types of gestures can

be distinguished: symbolic and conversational (Krauss, Chen and Chawla, 1996). Although Krauss, Chen and Chawla (1996) defined these relation to non-verbal communication, they are applicable to gestural interfaces. In that sense, symbolic gestures are arbitrarily mapped to actions such as lifting a hand to select something or doing a pinching and dragging motion to make an object bigger. An example of this type of interface is the gestural user interface used by AR systems like HoloLens (Microsoft, 2020a). In contrast, conversational gestures replicate hand/finger motion such as grabbing, releasing, pressing, pointing, and squeezing, which represent more natural forms of manipulation.

Concerning the second perspective, Kendon (2004) defines gestures as visible actions performed as utterances or as part of utterances, which gives them communicative intentionality and are aimed at providing information. This suggests that gestures have distinct boundaries and properties that distinguish them from other types of movements. As stated by Krauss, Chen and Chawla (1996), “all hand gestures are hand movements, but not all hand movements are gestures” (p. 392). In their typology of gestures, Krauss, Chen and Chawla (1996) propose that hand movements can be classified on a lexicalization continuum (see Figure 3.1).

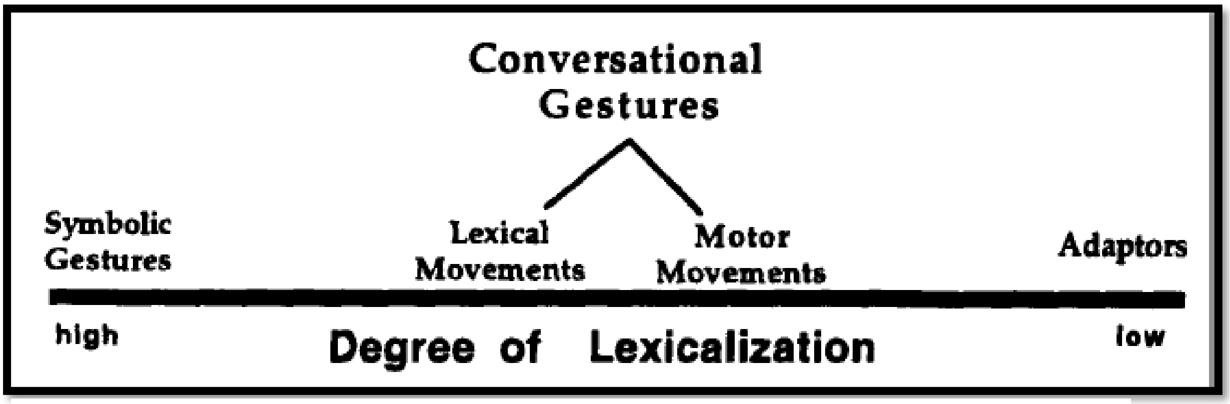


Figure 3.1. A continuum of gesture types (Krauss, Chen, and Chawla, 1996, p. 392).

At one end of the continuum Krauss, Chen and Chawla (1996) place adaptors which consist of movements that have no communicative intent, meaning, or lexical value. These actions do not constitute gestures as they are derived from manipulations like “scratching, fidgeting, rubbing, tapping, and touching that speakers often do with their hands” (p. 392).

At the other end of the continuum Krauss, Chen and Chawla (1996) place symbolic gestures, also known as emblems (Goldin-Meadow, 1999). These types of gestures have a communicative function, and their meanings are culturally defined or domain dependent. For example, lifting the thumb whilst making a fist with the remaining fingers (thumbs up) may signify a positive reaction in some cultures, but it may be offensive or have a different meaning in others. Comparatively, the same symbol is also used by divers to indicate that they need to ascend to the surface.

Lastly, the middle section of the continuum categorizes gestural movements that involve various degrees of lexicalization without being fully symbolic. These are gestures used in speech, hence the name conversational gestures, and they can be perceived as having deliberate expressiveness or being the result of an agent's control or communicative intention.

According to Goldin-Meadow (2009), conversational gestures can reveal knowledge that children are not necessarily vocalizing and that, in some circumstances, they are not yet able to articulate in speech. These types of gestures can depict both abstract and concrete ideas and their representations can draw from properties such as size, shape, weight, and spatial relationship.

As stated by Becvar, Hollan and Hutchins (2007) "gestures operate as instantiations of essential spatio-dynamic features that are not efficiently conveyed in other modalities, […] as such, [they] are essential resources for shaping theoretical understandings" (p. 117). In other words, conversational gestures, according to this view, could act as a window into the ways in which agents strategize and made sense of procedural tasks and conceptual information.

Kendon (2004) notes that gestures have been classified in the literature according to their naturalness and conventionality, how their meaning is established, and whether that meaning has a literal or metaphoric nature. Such distinctions and classifications reflect the different understandings that have been made concerning the expressive and communicative functions of gesture. This research takes McNeill's (1992) classification as the basis for a framework for the analysis of conversational gestures. More specifically, it is concerned with iconic, metaphoric, and deictic gestures that (1) support speech, (2) provide a view of the agent's thinking as suggested by gesture-speech mismatches, or (3) that instantiate the relationship between physical gestures and the way in which these are mapped to their visual representation and the content to be learnt.

For McNeill (1992), iconics are gestures that depict aspects of the semantic content of speech. However, as suggested by Streeck (2008), rather than representing visual resemblance, they are viewed in this research as grounded in action and the engagement with objects. Comparatively, metaphorics represent abstract ideas that depict a concept through a concrete gesture. Lastly, deictics are gestures with the function of pointing or indicating objects and events (McNeill, 1992).

Lastly, concerning the third point listed above, a framework for the analysis of the congruency of gesture has been developed and applied to the virtual environments that are employed in this research (see Section 5.3). This framework draws from Johnson's (1987) notion of image schemata as a "recurring, dynamic pattern of our perceptual interactions and motor programs that gives coherence and structure to our experience" (p. XIV). That is, gestures performed with the purpose of interfacing with a virtual environment are not always symbolic, but rather schematic as they capture sensory-motor experience. Resultingly, these gestures can integrate information from visual, auditory, kinetic, and tactile-kinaesthetic modes of interaction.

3.4 Immersion.

The second affordance of immersive virtual reality and from which several other key ideas explored in this research derive is the concept of immersion. As observed by Nilsson, Nordahl and Serafin (2016), immersion and presence have been applied inconsistently in the literature. Moreover, they have been frequently used interchangeably in relation to virtual reality systems. Nilsson, Nordahl and Serafin (2016) assert that this condition has not only diluted the definition of immersion, but can also confound the study of presence.

Immersion has been conceptualised in four distinctive ways (Nilsson, Nordahl and Serafin, 2016): (1) as the objective property of a system (Slater and Wilbur, 1997); (2) as a perceptual response (Witmer and Singer, 1998); (3) as a response to narrative (McMahan, 2014); and (4) as a response to challenges in the environment (Ermi and Mäyrä, 2005). This research concurs with the notion that immersion is defined by the extent to which a system can isolate agents from the physical world through its support for sensory-motor engagement, thus making it an objective property. However, it also acknowledges that this condition inevitably elicits a perceptual response from agents, thus making it a subjective state.

Although the definitions of immersion advanced by Slater (1999) and by Witmer and Singer (1998) contrast with each other, these are not conflicting and could be understood as two dimensions of the same concept. The first of those dimensions concerns the iVR system, whilst the second concerns how agents perceive it.

In its first dimension, immersion can be understood as an objective property of the system defined by its capacity (1) to integrate visual, auditory, and touch modes or interaction and representation; (2) to isolate agents from sensory input from the real world; and (3) to surround them by a virtual environment (Slater, 1999). Correspondingly, Slater (2009) argues that a system can be considered more or less immersive based on how it supports sensory-motor contingencies (SC) for perception and action. In that sense, “a first-order immersive system has SCs that are similar to those of everyday reality. A second-order system can be simulated within a first-order system and so on” (Slater, 2009, p. 3556)[18].

Moreover, Slater and Wilbur (1997) proposed that the illusion of reality that an immersive system must elicit should be: (1) inclusive to the extent that the agent is isolated from reality; (2) extensive in the range of sensory-motor modalities it supports; (3) surrounding concerning how it envelops the agent in a virtual environment; (4) vivid in terms of the visuals an simulation of behaviour; and (5) matching the agent’s proprioceptive sense and body movements.

In its second dimension, immersion can be understood as a perceptual or “immersive” response from agents, or as Witmer and Singer (1998) define it, “a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences” (p 227). It must be noted, however, that corresponding to the proposed conceptualisation of immersion in this research, immersion as a perceptual response is seen as an overarching psychological state achieved by the elicitation of the illusions of presence, body ownership, and agency, all of which are accommodated in the definition above. On that basis, a more immersive system would be expected to elicit a higher immersive response as it would accommodate multiple sensory-motor modalities in support of those illusions. Resultingly, whilst the immersiveness of a system can be objectively measured based on its properties, measuring an immersive

[18] This constituted the basis for the classification of headsets for the empirical work in this research as low-end, mid-tier, and high-end iVR systems. As such, the capabilities of low-level systems can be replicated by high-level ones (see Section 5.1 and Figure 2.2).

response is more nuanced as it depends on the elicitation of those three illusions, which are subjective to every agent.

Witmer and Singer (1998) argue that there are four factors that impact immersion, or rather how the immersiveness of a system is perceived, corresponding to the view of immersion proposed here: (1) the level of isolation of an agent from reality, which aligns to the property of being inclusive as described earlier; (2) the perception of being self-included in the virtual environment, which corresponds to the illusion of presence; (3) the integration of natural mechanisms for interaction and control, which have significant relevance to this research; and (4) the illusion of self-movement, which relates to locomotion and the sense of agency.

In summary, the notion of immersion being proposed here has a bi-dimensional nature. On the one hand, it is considered an objective property of an iVR system and, on the other, it is seen as an overarching psychological state or “immersive response” (Slater, 1999, p. 560) achieved by the elicitation of three perceptual illusions, thus making it subjective to every agent. This reframing of the notion of immersion attends to the analysis done on iVR systems (see Chapter 5) and how the definitions by Slater (1999) and by Witmer and Singer (1998) accommodate those findings. On the whole, this reframing of immersion is thought to provide a more robust framework to explore the notions of presence, body ownership, and agency that are central to this research.

3.4.1 The sense of presence.

Generally speaking, the notion of presence is not limited to external sensory-motor input. For instance, a reader can be so enthralled by the rich description of a scene in a book, that he or she could construct a mental model of the environment and vividly experience some form of presence (Wirth et al., 2007). When referred to immersive virtual reality, however, the perception of presence is not only mediated by the system, it is regarded as one of its “profound affordances” (Johnson-Glenberg, 2018).

As Slater (2009) posits, presence is supported by the valid sensory-motor and effectual actions enabled by the properties of the system. That is, the support to carry out behaviour that affects perception such as changes in posture or the spatial position of the body in the space, or actions that cause changes in the environment such as the manipulation of objects. In that sense, presence is not only a subjective illusion supported by perception, but it is also rooted in action (Slater, Lotto, et al., 2009).

Slater (2009) and Wirth et al. (2007) view presence as a two-dimensional construct that cannot be measured directly as it constitutes the subjective perception of an illusory experience. The first of those dimensions concerns the sense of being physically situated or self-located in the virtual environment, whilst the second refers to the acceptance of the virtual environment as the new frame of self-reference to which perception and behaviour are bound.

In other words, the sense of presence is comprised (1) by the illusion of being in a place, despite the awareness of the artificiality of such environment, and (2) by the believability that the behaviour experienced in that place is in fact happening, despite knowledge to the contrary, thus eliciting appropriate reactions or behavioural responses from agents. Staler (2009) refers to these dimensions as place illusion and plausibility illusion, respectively, and asserts that the former is “bound to the particular set of SCs [sensory-motor contingencies] available to allow perception within that environment” (p. 3552), thus making it conditional to the particular type of system being used.

Broadly speaking, the relevance of the notion of presence to this research is two-fold. Firstly, because it constitutes one of the fundamental affordances of iVR technology. As discussed in the previous section, the sense of presence is proposed here as one of the dimensions of the perceptual response that agents experience whilst using iVR systems. And secondly, it is relevant because of its prominence in the literature exploring embodied cognition in immersive virtual reality. Although there is evidence to support the idea that experiencing presence “influence[s] an individual’s ability to remember information in the physical world” (Bailey et al., 2012, p. 1), the directionality of such influence is less clearly defined as both positive (Ke, Lee and Xu, 2016) and negative (Makransky, Terkildsen and Mayer, 2019) effects in relation to learning have been reported. This justifies the need to explore this notion further, particularly regarding its relationship to interaction and the sense of body ownership and agency which, as it is discussed in the following section, can confound its effects.

3.5 The sense of embodiment.

Not to be confused with the previously discussed notions of embodiment and embodied interaction (see Section 3.2.1), the sense of embodiment encompasses the sensations resulting from “being inside, having, and controlling a body” (Kilteni, Groten and Slater, 2012, pp. 374–375), an idea that applies to avatars and other virtual body representations in video games and extended reality environments.

According to Slater and Sanchez-Vives (2014), the sense of embodiment can be experienced in iVR system configurations that support three conditions: (1) there must be visual-proprioceptive correspondence; that is, the virtual body must be positioned in the same place as the agent's physical body. (2) The agent should be able to see the environment from a first-person perspective as if looking through the eyes of the virtual body. And (3) the virtual body must be able to synchronously replicate the movements of the agent's physical body.

In order for iVR systems to support virtual body representations capable of replicating an agent's body movements, they need to integrate mechanisms to track the rotational and positional movements of different body parts (see Section 2.1.3). This can be done through peripherals like trackers, cameras, body suits, gloves, and most commonly controllers. However, whilst enabling embodied interaction, the mechanism used will also dictate or constrain the ways in which movement and interaction can be supported. For instance, a system using controllers, is not capable of replicating the position of the agent's arms or legs.

Given the definition provided above, Kilteni, Groten, and Slater (2012) argue that the sense of embodiment is a multidimensional construct achieved by eliciting three perceptual states: (1) the illusion or sense of self-location, (2) the illusion of body ownership, and (3) the illusion of agency. Although it has been suggested that these components can be dissociated because they are mutually independent (Sato and Yasuda, 2005; Tsakiris, Schütz-Bosbach and Gallagher, 2007), it has also been shown that together they can create a coherent experience of being embodied (Longo et al., 2008).

3.5.1 The illusion of self-location.

Self-location refers to the idea that one is physically located in a space which acts as the reference frame for any stimuli that is registered (Kilteni, Groten and Slater, 2012; Argelaguet et al., 2016). Although the illusion of self-location concerns an agent's spatial experience, this is confined to the agent's body and does not extend to the environment.

When applied to the field of immersive virtual reality, self-location is not limited to being inside a physical body, it can extend to the feeling of being inside an avatar or virtual body as well. As demonstrated by the work of Lenggenhager, Mouthon and Blanke (2009), agents "localize their self where they perceive to be touched, even if this tactile perception is mislocalized through visual capture" (p. 116). This suggests that the tactile and haptic feedback provided by the controllers could reinforce the localization of the self in the virtual hands.

Similarly, Perez-Marcos, Sanchez-Vives and Slater (2012) reported that synchronous visuo-tactile stimulation can evoke the illusion of hand ownership by reinforcing a sense of proprioception, although this did not require for the real and virtual hands to be aligned.

The findings above are of great significance for this research as visuo-tactile synchronicity between the physical and virtual representation of an agent's hands is one of the aspects being explored (see Section 4.2.4) along with the role that gestural congruency can have in shaping an agent's understanding of conceptual and procedural content (see Chapter 9).

3.5.2 The illusion of body ownership.

Being fundamental dimensions of the sense of embodiment, the notions of self-location and body ownership are interconnected. Most significantly, they can be evoked through synchronous visuo-tactile stimulation (Perez-Marcos, Sanchez-Vives and Slater, 2012).

Whilst the illusion of self-location sees the body as a space that an agent occupies and through which perceptuomotor stimuli are experienced, the notion of body ownership consists in the illusion of one's body being the source or origin of such experience (Slater et al., 2010). This suggests that the separation between physical and virtual body can be blurred.

Slater (2010), for instance, observed that synchronous touch and experiencing a virtual environment from a first-person perspective (1PP) acted as the main factors in evoking the illusion of body ownership. This finding "support[s] the notion that bottom-up perceptual mechanisms can temporarily override top-down knowledge resulting in a radical illusion of transfer of body ownership" (p. 10564). In other words, visuo-tactile stimulation has been found to elicit a sense of ownership of a virtual body despite the agents' knowledge of its artificiality.

Such condition has paved the way for the exploration of social anxiety (Guterstam, Abdulkarim and Ehrsson, 2015), racial bias (Maister et al., 2015; Hasler, Spanlang and Slater, 2017), and self-perception (Kilteni et al., 2015) by placing agents in virtual bodies that differ from their physical ones.

3.5.3 The illusion of agency

The last dimension of the sense of embodiment consists in the illusion of agency which is defined as the wilful motor control that agents experience over their body (whether real or virtual) (Argelaguet et al., 2016) and over the environment. As Gallagher (2015) puts it, agency consists in the “experience that I am the one who is causing or generating a movement or action” (pp.13-14). Extended to the virtual environment, this entails that agentic behaviour aimed at interaction or the manipulation of objects and embodied forms of engagement with the world like movement are self-regulated and intentional (see Blanke and Metzinger, 2009).

Experiencing agency encapsulates the dynamics between perception-action and body-environment. That is, seeing the synchronous replication of one’s actions and interactions with the virtual environment evokes the sensation that these originate from the self, whilst also building a sense of control over manipulatives and the power to alter such environment. As argued by Sheets-Johnstone (2000), this places agency “along the tactile-kinaesthetic/affective lines of its own body” (p. 349).

Based on the above, agency can be seen as an objective and measurable property of a system as it defines the control that it affords an agent over their virtual body and the virtual environment. In other words, the degree of movement and interaction supported by a system will directly dictate what an agent can do and to what extent control can be exerted to affect the environment. This creates a feedback loop where any impact on the virtual environment will cause an effect that will successively cause a behavioural response from the agent. However, as it was observed in this research (see Section 8.2.2 and Section 10.2.5), the notion of agency also refers to a perceptual state which makes it subjective to every agent. From this perspective, agency is seen as constitutive of the sense of embodiment, and it is defined by the perception of control over the virtual body and over the virtual environment regardless of the actual level of physical control being afforded.

Unlike the illusion of body ownership, agency does not rely on the realism of the visual representation of the agent’s hands. As the work of Argelaguet et al. (2016) shows, less realistic hands provide less mismatch between the participant’s actions and the animation of the virtual hand” (p. 3). However, agency does rely on movement and behaviour. As observed by Sato and Yasuda (2005), “the sense of self-agency might mainly depend on a comparison between the predicted and actual consequences of actions” (p. 250), and such actions are constrained by the mechanisms used for interaction such as the type of controllers, and the tracking system that allows for positional and rotational movements (see Section 5.2.3).

Chapter summary

In the first section of this chapter, it is argued that this research ascribes to an embodied view of cognition. From this position, representations are viewed as grounded in modality-specific systems in the brain and underpinned by an agent's capacity to physically engage with the world; that is, the interplay between perception and action.

The following section contextualizes the notion of embodied cognition and discusses the significance that body, mind, and situated experience have in immersive virtual reality for education. Here, it is argued that the notion of embodied interaction refers to the active bodily engagement (i.e., movements such as postures and gestures) that agents engage in to make sense of the environment.

The last section of this chapter argues that embodied interaction through immersive virtual reality is enabled by two main affordances of the technology, both of which are defined by the level of immersiveness of a system: (1) its support for gestural interaction; and (2) its capacity to elicit a sense of presence, constituted by the illusions of being in a place and its plausibility, and a sense of embodiment, constituted by the illusions of self-location, body ownership, and agency.

Chapter 4: Methodology

Chapter overview

This chapter discusses the methodological approach followed for the empirical work in this research. The different sections comprising this chapter discuss:

(1) A rationale for the mixed methods methodology chosen for data collection and analysis.
(2) The design of school interventions involving the apparatus, the strategy for the recruitment of participants, and the protocol for data collection.
(3) The methods for data collection and analysis, including a discussion on the reliability, validity, and replicability of the study.
(4) The ethical dimensions of the research.

4.1 Methodological approach.

From a deterministic standpoint, certain methods can be viewed as inextricably linked to particular paradigms. In that sense, some qualitative and quantitative methods are rooted in particular ways of seeing and interpreting the world, which may result in diametrically opposed positions that cannot be conciliated, or in divergent views of the same object of study. Furthermore, it is sometimes assumed that phenomena can be fully explained by qualitative or quantitative methods alone, which is not always the case as “there is no necessary connection between purpose and approach” (Punch, 1998, pp. 16–17). In contrast to these positions, this research concurs with the notion that:

> […] the research topic itself should play a prominent role in leading the researcher to design a methodology that is theoretically informed and sympathetic to the individual characteristics of the research being undertaken, as opposed to the researcher automatically using certain methodologies because their epistemological positioning stresses a particular approach to collecting information and data analysis. (Philip, 1998, pp. 273–274).

Resultingly, this research assumes a dialectic stance and follows a pragmatic approach in which the use of methods is predicated on the research questions and aims that drive the study. As such, it has been decided to follow a mixed methods approach to address the multidimensionality of the research questions and to offset the shortcomings of one method with the strengths of another. As Bryman (2016) and Hammersley (1992) posit, the very differences between qualitative and quantitative methods are what makes them worth using in conjunction, as they present separate, but complementary views of the object of study and they capture different aspects of the complexity of culture and society.[19]

This research integrated four phases (see Table 4.1) of which the first two, the preparatory work and the main empirical study, had distinctive aims. The research questions guiding the preparatory work are more descriptive in nature and have the purpose of gaining a better understanding of the capabilities of iVR technology and the ways in which hardware can enable certain affordances through software. This preparatory work was essential to identifying avenues of enquiry that could underpin the empirical work going forward.

[19] Mixed methods methodology is seen here as part of a continuum QUAL MM QUAN that can be tailored to the needs of the research being conducted as long as these methods are not ontologically incompatible (Ridenour and Newman, 2008; Teddlie and Tashakkori, 2009).

Comparatively, the research questions guiding the main empirical work explore the underlying dynamics between iVR hardware and software in relation to two aspects: (1) the effects of iVR-assisted instruction on measurable learning outcomes; and (2) the exploration of the ways in which the sensory-motor affordances of this technology could account for such effects. The first position constitutes an important step in the research process, as Deb Roy (in Goldstone, Landy and Son, 2008) argues, “if you don’t have a clear idea of what [something] is doing then it is problematic to ask how it is doing it” (p. 29). Whilst the second position

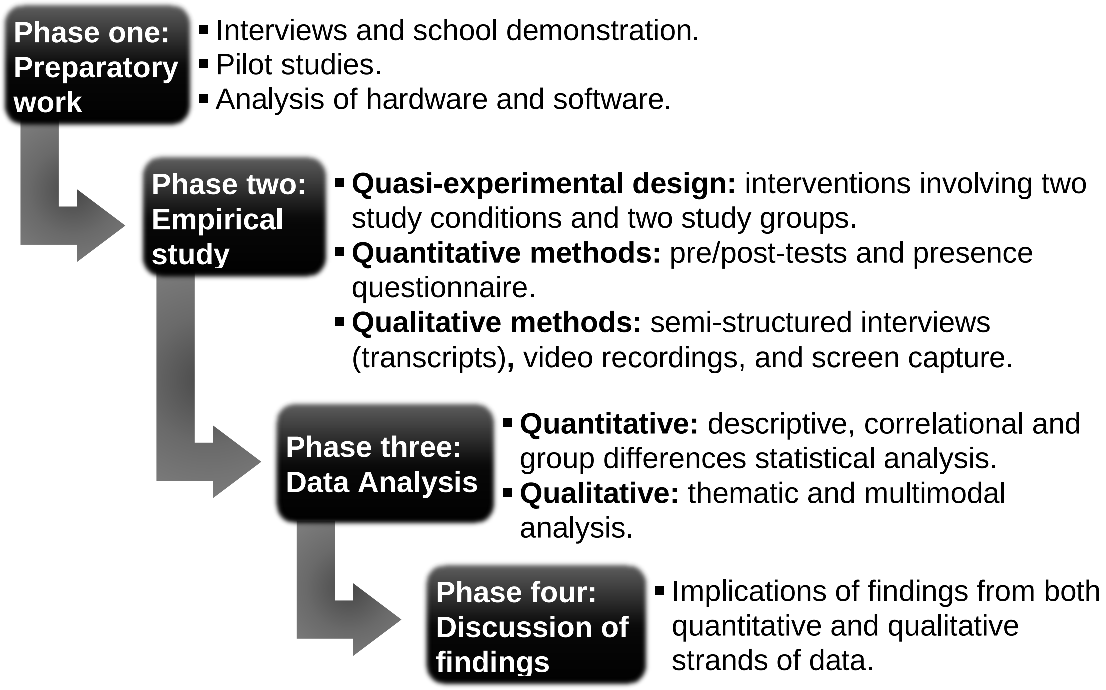


Figure 4.1. Methodological approach for the empirical study

considers the implications of such sensory-motor affordances in the way participants make sense of the conceptual and procedural content they are being presented with.

A mixed methods convergent parallel design was employed for the empirical work in this research. This was selected due to accessibility and time constraints. Whilst both strands of data needed to be collected simultaneously, they could be analysed separately, and then findings be discussed jointly to draw cohesive conclusions (Tashakkori and Teddlie, 2010). Figure 4.1 presents the tasks performed for each of the four phases that comprise the methodological approach, all of which are discussed in more detailed in the following sections.

The first phase involved the preparatory work that became the basis for the selection of hardware and software for the empirical study, the refinement of the research questions, and the operationalisation of the variables of study. The second phase concerned data collection and it involved the design of school interventions where students were asked to perform experiments in two virtual chemistry laboratories using two distinct types of iVR technology. The third phase involved the analysis of data derived from the different methods used during the empirical work. Lastly, the fourth phase consisted in the discussion of findings stemming from both strands of data and the drawing of conclusions.

4.2 The design of the school interventions.

As shown in Figure 4.1, the first phase of this research involved interviews with practitioners, a school demonstration, two pilot studies, and the analysis of different iVR hardware and software (see Appendix B.1). The outcome of this preliminary work is presented in Chapter 5 and takes the shape of the analysis of the features of different iVR hardware and software. In that chapter, it is argued that such features enable sensory-motor affordances dictating the design of iVR environments and the ways in which agents can interact with them.

Based on the above, it was determined that some of these sensory-motor affordances were worth exploring in more depth, particularly in the context of education and learning. To do this, the main empirical study, which conforms phase two of this research, was conceived as two school interventions following a quasi-experimental design. This approach was deemed the most viable to allow for a certain degree of control over those affordances as variables of study (see Table 4.1).

Carrying out parallel interventions using headsets would allow for participants to freely use the technology whilst being perceptually isolated from the physical space. Furthermore, this would allow for data to be collected, and observations to be made simultaneously without interrupting the flow of the experience. The following sections describe the different aspects concerning the two school interventions and the rationale for their implementation.

4.2.1 Study conditions.

The empirical work in this research involved participants (see Section 4.2.2) taking part in two experiences through two forms of immersive virtual reality technology (see Section 4.2.4). The selection of these was underpinned by the work done during the school demonstration and pilot studies (see Chapter 5). As a starting point, the typology of VR technology introduced in Section 2.1.2 was used to select hardware that was representative of consumer systems with more robust support in the field of education and training. This became the base system for one study condition and was denominated low-end iVR attending to the classification of the hardware in the typology. Subsequently, it was necessary to select a second system whose properties supported the same types of variables of study (i.e., the illusion of presence, self-location, body ownership, agency, support for movement, and gestural interaction), whilst enhancing them to the best of its capabilities. This became the base system for the second study condition which was denominated high-end iVR attending to the classification of the system in the typology.

Table 4.1 below lists the different variables being explored in the interventions and how the iVR systems in each condition supports them. Freedom of movement is fully supported in the high-end iVR condition, but only partially enabled in the low-end iVR condition due to the system only being capable of tracking the rotation of the headset and remote controller. In relation to the mechanisms of interaction, both systems integrate controllers. However, only the high-end iVR system is capable of full range of motion, and of supporting gestures such as grabbing and pinching. In contrast to this, the high-end iVR system does not involve a visual representation of the users' hands, whilst the low-end iVR system does, albeit without the tracking of movements. Regarding the elicitation of a sense of agency, both systems require active engagement from users. However, only the high-end iVR environment supports and encourages free exploration and experimentation which could impact how this is experienced. Lastly, both immersive systems offer perceptually surrounding environments that could elicit the illusion of presence, but this could be influenced by the other variables.

Table 4.1. Support for variables of study between study conditions.

Variables of study	Study conditions	
	Low-end iVR condition	High-end iVR condition
Perceptions of presence and body ownership	Not controlled across conditions as they constitute subjective perceptual states, rather than objective affordances of the system; however, these can be affected by the variables below.	
Hand representation and controllers	Visual representation of hands. Single remote controller with no support for translational tracking.	Visual representation of controllers in the place of hands. Motion-tracked and finger-sensing dual controllers.
Interaction	Support for point-and-click interaction with manipulatives. Virtual objects become selectable only when they are needed.	Direct manipulation of virtual objects by grabbing or pinching motion. Button pressing needed only for the operation of the pipette.

Agency	Free exploration is not supported. It is a guided experience with oral step-by-step instructions and a tablet with theory. Mistakes impeding progression cannot be made. Interactions are initiated by participants but limited to the manipulatives needed for the next step in the experiment.	Free exploration and experimentation are supported. The experience is not guided, but there is support in place in the form of a book with instruction. Progression is conditioned by the achievement of small goals which act as controls for when mistakes are made.
Freedom of movement (locomotion)	Not supported. Only the rotation of the right hand (controller) and head are tracked.	Full range of motion for head (headset) and hands (controllers) is supported, as well as partial movement of fingers (lifting). Movements such as walking, swaying, reaching out, bending, and grabbing and pinching gestures are possible.

4.2.2 **Study groups and pathways for participation.**

When designing the quasi-experimental interventions, a within-subjects design for the groups was selected as the best approach to involve all eligible participants in two 90-minute sessions, one per full intervention. This approach would allow to draw comparisons about the different ways in which participants engaged with the virtual environments and discuss them during interviews. However, foreseeing potential scheduling issues and loss to follow-up, it was decided to create a second experimental group following a between-groups design where participants would only take part in one of the two 90-minute sessions. By employing separate designs, it would be possible to draw comparisons across and within these experimental groups and conditions. Most significantly, by taking the between-groups group as the basis, it would be possible to look at measured learning and reported perceptual experiences and assess whether participants in the within-subjects group were experiencing anchoring bias (see Chapter 7).

As a result of the above, the design of interventions involved two interventions, low- and high-end iVR, across the two experimental groups. This required for the involvement of participants to be carefully organised by allocating them to pathways dictating the type of intervention they would be a part of and when. Figure 4.2 illustrates these pathways.

Experimental group 1 follows a within-subject design. Participants in this group took part in both interventions fully (low- and high-end iVR) on separate sessions. This means that the amount of data collected from participants in this group was double. To address the potential for an ordering effect, participants in this group were randomly allocated to one of two pathways for participation as a counterbalance. In pathway 1, participants took part in the low-

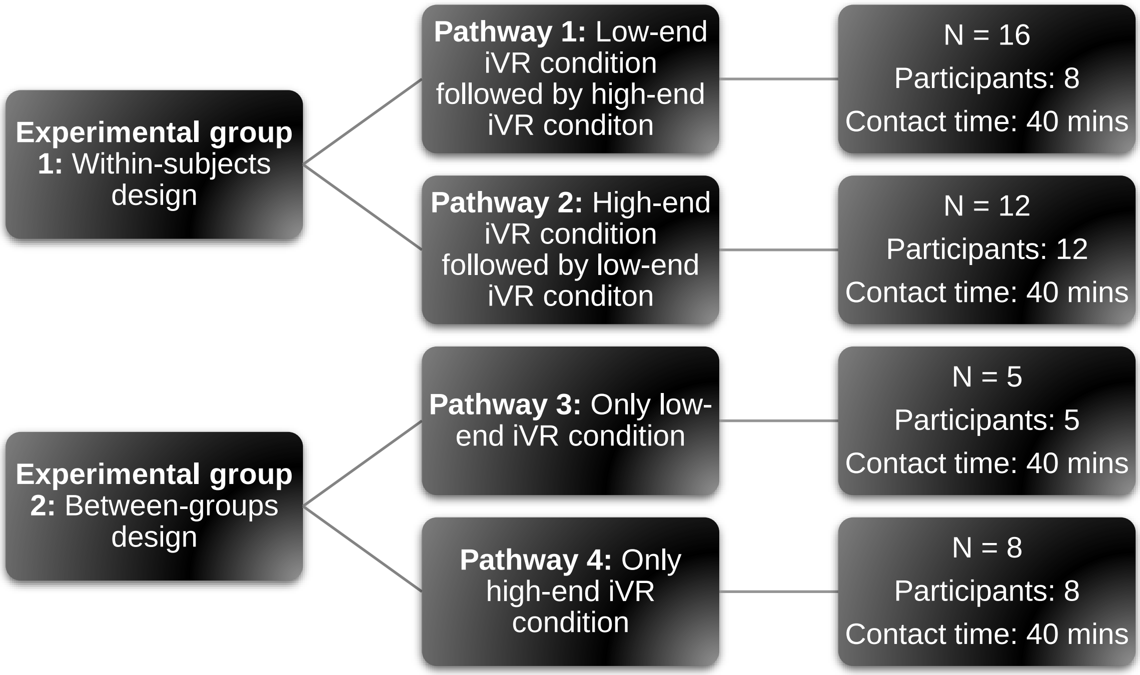


Figure 4.2. Organisation of participation pathways for each study condition according to experimental group.

end iVR condition for the first session and in the high-end iVR condition for the second session on a separate day. Conversely, participants in pathway 2 took part in the high-end iVR condition for the first session, and in the low-end iVR condition for the second session.

Experimental group 2 follows a between-groups design. Participants in this group took part in a single intervention and were randomly allocated to one of two pathways. In pathway 3, participants took part solely in the low-end iVR condition, whilst in pathway 4, participants only took part in the high-end iVR condition.

Although several aspects of this empirical work correspond to an experimental design, it was decided not to characterise this research as such due to the limited control over some of the variables (see Table 4.1) resulting from the use of commercial software in the interventions (see Section 4.2.4). Moreover, the use of different virtual chemistry laboratories for each intervention would make it problematic to designate one condition as control and the other as treatment in all circumstances as there is no full parity of content, despite the comparable support for the variables of study (see Table 4.5).

4.2.3 Recruitment and eligibility of participants.

School invitations and recruitment of participants for this research took place in the autumn of 2019 in two stages. The first stage of recruitment concerned three activities carried out in preparation for the main study: (1) interviews with three practitioners who were selected purposefully and extended invitations over email; (2) a secondary school demonstration carried out as part of a STEAM event where 8 pupils approached the booth to try out the VR experiences being showcased; and (3) two pilot studies for which a sample of 2 academics, 5 postgraduate students, and 24 secondary school students were chosen purposefully and invited to take part.

The second stage of recruitment concerned the main empirical study and was initiated after the pilot studies concluded. Firstly, invitations to several secondary schools in London were extended via different means such as email, physical visits, phone calls, the publication of a bulletin invite on UCL Knowledge Lab's Twitter account, and the distribution of digital handouts with the help of a tutoring agency.

As a result of the recruitment activities, three schools declared their interest in being involved in the study. A meeting was agreed to discuss the extent of their involvement and to showcase the technology. After this meeting, all three schools accepted to take part and a second meeting was agreed to invite students and brief them about the research study.

Table 4.2. Eligibility criteria for student participants.

The potential participant…

- ☑ …is a current student at the secondary school where the interventions will take place.
- ☑ …has the wilful intention to participate in the study and has returned the signed consent forms (parental consent is required).
- ☑ …is able to use the technology and has no visual, auditory, or any other physical impairment that would prevent him/her from using the VR systems.
- ☑ …is not prone to epileptic seizures or has any condition that could be triggered or exacerbated by the use of VR headsets.
- ☑ …has not reported or shown to be prone to motion sickness during the induction.
- ☑ …has not indicated having experienced any significant discomfort during the adjustment of the lenses and the fitting of the headsets and controllers.

The selection of participants attended the criteria listed in Table 4.2. In total, 27 pupils whose ages ranged from 11 to 18 years met the eligibility criteria for the interventions in the main empirical study. 17 students participated from school A (8 female and 6 male), 8 from school

B (4 female and 4 male), and 5 from school C (2 female and 3 male) (see Table 7.1 for the distribution of participants across year of schooling, age, and gender). Student participations were scheduled immediately after signed consent forms were handed over to the head of science or designated administrator at their respective schools. This included parental consent.

Table 4.3 presents the final allocation of participants to the pathways for participation. Of the 27 participants in the main study, 14 were allocated to experimental group 1 (8 in pathway 1, and 6 in pathway 2) and 13 were allocated to experimental group 2 (5 in pathway 3, and 8 in pathway 4). It must be noted that the 14 participants in experimental group 1 took part in both interventions. Resultingly, they contributed with double the amount of data to the study bringing the total number of data points to 41, 19 of which correspond to the low-end iVR condition (Labster: Pipetting Simulation), and 22 to the high-end iVR condition (HoloLAB Champions: Chemiluminescence). That is, the dataset is comprised of sets of 41 entries of data stemming from each of the instruments used for data collection (i.e., 41 transcripts of interviews, and the same number of tests responses, video recordings / screencasts, and responses to the presence questionnaire).

Table 4.3. Final random allocation of participants to pathways.

Experimental group	Total participants	Pathway	Allocation per pathway	Study conditions		Total data points or sessions
				Intervention 1	Intervention 2	
Experimental group 1: Within-subject design	14	1: Labster-HoloLAB	8	Low-end iVR	High-end iVR	16
		2: HoloLAB-Labster	6	High-end iVR	Low-end iVR	12
Experimental group 2: Between-groups design	13	3: Labster	5	Low-end iVR	-------	5
		4: HoloLAB	8	High-end iVR	-------	8
	27					41

Lastly, during the research, there were only two instances of loss to follow-up where participants failed to show up at the second scheduled session and no notification was given. One of those instances happened during the second pilot study, and the other during the main study. In both cases, participants were contacted to confirm that the data that had been previously collected could still be used in the research. Additionally, in the case of the participant from to the main study, it was decided to reallocate the data to a pathway in experimental group 2. None of the participants requested data to be removed or mended in any way and only one participant requested a copy of the video recording of his intervention for personal use.

4.2.4 **The apparatus and virtual environments.**

As indicated in the previous section, each of the interventions in the empirical study was designed around a type of immersive VR technology. This would make it possible to explore the impact that their diverse feature set could have on how they integrate multiple modes of representation to support embodied interaction (see Chapter 5).

Table 4.4 lists the hardware and software configuration used for the study conditions in the main empirical study. In the case of the low-end iVR condition, the hardware is comprised of a Google Daydream View 2 headset with a remote controller (Google LLC, 2017) and a Samsung Galaxy S8+ smartphone. This hardware was paired with the Pipetting Simulation by Labster.

Table 4.4. Description of iVR systems used in each study condition.

Components	iVR system configuration	
	Low-end iVR condition	High-end iVR condition
Hardware	▪ Google Daydream View 2 headset with remote controller. ▪ Samsung Galaxy S8+ smartphone.	▪ HTC Vive headset and tracking system. ▪ Valve Index Controllers (prototypes provided by the developer). ▪ MSI GT62VR 6RE Dominator Pro gaming laptop. ▪ Wired Sennheiser Urbanite Nation on-ear headphones.
Software	▪ Labster: Pipetting simulation (used with permission from the developer).	▪ HoloLAB Champions: Chemiluminescence (used with permission from the developer).

In the case of the high-end iVR condition, the hardware is comprised of an HTC Vive headset (HTC Corporation, 2016) for which the original controllers were substituted with Valve Index Controllers (Valve Corporation, 2019) as these provide support for hand gestures. To isolate participants aurally, a pair of wired Sennheiser Urbanite Nation on-ear headphones was used. The computing and graphical power were supplied by an MSI GT62VR 6RE Dominator Pro gaming laptop with an NVIDIA GeForce GTX1070, Intel Core i7-6700HQ CPU @ 2.60GHz, and 16.0 GB of RAM memory. This hardware was paired with the HoloLAB Champions Chemiluminescence experience by Schell Games (Schell Games, 2018).

The Google Daydream View 2 headset (see Figure 4.3) is a standalone device that acts as a chassis. It holds no computing components, but it houses the lenses that allow for a stereoscopic 3D view of virtual environments. Additionally, the headset is bundled with a single remote controller that only supports the indirect manipulation of objects through point-and-click behaviour, the same mechanic that is employed to enable locomotion through teleportation.

Figure 4.3. Google Daydream View 2 headset with remote controller (Google LLC, 2017).

The headset requires a compatible smartphone to be placed inside to provide visuals, audio, and computing and graphical power. For this study, the headset was paired with a Samsung Galaxy S8+ which has a super AMOLED screen with a resolution of 2960 x 1440 pixels, a refresh rate of 60Hz (low for VR headsets), and a field of view of 90^{o}.

The HTC Vive headset (see Figure 4.4) requires to be tethered to a high-performance computer for processing and graphical power. The headset uses Fresnel lenses and an OLED screen with a resolution of 1080 x 1200 pixels, a 90Hz refresh rate (standard for VR headsets), and a 110^{o} field of view.

Figure 4.4. Composite image showing the HTC Vive headset with SteamVR tracking base stations (HTC Corporation, 2016) and Valve Index controllers (Valve Corporation, 2019).

Although both types of iVR hardware are considered immersive as they offer stereoscopic 3D views of the surrounding virtual environments, they significantly differ in the way they support movement and interaction, which has important implications for how environments can elicit perceptual states such as the sense of presence, as well as how they can provide kinetic tactile-kinaesthetic affordances (see Chapter 5). Such support for movement and interaction is enabled by the integration of a rotational and positional tracking system (see Section 2.1.3).

Although the Google Daydream View 2 headset does not have internal components, the gyroscope and accelerometer in the smartphone provide rotational tracking (3DoF). This consists in the rolling, yawing, and pitching movements (see Figure 2.3) that are performed when twisting the wrist with the controller, tilting the head side to side, backwards or forwards, or when turning it left or right. Due to the absence of a translational tracking system, the Google Daydream View 2 headset only supports teleportation as a mechanism for locomotion. Furthermore, as there is no way of tracking movements of the controller or headset, environments must be designed to be experienced whilst seated or standing on a fixed spot.

Comparatively, the HTC Vive headset incorporates a tracking system called SteamVR Tracking (Valve Corporation, 2016) that allows for rotational and positional movements of the headset and controllers to be replicated in the virtual environments. This enables support for a full range of motion (6DoF) that incorporates translational movements. That is, surge, heave, and sway (see Figure 2.3) which are performed when walking, reaching, bending, or crouching. Support for 6DoF allows for the design of seated, standing, or room-scale experiences where users can physically move around within a pre-defined area. Additionally, this setup also includes a pair of controllers with sensors capable of detecting touch, pressure, and track the movement of individual fingers. This is possible due to the use of an algorithm called SteamVR Skeletal Input (Valve Corporation, 2018) that enables the manipulation of virtual objects through gestures such as grabbing or pinching.

Concerning the software, several immersive virtual reality experiences were evaluated (see Appendix B.1) and trialled during the school demonstration and pilot studies. The final selection attended to the similarity of content, as it was decided to focus on a STEM subject, and how sensory-motor engagement was supported. In particular, it was important that these iVR experiences employed different mechanisms for the elicitation of the perceptions of presence, agency, body ownership, and hand representation. Furthermore, it was of relevance that only one of these iVR experiences supported freedom of movement, locomotion, and the direct manipulation of objects through natural gestures as all of these aspects constitute the variables of study (see Table 4.1).

The iVR experiences selected for the empirical study are Labster: Pipetting Simulation (Labster, 2018) and HoloLAB Champions: Chemiluminescence (Schell Games, 2018), both of which were used with the consent of their respective developers. Thematically, both experiences explore concepts or notions common in chemistry such as taring, dilutions, and chemical reactions. Furthermore, both experiences take place in virtual wet laboratories. In the case of Labster, the main focus is the performance of a serial dilution to determine the concentration of lysine in genetically-modified corn, which is done by practicing a pipetting technique. In the case of HoloLAB Champions, the focus is on mixing substances to create a chemiluminescent reaction, which involves procedures such as measuring volume and mass, and scaling up. Both iVR environments required agents to transfer, mix, and appropriately read measured substances whilst learning separate pipetting techniques.

Table 4.5 lists the design features of the two iVR experiences used in the empirical study. This establishes a basis for their comparison. Whilst this illustrates the commonalities upon which some of the variables of study can be explored such as the elicitation of the sense of presence, hand ownership, and agency, it also highlights the contrasting aspects that allow for the exploration of the effects of other variables such as the presence or absence of movement, locomotion, gestural interaction, hand representation, and the congruency of gestural interactions with the visual simulation and the content to be learnt. For a more detailed account of the aims, learning outcomes, and activities in both iVR experiences, see Appendix B.2 for Labster: Pipetting Simulation, and Appendix B.3 for HoloLAB Champions:

Chemiluminescence, and for a mapping of the gestural interactions see Table 5.3 and Table 5.4, respectively.

Table 4.5. Comparative of iVR experiences used in the empirical study.

	Comparative of iVR experiences	
	Labster: Pipetting Simulation	**HoloLAB Champions: Chemiluminescence**
Proxemics	▪ Proximal (button pressing, pointing, twisting). ▪ Distal (teleportation, manipulation of objects).	▪ Proximal (tapping, dragging, grasping, moving, twisting, and tilting). ▪ Intermediate (leaning, bending, throwing). ▪ Distal (walking).
Aim	▪ Create a serial dilution for a Bradford assay to determine the concentration of lysine in corn.	▪ Mix substances to create a chemiluminescent reaction.
Embodied tasks and behaviour	▪ Measuring. ▪ Weighing. ▪ Moving / placing. ▪ Pushing / pulling. ▪ Changing viewpoint. ▪ Reaching. ▪ Navigating / locomotion.	▪ Measuring. ▪ Weighing. ▪ Pouring. ▪ Shaking / mixing. ▪ Moving / placing. ▪ Lifting / lowering. ▪ Pushing / pulling. ▪ Changing viewpoint. ▪ Organising. ▪ Reaching. ▪ Navigating / locomotion.
Equipment	▪ Micropipettes. ▪ Pipette tips. ▪ Microcentrifuge. ▪ Test tubes. ▪ Microplate shaker. ▪ Microplate reader.	▪ Beakers. ▪ Erlenmeyer flasks. ▪ Flask stoppers. ▪ Graduated cylinders. ▪ Mohr pipette. ▪ Scoops. ▪ Weighing boats. ▪ Analytical balance.
Conceptual understandings	▪ How does a serial dilution work? ▪ How does scaling up or down a substance impact a dilution. ▪ What is a Bradford assay? ▪ How are micropipette measurements taken?	▪ What is a chemical reaction and a chemiluminescent? ▪ How is laboratory glassware more appropriate for certain uses? ▪ How to scale up or down a substance. ▪ What is a meniscus and how it is read according to the substance? ▪ What is taring?

Procedural understandings	▪ Choosing a micropipette according to the volume of a substance. ▪ Choosing and disposing of pipette tips. ▪ Technique to draw, transfer, and release a substance with a micropipette. ▪ Using the two stops of the pipette. ▪ Mixing fluids in a microcentrifuge tube.	▪ Choosing appropriate glassware for the amount of a substance to be measured. ▪ Technique to pour and transfer liquid and powdered substances using different glassware. ▪ Pipetting technique using a Mohr pipette. ▪ Mixing substances to create chemical reactions.
Interaction mechanics	▪ Distal, surrogate manipulation of objects through point-and click behaviour.	▪ Direct manipulation of objects through natural gestures (i.e., grab, release, throw, twist / turn, tilt, pinch, or shake).
Visual design and gameplay	▪ Environment that simulates a real wet laboratory. ▪ Natural visual design and use of light and colour. ▪ Guidance system in place through a virtual tablet and a floating robot. ▪ Sterile white environment.	▪ Environment with the elements of a laboratory contained within a studio set with an audience. ▪ Cartoon-looking environment with saturated colours and special studio lighting. ▪ Guidance system in place through a virtual book and robot TV host. ▪ Television studio with an audience comprised of floating brains cheering.
Game mechanics	▪ Simulation of realistic tasks. ▪ No gamified elements.	▪ Simulation of realistic tasks, behaviour, and consequences of actions. ▪ Gamified elements such as the use of a scoring system to assess performance.
Support for learning	▪ Rigid guidance system that tells agents what to do. This includes written instructions and a virtual tablet containing additional information. ▪ Free exploration is not supported, and mistakes cannot be made. ▪ Constructivist approach where knowledge is scaffolded progressively.	▪ Flexible guidance system that provides instructions and diagrams in a virtual book, evaluates performance by assigning or deducting points, and assesses deliverables from a task. ▪ Free exploration is supported, and agents can make mistakes. ▪ Constructivist approach where knowledge is scaffolded progressively.

The Pipetting Simulation by Labster (2018) (see Figure 4.5) consists in a STEM experience where users engage in several guided tasks to perform a Bradford assay and determine the level of concentration of lysine in a corn cob in a chemistry laboratory. This acts as the backdrop to practice the appropriate pipetting technique using micropipettes. In the experience, participants are first taken to a laboratory where corn is grown to give them some context in relation to the experiment they will perform, later they must observe some safety measures, and subsequently go into the main laboratory where a guidance system gives them oral instructions. As part of the guidance, participants have access to a virtual tablet where they can review the instructions and consult additional theory related to the experiment.

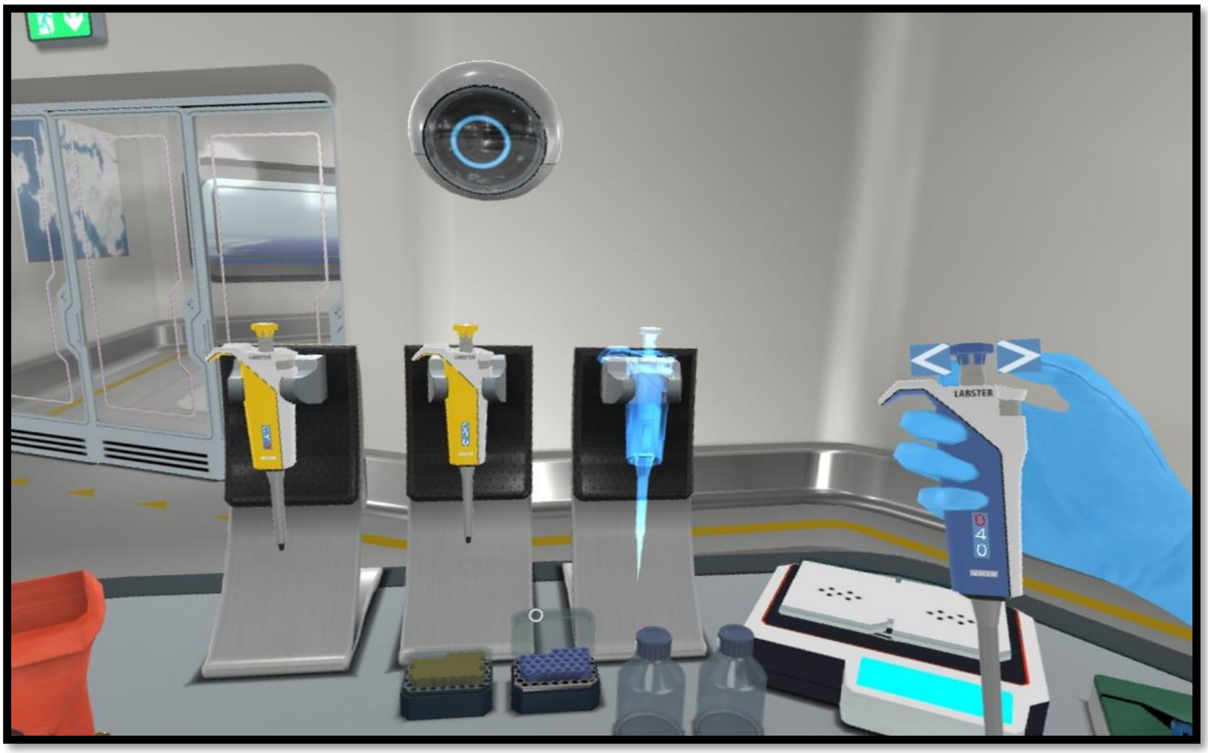


Figure 4.5. Screen capture of the Pipetting Simulation in Labster (Labster, 2018).

This virtual laboratory does not support freedom of interaction or movement as manipulatives become interactable only when they are required for the current task. For instance, a pipette cannot be picked up unless it is needed, or a substance cannot be drawn, unless the appropriate one has been selected. Consequently, participants cannot make mistakes as the guidance system blocks the improper behaviour and signals the attempted error. Although this ensures that the correct procedure for the experiment be performed, it impedes experimentation or learning by trial and error.

Comparatively, the HoloLAB Champions Chemiluminescence experience by Schell Games (2018) (see Figure 4.6) consists of a gamified virtual laboratory where users have to perform 10 common tasks using laboratory instrumentation such as measuring mass and volume, and transferring substances. The experience is aimed at practicing such procedures and applying them in a final large experiment about chemiluminescent reactions.

This virtual environment fosters experimentation and trial and error, and allows participants to advance at their own pace, as well as to interact freely with the space. Although it is not a guided experience, it integrates guidance in the form of a book which contains the procedure for the task to be performed and theory about the chemicals, procedures, and instruments needed. Additionally, a non-playable character (NPC) in the virtual lab occasionally offers oral cues about the task being performed.

Figure 4.6. Screen capture of the Chemiluminescence experience in HoloLAB Champions (Schell Games, 2018).

These iVR experiences were selected due to their similarities in content and conceptual and procedural knowledge, as well as their contrasting mechanisms for embodied interaction, their visual design, and approaches to supporting learning. Although thematically, Laster revolves around a serial dilution to determine the concentration of an amino acid in food and HoloLAB Champions focuses on chemical reactions to create a chemiluminescent substance, they both take place in the context of virtual chemistry laboratories. More importantly, as listed in Table 4.5. Comparative of iVR experiences used in the empirical study.Table 4.5, the underlying conceptual and procedural knowledge being presented involves measuring, scaling, and transferring substances, as well as the use of laboratory equipment such as pipettes and appropriate pipetting technique. This provides a common ground on which to compare contrasting mechanisms for embodied interaction. As shown in Table 4.5. Comparative of iVR experiences used in the empirical study.Table 4.5, these can be more direct or distal and involve different degrees of physical engagement. On the other hand, the differences in visual design and gameplay are ideal to assess how perceptual states such as the sense of presence and hand ownership can be experienced differently by the influence of factors like visual realism and gamification. Lastly, it was important for these iVR experiences to provide similar underlying support for learning, whilst taking different approaches whose effects could be explored. These environments follow a constructivist approach in which agents are guided whilst maintaining a certain degree of freedom either in choosing or triggering an action (Labster) or providing full freedom of exploration manipulation of objects (HoloLAB Champions) (see Table 4.5. Comparative of iVR experiences used in the empirical study.Table 4.5). As a way to scaffold learning, these experiences offer agents progressively more complex tasks and instrumentation requiring them to perform the following steps in the experiment more independently. However, each experience afforded agents with different levels of control, freedom, and guidance.

4.2.5 **Protocol for data collection.**

Interventions took place between the months of November 2019 and March 2020 and due to limitations of space and availability of hardware only two interventions could be carried out simultaneously as part of the s90-minute sessions.

Figure 4.7 shows the protocol followed during every intervention. Although student participants had been previously given an information brochure during a briefing session, each intervention started with a short induction comprised of three phases: (1) a short briefing on what participating in the study would entail and to answer any questions from participants; (2) a fitting of the equipment in which the headset, controllers, and lenses were adjusted to make sure that participants felt comfortable. This moment was also used to evaluate whether participants presented any signs of motion sickness or other type of discomfort that would prevent them from continuing; and (3) a short tutorial on how to use the equipment such as the operation of the controllers, navigation, and the manipulation of objects.

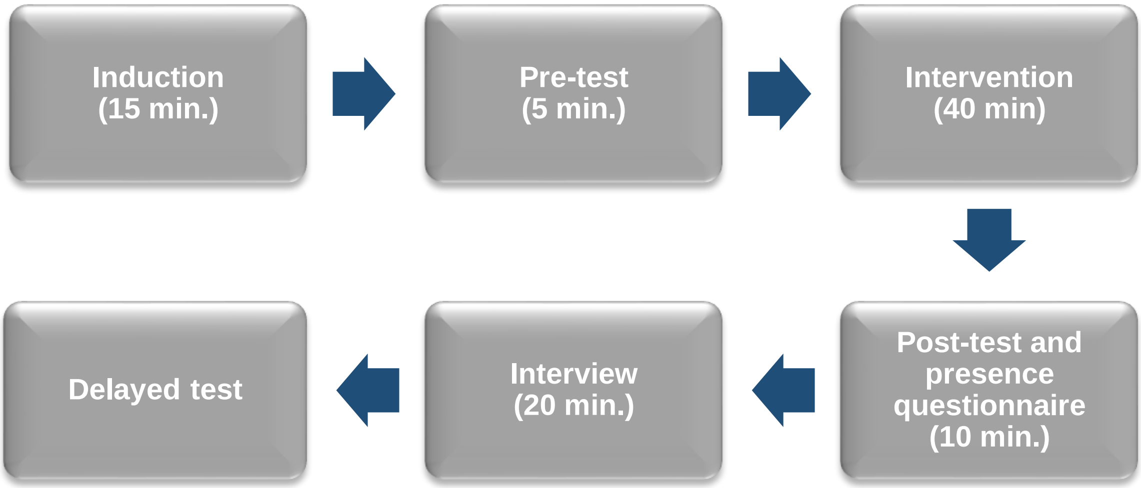


Figure 4.7. Protocol followed for every intervention.

The next phase involved participants answering an online pre-test based on the contents of the virtual experience that they would participate in during that session. As indicated previously, tests and questionnaires were submitted through Google Forms using a tablet.

The intervention itself was designed to be self-contained and carried out without any involvement from the researcher. Based on observations of the pilot studies, it was determined that participants would spend 40 minutes performing the experiments after which the experience was stopped regardless of whether they had finished. On 10 instances, the systems failed, and participants had to restart the experiments. However, in only three of those cases progression and contact time was affected as there was not enough time to get past the point in the experience when the system failed. In the remaining 7 cases, measures were taken to mitigate the impact and participants were able to carry on.

The final phases required that participants answer the post-test and presence questionnaire, and subsequently take part in a semi-structured interview where they were asked about their perception of the virtual environment, the content of the experience, and the ways in which they interacted with the manipulatives.

As a last requirement to conclude the study, participants were asked to answer a delayed test. Due to scheduling conflicts and the lockdown that went into effect in London during the month of March 2020, this had to be done asynchronously online, which resulted in significant variations in the time elapsed between the last intervention and the administration of the delayed test. On average, responses were received 43 days after the participant's last session.

4.3 Methods of data collection.

This research involved two moments of data collection. The first of these took place during the preliminary work comprised of a school demonstration, interviews with secondary school practitioners, and two pilot studies. The aim of these was to enquire about pupil's use of technology in the classroom, inform the selection of virtual reality experiences, and identify issues with the design of school interventions.

During this phase, interviews with practitioners were audio recorded, notes were made based on observations of participant engagement with multiple immersive environments, and survey data were collected from every participant in the school demonstration. Additionally, the pilot studies allowed to orchestrate and time the different components of the intervention from the initial briefing and tutorial to the application of tests. Although participants involved in the pilot studies were asked to answer a presence questionnaire and several tests, responses were not analysed, instead notes were made concerning the clarity, design, and reliability of such instruments.

The second moment of data collection took place during the main empirical study. The instruments employed in this phase of the research involved: (1) several tests looking to assess conceptual and procedural learning; (2) a presence questionnaire meant for participants to self-report their perceptual experience; (3) video recordings of interviews with participants in which they discussed their engagement with the technology; and (4) video recordings / screen capture of the intervention itself showing how participants carried out different tasks.

4.3.1 Testing.

In order to evaluate and compare the effectiveness of the two iVR systems used in this research to support learning, a battery of tests was designed. These tests were based on the learning aims and procedural and conceptual learning outcomes of each of the iVR experiences used. This information was obtained from the developers' websites, documentation pertaining the experiences, and from observations made during the playtesting sessions carried out by the researcher (see Appendices B.2 and B.3). It is important to note that interventions were independent from each other. As a result, each had its own custom-designed battery of tests.

As part of the interventions, three testing points were defined: (1) a pre-test right which took place before participants started the VR experience and whose results were used as a baseline to measure learning improvements; (2) a post-test which took place after the 40-minute intervention and whose results were used to measure immediate learning gains; and (3) a delayed test which was administered days after the intervention and was intended to measure knowledge retention as it was identified as a potential point of interest from the literature (Chittaro and Buttussi, 2015; K. Babu et al., 2018; Meyer, Omdahl and Makransky, 2019). It must be noted that due to scheduling issues and the lockdown that went into effect in London at the time, answers to the delayed tests had to be submitted asynchronously online, which resulted in a period of retrieval ranging from 7 to 89 days ($M = 42.5$, $SD = 22.5$).

Initially, two questionnaires were designed, one for each of the study conditions (low- and high-end iVR). As stated above, these were designed taking into consideration the content, and learning aims and outcomes of the iVR experiences for each of these conditions: Labster: Pipetting Simulation for the low-end iVR condition, and HoloLAB Champions: Chemiluminescence for the high-end iVR condition. The full questionnaire designed for the low-end iVR condition is comprised of 12 items and it was used in full as a delayed test (see Appendix C.3.3). Similarly, the full questionnaire designed for the high-end iVR condition was used as a delayed test and is comprised of 16 items (see Appendix C.4.3). Table 4.6 below summarises the questions developed for each questionnaire.

To create pre- and post-tests, a split-half technique was used which meant that each of the full questionnaires was split in half to create forms A and B (see Appendices C.3.1, C.3.2 for the low-end iVR condition tests and Appendices C.4.1 and C.4.2 for the high-end iVR condition tests). These tests were then randomly administered as pre- or post-tests following a counterbalanced approach[20]. It is important to note that tests did not differ across experimental groups. That is, the same tests were used for participants who took part in a

[20] Half of the participants received Form A as a pre-test and Form B as a post-test, and this was inverted for the other half. Resultingly, all participants were administered the same battery of tests, except in a different order to address ordering effects or the memorization of answers. A private record was kept ensuring all participants received the appropriate set of tests.

single intervention (between-groups) than for those who took part in both interventions (within-subjects).

Table 4.6. Summary of questions employed in both interventions.

Summary of questions	
Labster: Pipetting Simulation	**HoloLAB Champions: Chemiluminescence**
▪ What is a Bradford assay used for? ▪ The Bradford assay only works at low protein concentrations (0.05 to 0.5 mg/mL). How can the concentration of protein in a sample be reduced? ▪ Why is it important to use a micropipette of the size or volume range that is appropriate to the amount of the substance to be measured? ▪ Look at the image and indicate what the range of the P20 micro pipette is. ▪ Look at the image and indicate what the range of the P200 micro pipette is. ▪ Look at the image and indicate what the range of the P1000 micro pipette is. ▪ Look at the images. Which of the following readings of the P1000 micro pipette shows a volume of 240 µl? ▪ What should be done with the pipette before and after every use? ▪ Why are only sterile pipette tips used in the lab and why are they replaced after every use? ▪ Micro pipettes have a plunger with two stops. What is the purpose of the second stop? ▪ Which of the following is the appropriate technique to draw a substance with a micro pipette? ▪ Which of the following is the appropriate technique to dispense a substance with a micro pipette?	▪ It is graduated glassware used for pouring solutions and storing them. It can be closed with a stopper, and it has a cylindrical neck, flat bottom, and conical body. ▪ It is graduated glassware that is used for mixing, heating, or simply holding substances. ▪ It is graduated glassware that is used for measuring precise amounts of liquids. ▪ Instrument used to transfer small, more precise amounts of a liquid between different glassware. ▪ It is an instrument used to transfer solid substances from one container to another. ▪ It is an instrument used to hold solid substances when measuring their mass. ▪ It is an instrument used to measure the mass of substances. ▪ When you look at a liquid in a tube, its surface looks curved. What is the name of that curvature? ▪ Describe the appropriate way to read the amount there is of a liquid in a tube. ▪ What is mass? ▪ What is volume? ▪ How is mass measured? ▪ How is volume measured? ▪ Symbol of the units used to measure mass. ▪ Symbol of the units used to measure volume. ▪ What is the tare function in the analytical balance used for?

All pre- and post-tests were administered digitally through Google Forms using a tablet. Although hard copies were produced, these were only intended to be used in case the online versions could not be accessed. Administering tests digitally resulted in faster responses as participants simply had to tap the screen to select their preferred responses. Furthermore, data processing was more convenient as responses could be easily transferred to a Microsoft Excel spreadsheet for marking and subsequently to IBM SPSS Statistics V26 for analysis. Similarly, delayed tests were administered through Google Forms. However, as this was done remotely and asynchronously, participants were sent a URL via email, thus reducing the level of control which resulted in variable rates of submission.

4.3.2 Questionnaire.

As discussed in the previous chapter, immersive virtual reality technology is characterised for its capacity to surround users with visual and auditory stimuli that encourages kinetic tactile-kinaesthetic engagement (i.e., bodily interaction involving movement, touch, and a sense of proprioception) (see Section 3.2). This condition makes it possible for users to experience a sense of presence.

Although this research concurs with the postulation that the illusion of presence cannot be understood solely through post-experience questionnaires or surveys (Slater, 2004), these types of instruments continue to be extensively used due to the absence of a more viable method of quantification for such qualia. Youngblut (2003), for instance, presents an account of thirty two presence questionnaires that have been developed and implemented in research over the years. Similarly, Schwind et.al. (2019) describe fifteen of the most cited questionnaires in the literature including the Slater-Usoh-Steed Questionnaire (SUS) (Slater and Steed, 2000; Usoh et al., 2000), the Witmer-Singer Presence Questionnaire (PQ) (Witmer and Singer, 1998), and the iGroup Presence Questionnaire (IPQ) (Schubert, Friedmann and Regenbrecht, 2001). Ultimately, it was decided to implement a questionnaire in this research. However, in order to supplement this data, the perceptual experience of presence was also discussed during interviews with participants. Three questionnaires commonly used in the literature were considered for this research:

(1) The Presence Questionnaire (PQ) (Witmer and Singer, 1998) integrates 32 items measured on a seven-point scale with opposing descriptors on both ends and a middle-point anchor. This questionnaire involves six sub-scales: involvement/control, natural, auditory, haptic, resolution, and interface quality; and four factors: control, sensory, distraction, and realism. The questionnaire is reported to have good internal consistency with a Cronbach's Alpha of 0.81 giving it good reliability. It must be noted, however, that the length of the questionnaire may lead to fatigue effects. Furthermore, as pointed out by Slater (1999), several items do not seem to measure presence

directly which rises concerns regarding how some of its items might confound results by picking up correlations to other measures.

(2) The Slater-Usoh-Steed Questionnaire (SUS) (Slater and Steed, 2000; Usoh et al., 2000) is comprised of 6 items covering “the sense of being in the VE, the extent to which the VE becomes the dominant reality, and the extent to which the VE is remembered as a ‘place’” (Usoh et al., 2000, p. 498). Responses to the items are reported on a seven-point Likert scale with anchors labelled only at the extremes. Although this questionnaire covers three themes that can be used as indicators of presence, the number of items is too small to allow for statements posing contrasting views as a control measure for participants exhibiting response sets. Additionally, the number of points in the Likert scale might allow for responses to be spread out which can be an issue, particularly when applied to small samples as is the case in this research.

(3) The iGroup Presence Questionnaire (IPQ) (Schubert, Friedmann and Regenbrecht, 2001) includes 14 items covering 4 themes: general presence, spatial presence, involvement, and experienced realism. This questionnaire borrows some of its items from other instruments; for instance, item 1 is taken from the SUS questionnaire (Slater and Steed, 2000; Usoh et al., 2000), items 7 and 12 are borrowed from the PQ questionnaire by Witmer and Singer (1998), item 11 comes from the work of Hendrix (1994), and item 13 is taken from the work of Carlin, et al. (1997). It is important to note, that while each of the items’ responses is registered on a Likert scale, the authors do not specify the number of anchors. Furthermore, these vary from item to item, thus contributing to its pastiche look.

In their study comparing the implementation of the PQ, SUS, and IPQ questionnaires, Schwind et al. (2019) point out that the IPQ questionnaire provides the highest reliability of the three instruments. As a result of this and coupled with the number of items and themes it covers, the IPQ questionnaire was selected to be adapted to this research. To avoid confusion with the original questionnaire, the version used for the empirical work in this research will be referred as the Immersive Virtual Reality Presence Questionnaire (iVRPQ) (see Appendix C.5). Although the number of subscales and items was maintained, some minor changes were made to adjust the iVRPQ to the nuances of this study:

- Items 1 through 9 were rephrased in order to make the language more appropriate to the age group of the participants, whilst item 10 was kept as in the original.

- Items 11 through 14 were replaced with statements denoting more differentiable indicators.
- Responses were adjusted to five-point Likert scales with descriptive anchors. This was done to make the questionnaire more cohesive and to improve clarity as the original only described the anchors at the extremes.
- In order to identify participants exhibiting response sets, items 3, 4, 7, and 9, which express opposing views of the construct of presence, were reverse scored.
- The original questionnaire included 4 items as questions, these were rephrased into statements to make them more appropriate to the use of Likert scales and to ensure uniformity with the rest of the items in the questionnaire.

The iVRPQ was evaluated during the pilot studies to make refinements. Results indicate a high inter-item reliability with a 0.924 Cronbach Alpha. Once the main data collection ended, the same test was performed with the larger sample. Results reported a Cronbach alpha level of 0.876 which suggests good inter-item reliability. Further analyses indicated that the deletion of items, 3, 4, and 12 would increase the reliability of the scale. However, with a 0.02 difference, improvement was marginal and did not justify leaving out data from any of those items.

4.3.3 **Semi-structured interviews.**

At the end of every intervention, participants were asked a few questions in relation to their engagement with the virtual environments. As posited by Braun and Clarke (2013), semi-structured interviews are particularly suited to research questions looking at an individual's experience. In the case of this study, they had two main aims: (1) to enquire about the ways in which participants perceived the VE and how that contrasted with their expectations from reality; and (2) how they understood the concepts and procedures presented in the virtual reality experiences.

The interview schedules for the low-end iVR condition (see Appendix C.1.1) and for the high-end iVR condition (see Appendix C.1.2) were designed around four themes:

(1) Perceived new knowledge. Participants were asked to reflect on the things they did not know before the intervention and to explain some central ideas presented in the virtual experiences. This was intended to enquire about conceptual understanding.

(2) Task performance. Participants were asked to explain the different tasks they performed for some of the experiments such as the use of laboratory equipment. This had the aim of probing about procedural understanding.
(3) Bodily interactions. Participants were asked to reflect on their awareness and perception of the freedom of movement they had when conducting the experiments, their physical engagement with manipulatives, and aspects such as control over the environment and the pace of the experiments.
(4) As a complement to the iVRPQ questionnaire, participants were asked to describe their perception of self-location, body ownership, presence, and to answer some questions in relation to their sense of proprioception.

Although the themes in the interviews guided the flow of the conversation and, in some ways, restricted it to the boundaries of what needed to be enquired, it was important to design a semi-structured schedule comprised of a mix of prompts and questions to make it flexible enough for slight deviations from the core ideas that were being discussed such as nuances observed during the interventions, or drawing examples and comparisons to situations beyond the interventions themselves. The interview schedules for both interventions follow a very similar structure and only deviate in the questions related to concepts and procedures that were unique to each VR laboratory.

4.3.4 Screencasting and video recordings.

One final method for data collection implemented in the main study was the video recording of interviews, as well as the video recording of participants performing the experiments along with screencasting of the virtual environment.

Two small action cameras were used, one to record the intervention and another to record the interview area. XSplit Gamecaster V3.4.1812.0308 was used to capture the visual of what was happening in the virtual environment simultaneously. During the data processing phase, Adobe Premiere Pro CS6 was used to join both recordings into a single video with a picture-in-picture layout. This allowed for the analysis of both visuals side by side.

4.4 Methods of data analysis.

The main empirical study included 41 sets or data points stemming from each instrument; that is, 41 interview transcripts and video recordings, and the same number of responses to the iVRPQ questionnaire, responses to the pre-, post-, and delayed tests, and video recordings / screencasting of participants' interventions.

Data were analysed separately attending to the research questions. Initially, several types of statistical analysis were performed with responses from the pre-, post-, and delayed test scores, as well as from the iVRPQ questionnaire responses. Microsoft Excel was used to process the data into a single database and to assign marking to the tests. Subsequently, IBM SPSS v.26 was used to perform descriptive analysis of the data through measures of central tendency, looking at group differences, and exploring potential correlations between the variability in scores and demographics such as gender, year of schooling, and the type and order of interventions (pathways). All statistical analyses were performed on the full dataset, except for when it was necessary to split the sample into groups for the purpose of drawing comparisons, in which case this is clearly stated.

Based on some of the findings from the quantitative analysis, interview transcripts were coded using NVivo 12 un preparation for thematic analysis. The themes that were identified (see Appendix C.2) were used for the organization and presentation of findings in combination with the data from the quantitative strand. The approach taken for the coding process was abductive. That is, a deductive approach was taken initially using the research questions as the basis, and subsequently, a second round of coding was performed following an inductive approach to expand codes.

Lastly, findings from the interviews were used to select a complementary subsample of video recordings / screencasting for which the focus was the analysis of gesture and postures as a form of embodied interaction. This approach helped elucidate the ways in which the conversational gestures agents make when talking about a VR experience may reflect the physical gestures they used to interface with the virtual environment, and subsequently, how these gestures are mapped to their visual representation and to the educational content they relate to.

4.5 Reliability, validity, and replicability of the study.

Bryman (2016) posits that all social researchers must take into consideration the reliability, validity, and replication of their research methods. On that consideration, several measures were taken:

- The feedback and notes made during the school demonstration informed the selection of the VR experiences for the interventions.
- The first pilot study allowed for the selection of methods of data collection that would be appropriate for the research questions and the conditions in which the interventions would take place.
- The second pilot study helped in evaluating and refining all the tests, the iVRPQ questionnaire, and the interview schedules to assess their reliability and validity. This pilot study did not only involve age-appropriate participants, but also some colleagues whose involvement acted as a measure of inter-observer consistency.
- The second pilot study also allowed to identify issues with the hardware and software, and refine the orchestration of cameras, VR systems, and software for screencasting, as well as the timing of every stage of the intervention, all of which would support the consistent replication of the study at different schools.
- The use of VR headsets and headphones provided participants with visual and auditory isolation from reality. Although Hawthorne effects (Seale, 2012) cannot be fully avoided, this isolation and the immersion experienced by participants could minimise the effect as they could forget about the experiment temporarily and not feel observed.
- Lastly, the validity or integrity of the conclusions was addressed by the triangulation of data from both quantitative and qualitative methods.

4.6 Ethical dimensions.

This research abides by the Ethical Guidelines for Educational Research by the British Education Research Association (BERA), the Framework for Research Ethics by the Economic and Social Research Council (ESRC), and University College London's code of ethics. University College London acted as the data controller through the Data Protection Office under registration number Z6364106/2018/02/89 (see Appendix A.3).

In accordance with UK law through the General Data Protection Regulation (GDPR), data were collected using the legal basis of a task in the public interest. Participants who took part in the school demonstration were orally briefed and those who participated in the interviews, pilot studies, and main empirical study were given both an oral brief and an information brochure detailing the conditions of their participation. Additionally, informed consent was obtained from all participants. In the case of secondary school student participants, this included parental consent.

All data, including video recordings / screencasting of interventions and interviews, were dissociated from participants at the moment of collection. This was done to minimise the risk of participant identification in the event of any data breach. All data were managed, processed, and stored using a unique identification number (ID) to protect the participants' confidentiality.

IDs are comprised of a combination of nine alphanumeric characters with the following structure: Taking the fictitious ID "28LKA064A", the first two digits (28) indicate the participant number which is assigned in order of participation in the study, the following three letters (LKA) constitute a code to identify the school where data were collected, this is followed by a two-digit number (06) indicating the participant number which corresponds to the order of participation in that school cohort, and lastly, the last two digits indicate the pathway in which the participant was randomly assigned (4) and the test form that was administered (A).

A password protected file was generated as a record to manage participants and their assignment into the pathways of study, as well as to keep track of the type of data that were collected and the limitations to how that data could be processed according to the consent given. This constituted the only record of identifiable information as it also included the participants' names, IDs, and schools.

In the case of tests, and the iVRPQ questionnaire, which were administered using Google Forms, all responses were uploaded to UCL's encrypted N drive via the remote desktop functionality and removed from the cloud service at the end of each session. In the case of video recordings / screencasting, these were stored in an encrypted portable hard drive due to their large sizes.

Lastly, as expressed in the information sheets given to participants (see Appendices A.1 and A.2), video recordings and any other form of personal, identifiable data will be safely destroyed once the degree is conferred and all activities aimed at disseminating the research findings have concluded.

Chapter summary

The present chapter provided a detailed account of this research's methodological approach and was organised into four sections:

(1) The first section discussed how using a mixed methodology would provide a more comprehensive understanding of the impact that the affordances of iVR technology could have on students' understanding of conceptual and procedural knowledge.

(2) The second section described the design of the two interventions that comprise the empirical study. This considered the characteristics of the study conditions, low- and high-end iVR, and the technology to be used. Additionally, it presented aspects concerning the study such as the recruitment of participants and the protocol to be followed to collect data during the school interventions.

(3) The third section discussed the selection of methods of data collection and analysis including statistical analysis of questionnaire and tests responses, and thematic analysis of interview transcripts and video recordings /screencasts of interventions.

(4) Lastly, the fourth section discussed the measures taken in accordance with the GDPR, as well as BERA and ESRC's research ethics guidelines including the procurement of informed consent, the use of encrypted storage, and the dissociation of data.

Chapter 5: The features and affordances of iVR technology

Chapter overview

This chapter explores aspects concerning immersive virtual reality hardware and software and their interrelation. This preliminary work underpins the main empirical study for this research, and it is guided by three research questions:

- What are the features of immersive virtual reality technology?
- What sensory-motor affordances can the features of an iVR system enable?
- In what ways can embodied interactions be congruently mapped to conceptual and procedural knowledge in an educational virtual environment?

5.1 Defining the features of virtual reality hardware.

It is argued in this research that different configurations of properties of iVR hardware can enable different sensory-motor affordances in the virtual environments they support. Based on this, it is hypothesised that such sensory-motor affordances have the potential not only to define an agent's perceptual experience, but also to shape the way they make sense of what is happening in the environment. Concerning the use of iVR technology for education, this may pose significant implications for how students construct conceptual and procedural understandings of the content to be learnt.

This section explores what those features are and discusses the ways in which they support sensory-motor engagement. This work stems from the analysis of the components of different VR hardware and from observation notes made during a secondary school STEAM event where pupils engaged with two types of iVR systems and several educational VR experiences. The features described in the following two sections concern the components of VR systems that provide them with visual, auditory, kinetic, tactile, and kinaesthetic capabilities.

5.1.1 Audio-visual features.

In addition to processing and auditory capabilities, commercial VR systems have four visual features which are defined by the distinct attributes of their screens: (1) type, size, and shape, (2) viewpoint, (3) resolution, and (4) refresh rate. These are all presented in Table 5.1 indicating the types of immersive and non-immersive VR hardware that supports them. The organisation of the hardware attends to the typology proposed in Section 2.1.2 and illustrated in Figure 2.2.

The visual output of any VR hardware is impacted by the type of screens or projection that they use to present the virtual environments. These screens and projections can vary in type, size, and shape, which influence the viewpoint of the environment, as well as in resolution, and refresh rate, which can influence not only the image quality, but also comfort.

Screen type, size and shape can vary greatly among VR systems (Sherman and Craig, 2003). Generally speaking, these consist of LCD, OLED, or AMOLED rectangular panels. In the case of vehicle simulators, screen walls, screen floors, and CAVE systems[21], these panels can be large enough to cover most or all of the agent's field of view. In the case of computers and tablets, screens are smaller, and they visually frame virtual environments as if looking through a small window. And in the case of HMDs, depending on their type, screen panels can be embedded in the chassis or incorporated through the placement of a smartphone inside them, which makes these screens the smallest among VR hardware.

Although screen panels in HMDs can also vary in size, these remain significantly smaller compared to other types of VR hardware. Despite their size, they are capable of covering a large area of an agent's field of view by being placed at a distance of centimetres from the agent's eyes. This has direct implications for the viewpoint, which designates how much of an agent's field of view is covered by the screen, thus eliciting the illusion that the virtual environment is a continuous surrounding space (Lin et al., 2002). A narrow field of view can cause the agent's peripheral vision not to be entirely covered by the screen and, as a result, the virtual environment would be perceived as if looking through a cuboid or a monocular. Contrastingly, a wide field of view that covers most or the entire field of human vision (210°) would give an unobstructed perspective of the VE (Rakkolainen et al., 2017).

Another attribute of screens is their resolution, which is responsible for producing sharp visuals, thus making text and other graphical representations clearer. Screen resolution is particularly important with HMDs due to the positioning of the screen panels at a closer distance to the agents' eyes. Coupled with the magnifying effect of the HMD's lenses, this could make it possible for agents to see the blank space between the pixels in the screen. This is a visual artefact known as screen door effect and it is more visible with light-coloured backgrounds. The effect causes the environment to look as if it were being observed through a mesh or screen door (Cho et al., 2017).

The last attribute of screens that impact the visual output of VR hardware is, refresh rate, which is responsible for the fluidity of motion such as when walking, changing the viewpoint, moving the hands, or observing an object move in the environment. In general terms, the faster a screen refreshes the image being displayed, the more fluid the motion will appear (Louis et al., 2019). Although this is applicable to all types of screens, the effects of low

[21] Although CAVE systems use projections instead of screens, the properties of type, size, and shape are still applicable.

refresh rates are more impactful with HMDs as this could elicit cybersickness or simulator sickness due to visual lag or the environment looking blurry during fast movements (Nemec et al., 2017; Choroś and Nippe, 2019). Simulator sickness consists of physiological responses such as dizziness, loss of balance, and vomiting that are experienced when there is a disconnect between visual and vestibular stimuli (Dużmańska, Strojny and Strojny, 2018).

Table 5.1. Audio-visual and processing features of virtual reality hardware.

Audio-visual and processing features of VR							
Categories and features			**Type of VR hardware**				
			NiVR		**iVR HMDs**		
			Computer -based	**Mobile-based**	**Low-end (3DoF)**	**Mid-range (Hybrid)**	**High-end (6DoF)**
Screen type, size, and shape	Computer screen		✓	✗	✗	✗	✗
	Mobile device	Smartphone screen	✗	✓	✓	✗	✗
		Tablet Screen	✗	✓	✗	✗	✗
	Headset/lenses		✗	✗	✓	✓	✓
	Rear projected walls and large wall screens		✗	✗	✗	✗	✓
Viewpoint	Narrow field of view (94º or less)		**N/A**	**N/A**	✓	✓	✓
	Standard field of view (95º to 114º)				✓	✓	✓
	Wide field of view (120º or higher)				✓	✓	✓
Screen resolution	Medium screen resolution (1440 × 1440 pixels or lower)		✓	✓	✓	✓	✓
	High screen resolution (1440 × 1600 pixels or higher)		✓	✓	✗	✓	✓
Screen refresh rate	Low screen refresh rate (75Hz or lower)		✓	✓	✓	✗	✗
	Standard screen refresh rate (75Hz – 90Hz)		✓	✓	✗	✓	✗
	High screen refresh rate (120Hz or higher)		✓	✓	✗	✗	✓
Source of computing and graphical processing	Using a mobile device for power		✗	✓	✓	✗	✗
	Comparable to a mobile device		✗	✗	✓	✓	✗
	High-performance computer or gaming console with dedicated GPU		✓	✗	✗	✗	✓
Audio	Stereo		✓	✓	✓	✓	✓
	3D / spatial audio		✓	✗	✗	✓	✓

The last two features of VR hardware concern their source of computing and graphical processing power, and their audio capabilities. Computing processing is handled by a CPU, and graphical processing can be done either by sharing the CPU's memory bank, or by a discrete GPU with its own power and memory source (Intel, 2020). Typically, mobile devices, as well as low-end and mid-range computers and standalone HMDs follow the former approach, whereas high-end computers and tethered HMDs follow the latter. Although systems that require a high-performance computer with a discrete GPU typically need to be tethered, are more power hungry, and have higher internal thermals, they are also capable of producing more photorealistic visuals and robust simulations that low-end HMDs and non-immersive mobile-based systems like tablets cannot.

Lastly, although all VR hardware is capable of delivering stereo audio either thorough embedded speakers or via an audio port where agents can plug headphones, only high-end HMDs and computer-based non-immersive virtual reality hardware can support spatial audio. Spatial or 3D audio consists in "the ability to play a sound as if it is positioned at a specific point in three-dimensional space" (Facebook Technologies, 2020). Resultingly, audio is dynamically adjusted according to the movements of an agent in the virtual environment.

5.1.2 Kinetic tactile-kinaesthetic features.

These features enable movement and touch and elicit proprioceptive stimuli on agents. Coupled with the properties described in the previous section, VR hardware can provide opportunities for sensory-motor engagement that involve embodied interaction through locomotion, posture, and gesture. Table 5.2 lists the kinetic tactile-kinaesthetic properties that different VR technologies support. These are organised around five categories: (1) the tracking system, (2) compatible input devices or peripherals, (3) the types of interactions that are supported, (4) how locomotion is enabled, and (5) the type of setup in which the VE can be experienced.

Based on the role that it has in enabling perceptual affordances and motor control, it can be argued that the tracking system constitutes one of the most significant components of immersive technologies (see Section 2.1.3 and Figure 2.3). Furthermore, it is the tracking system that binds all the kinetic tactile-kinaesthetic features in Table 5.2.

Table 5.2. Kinetic tactile-kinaesthetic features of virtual reality hardware.

Kinetic tactile-kinaesthetic features of VR							
Categories and features			Type of VR hardware				
			NiVR		iVR HMDs		
			Computer-based	Mobile-based	Low-end (3DoF)	Mid-range (Hybrid)	High-end (6DoF)
Tracking system	Headset	3DoF (only rotational movement)	**N/A**	**N/A**	✓	✗	✗
		6DoF (rotational and translational movement)			✗	✓	✓
	Input device	3DoF (only rotational movement)			✓	✓	✗
		6DoF (rotational and translational movement)			✗	✗	✓
Input devices	Joystick		✓	✗	✗	✗	✗
	Keyboard		✓	✗	✗	✗	✗
	Mouse		✓	✗	✗	✗	✗
	Touch screen		✗	✓	✗	✗	✗
	Gaze		✗	✗	✓	✗	✗
	Touchpad		✓	✗	✓	✗	✗
	Pointer/controller		✗	✗	✓	✓	✗
	Controllers/gloves/camera for hand gesture/finger tracking sensors		✗	✗	✗	✗	✓
Types of interactions	Indirect	Gaze and hold	✗	✗	✓	✗	✗
		Tap to select (touchpad)	✓	✓	✓	✗	✗
		Point and click (button pressing)	✗	✗	✓	✓	✗
	Direct	Tap or click and drag	✓	✓	✗	✗	✗
		Controller button pressing	✗	✗	✗	✗	✓
		Hand or finger gestures	✗	✗	✗	✗	✓
Locomotion (movement)	Avatar control (if compatible)		✓	✓	✓	✓	✓
	Physical user movement (walking)		**N/A**	**N/A**	✗	✓	✓
	Teleportation				✓	✓	✓
	Seated		✓	✓	✓	✓	✓

Type of setup	Standing	✗	✗	✓	✓	✓
	Room-scale	✗	✗	✗	✓	✓

Concerning the hardware, low-end HMDs are characterised for only supporting the rotational movement of the headset and controller on a fixed axis (3DoF). Mid-range HMDs are hybrid systems as they incorporate three additional dimensions of translational movement for the headset (6DoF), whilst keeping only rotational movement for the controller. Lastly, high-end HMDs integrate a 6DoF-enabled headset and controller giving these types of systems full range of motion.

The next category of features concerns input devices or peripherals which mediate an agent's motor engagement in a virtual environment. These incorporate touch in two ways: (1) through the feeling of holding the physical peripheral itself, and (2) through the haptic feedback that the peripheral provides during interaction. Of all the input devices listed, only gaze, pointers, controllers, gloves, and cameras are implemented in current commercial iVR systems. Furthermore, they rely on the tracking system and together with the visual representation of an agent's hands and the replication of their movements, they can more accurately evoke the illusion of hand presence, ownership, and agency.

Concerning the types of interactions that a VR system can support; these can be indirect or direct. Generally speaking, indirect interactions are employed by non-immersive, low-end, and mid-range 3DoF iVR HMDs and they are limited to gaze, tapping, and point-and-click behaviour. Through these mechanisms for interaction, agents have control of what happens in the VE by selecting the manipulatives with which they want to engage. However, agents do not directly manipulate objects, they simply trigger the action distally and it is subsequently performed automatically.

Direct interactions, on the other hand, rely on 6DoF. Consequently, they are only possible with high-end iVR HMDs. In this case, agents have full control over which manipulatives they want to engage and over how and when they can interact with them. In that sense, agents must approach the virtual objects and physically enact the required behaviour. Depending on the input device used, this could involve pressing buttons on a controller, performing symbolic hand gestures mid-air to be tracked by a camera, or making natural hand movements such as grabbing and pinching using gloves, controllers, exoskeletons, or cameras.

The next category concerns movement and it can refer to the hands, head, or the whole body when agents require to walk in the space (locomotion). Regardless of the presence of an avatar or body representation that agents can inhabit or embody in the VE, movement can be tracked, provided the iVR system integrates the peripherals necessary. Whilst hands and head are covered by the headset and input devices, full body tracking requires more equipment such as a body suit or trackers that can be attached to limbs and joints.

The last category designates the setup in which agents can experience the virtual environment. Seated and standing experiences typically rely only on agents changing the viewpoint whilst remaining in a fixed position in the space. Comparatively, room scale experiences require support for 6DoF as agents are free to move within the limits of a predefined play area.

Ultimately, these visual, auditory, kinetic, tactile, and kinaesthetic features of VR hardware can shape how virtual environments are experienced by providing sensory-motor opportunities for action as it is explored in the following section.

5.2 Defining the affordances of immersive virtual reality HMDs.

As defined by Gibson (1977, 2014), affordances are the inherent properties of an object, space, or medium that can be perceived by an agent as providing opportunities for enation. Applied to immersive virtual environments, for instance, objects in the space could be perceived as tools to perform a task, they can be picked up, combined, or thrown, or they can act as receptacles for substances. Similarly, the environment could invite exploration and encourage agents to walk or carry out actions to test the ways in which it behaves differently from reality or deviates from the agent's expectations.

It must be noted, however, that evoking a sense that something is offering an opportunity for action only partially defines an affordance in this context as there needs to be support for such actions to take place. Just because an agent may perceive that an object can be approached, picked up, or broken, it does not mean that the hardware is capable of supporting such actions, or that the environment was designed to simulate them.

The above indicates a departure from how affordances are perceived in reality. In this case, agents perceive opportunities for action based on the notion that the properties of an object, space, or medium align with the capabilities of their own bodies as well as with the capacities of the environment in which they find themselves. For instance, grabbing a cup from its handle as opposed to its body in reality can be predicated on several factors such as its shape, whether it is hot or cold to the touch, or simply the fact that the agent has opposable thumbs and fingers in a shape and size that make it physically possible and comfortable to hold the cup. In a virtual environment, however, some of these properties are simply not supported or present. Resultingly, factors such as temperature or weight would not be expected to influence the perception of an affordance. In this way, affordances can be seen as constrained by the rules of the environment and the physical capabilities of an agent within that space.

Although the notion of affordance as defined by Gibson (1977, 2014) is still applicable here, this research uses the concept with the caveat that the features of immersive virtual environments constitute an additional dimension. Based on this, it is proposed that immersive virtual reality HMDs can provide agents with three types of affordances which attend to the ways in which these systems engage perception and support bodily interaction distinctively from other types of immersive and non-immersive VR technologies. These are: (1) the sense of presence, (2) the sense of embodiment, and (3) movement.

Given the distinction between what it means for an object, space, or medium to afford something in reality compared to a virtual environment, it is important to briefly discuss what it means to simulate reality or some aspect of it and to what degree such simulations need to be faithful to the real world. Alexander et al. (2005) uses the term fidelity to refer to the notion of reality and defines it as “the extent to which the virtual environment emulates the real world” (p. 4). Furthermore, Alexander et al. (2005) point out that the notion of reality has been described in the literature through multiple subcategories and dimensions including physical fidelity and functional fidelity in relation to the simulation itself, and psychological fidelity in regards to its perceptual effects on agents.

This research is particularly concerned with physical fidelity which measures the degree to which a virtual environment resembles reality through visuals, audio, and controls (see Baum et al., 1982; Hays and Singer, 1989) and functional fidelity which measures resemblance around behaviour, interactions, and how things act in the environment (see Baum et al., 1982; Allen, Hays and Buffardi, 1986). As observed in this research (see Sections 7.2, 7.3, and 7.4), high fidelity in one dimension can offset the effects of low fidelity in another, thus maintaining the perception of realness through illusions like presence, body ownership, self-location, and agency. This is consistent with findings reported in the literature (Alexander et al., 2005). It was also found in this research, however, that in addition to one dimension offsetting the effects of another, participants also exhibited behaviour which denoted the assimilation of conditions that were not necessarily ideal and that could break perceptual illusions, thus potentially impacting how real the environments were considered (see Sections 7.2 and 10.2.3). In that sense, it was found that the "effectiveness" of a virtual environment is not solely dependent on its realism, or a single affordance for that matter (see Section 10.2).

5.2.1 The sense of presence.

Slater (2009) argues that presence is a qualia and cannot be measured directly. However, it can be indirectly assessed through the elicitation of perceptual states that can act as its indicators (see Section 3.4.1 for a more complete discussion of what the concept entails). Slater and Sanchez-Vives (2014) describe such indicators as place illusion (PI), which consists of the feeling of inhabiting or being in a place, and plausibility illusion (Psi), which refers to the feeling that what is being experienced is truly happening (see 3.4.1).

Place illusion or spatial presence can be achieved by situating agents in a surrounding environment that is consistent, uses coherent auditory stimuli, and detaches agents from reality (Slater, 2009), something that most immersive VR technologies are capable of achieving from a technical standpoint. For instance, the two types of HMDs used in this research provide an enveloping visual of the virtual environments (i.e., Labster and HoloLAB Champions) that agents can experience from a first-person perspective (1PP). This can help in creating the illusion of being situated in that space and in detaching agents from reality by isolating them from external audio-visual stimuli. However, although both systems have comparable features, they engage visual, auditory, kinetic, and touch modalities in ways that can result in different experiences of place illusion (see Section 4.2.4 and Table 4.5 for description of the underlying goals, assumptions, and affordances of each virtual environment).

Figure 5.1*[22] illustrates the visual consistency of the surrounding virtual environments used in this research. Labster (left) places agents in an environment that simulates a real

[22] All figures marked with an (*) portray gestures or postures that participants performed during the interventions. As these are not always clearly illustrated through still images, animated gifs have been created capturing movement. These can be found in Appendix D.

laboratory with interactable equipment, whilst HoloLAB Champions (right) places agents in a non-conventional laboratory inside a television studio surrounded by screens and an audience. Although both environments visually and aurally isolate agents from the physical world, interactions and movement are supported differently which can provide different affordances to ground agents in the space. Although Labster looks more realistic, this contrasts with the lack of support for physical movement as all behaviour is only virtually simulated. HoloLAB Champions, on the other hand, despite looking less photorealistic, accurately replicates the agents' movements in the environment, thus allowing them to physically walk and approach objects to manipulate them.

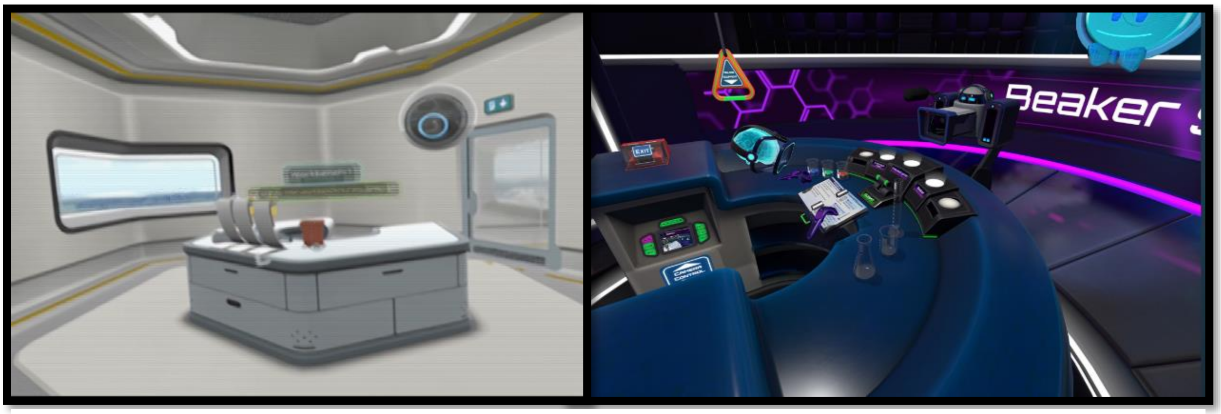


Figure 5.1*. Screen capture illustrating the surrounding virtual environments in Labster (2018) and HoloLAB Champions (Schell Games, 2018).

Another aspect that can visually situate agents in the space is the use of visual cues which can have different aims. In Labster, for instance, agents are often presented with blue flashing arrows to draw their attention to something outside of their current field of view. These visual cues, however, are more commonly employed to indicate the capacity for interaction of an object or to aid in their identification. In that sense, they highlight the opportunities for action that the space provides. Figure 5.2, for example, illustrates how hovering with the pointer in Labster (left) lightens objects that can be manipulated and shows a bubble with their name. Comparatively, in HoloLAB Champions (right), a blue light is used to indicate that an object is being virtually touched, which also gives a sense of depth of field as agents are expected to approach an object with no physical properties (i.e., mass or volume) and a visual aid is needed to gauge their distance.

Concerning the auditory mode, both environments situate agents in the space through the coherent reproduction of sound and dialogue. These stem from ambient sounds like the glassware clinking, substances being poured, buttons being pressed, and from the voice of

NPCs. In Labster, a floating robotic orb acts as a virtual assistant who provides brief explanations, asks questions, and reminds agents of the additional support available to them in the “LabPad.” In HoloLAB Champions, because the experience is presented as a competition taking place in a laboratory within a television studio, there is an audience comprised of brains who cheer the agent or react to mistakes, there is a robotic floating camera that makes recording sounds, and there is a holographic emoji acting as a show host who tells jokes, reacts to progression and to mistakes with the experiments, and gives hints about how to perform the tasks.

Figure 5.2. Visual cues signalling interactable objects within Labster (2018) and HoloLAB Champions (Schell Games, 2018).

Lastly, the mode of touch situates agents more meaningfully in HoloLAB Champions where agents use touch and pressure sensitive controllers with a mechanism that attaches them to their hands and allows them to fully open their hands without dropping the controllers. As observed in Figure 5.3, the participant on the left is holding the pointer at all times, whilst the participant on the right only grabs the controller to simulate grabbing an object in the virtual environment, which provides the sensation that the virtual objects is being physically touched.

The second indicator of presence as defined by Slater and Sanchez-Vives (2014) is plausibility illusion, which consists in the believability of what is happening in the virtual environment. This could be described as the notion of experienced realism despite the agents’ knowledge of the artificiality of the space.

Although the most evident instantiation of realism is photorealistic visuals (Hvass et al., 2017), a virtual environment being plausible also concerns other modes such as sound and movement in relation to behaviour taking place within it and how these “correspond with the viewer’s own understanding of these phenomena in daily life” (Prince, 1996, p. 32). Moreover, these could be more significant in making a space feel realistic and plausible than computer-generated graphics that closely resemble reality. As Prince (1996) argues, “unreal images may be referentially fictional, but perceptually realistic” (p. 32).

Figure 5.3*. Screen capture illustrating the kinaesthetic mechanisms used to elicit and support active engagement in Labster (2018) and HoloLAB Champions (Schell Games, 2018).

Figure 5.4* illustrates how experienced realism is afforded by both virtual environments. Whilst Labster (left) takes a visual approach that is closer to photorealism, HoloLAB Champions (right) approaches realism through the accurate replication of movement and embodied interaction such as posture and hand gestures despite the space looking cartoon-like with its saturated colour palette.

Figure 5.4*. Screen capture illustrating plausibility illusion or experienced realism in Labster (2018) and HoloLAB Champions (Schell Games, 2018).

As Slater and Wilbur (1997) posit, the more an agent is displaced from reality, the more likely s/he is to experience a greater sense of presence, thus inciting congruent reactions that instantiate their perceptual state. These types of reactions were observed during the school demonstration such as when some participants tried leaning against the virtual workstation as if it were physically there, or when they engaged in reactive behaviour like stepping away from the workstation after a beaker was broken or a substance was spilled suggesting they were trying to avoid cutting themselves with the shards or staining their clothing. Alternatively, some participants also tried to test the plausibility of the environments. For example, they would knock glassware together to see whether they could break, or they would throw the scoops across the laboratory at the NPCs to see if this would elicit a response.

5.2.2 **The sense of embodiment.**

The second category of affordances of immersive virtual reality HMDs concern the sense of embodiment which constitutes a perceptual experience defined by the elicitation of three dimensions (Slater and Sanchez-Vives, 2014) (see Section 3.5 for a more complete discussion of what the concept entails): (1) self-location, which consists in feeling as if being inside the virtual body; (2) body ownership, which refers to the notion that the virtual body is the source of behaviour; and (3) the illusion of agency, which describes having wilful motor control over the virtual body.

As described by Slater and Sanchez-Vives (2014), experiencing a sense of embodiment is dependent on three conditions: (1) visual-proprioceptive correspondence between the virtual and real bodies of agents, (2) experiencing the virtual environment from a first-person perspective, and (3) the synchronous replication of movement.

The experiences used in this research involve the use of head-mounted displays. Resultingly, their surrounding stereoscopic 3D view of the virtual environments fulfil the need for a first-person perspective to evoke the feeling of self-location. Although neither of the VR experiences provide a full body representation for agents to embody, arguably, the illusion of being self-located can be achieved regardless, as agents do not need to have a constant view of their own body.

An exception to the above is the agents' hands which are constantly in the line of sight. Labster, for instance, provides agents with virtual hands that perform all the tasks, whilst HoloLAB Champions replaces them with a visual of controllers (see Figure 5.5). Despite both iVR systems integrating some form of visual representation, the way they can elicit self-location, hand ownership, and agency is restricted by the capabilities of the hardware.

As described in Section 4.2.4, the HMD used with Labster does not integrate a positional tracking system. Resultingly, the virtual hands cannot replicate the agents' hand movements or show visual-proprioceptive correspondence. Comparatively, the HMD used with HoloLAB Champions involves a tracking system capable of replicating the agents' hands and body movements synchronously, which can contribute to evoking the illusion of self-location and ownership.

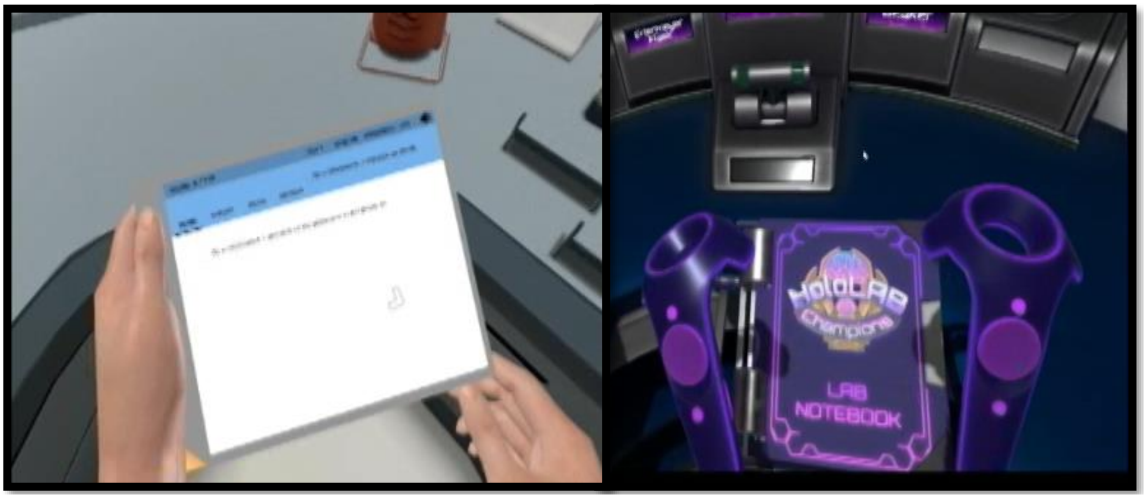


Figure 5.5. Screen capture illustrating the sense of embodiment in Labster (2018) and HoloLAB Champions (Schell Games, 2018).

Lastly, regarding the illusion of agency (see Section 3.5.3 for a more complete discussion of what the concept entails), it was observed during the pilot studies in this research that regardless of the actual amount of control given to participants over the VE, they reported a stronger illusion of having control in situations where their active involvement with the tasks had a more physical nature. This included walking, picking up things, being able to combine elements, rearranging the workspace, and performing the tasks at their own pace and in their preferred order.

Interestingly, although Labster requires agents to have an active role in the execution of the experiments, this is the environment in which participants in the pilot studies reported a diminished feeling of agency. As it is discussed in Section 8.2.2, this could be attributed to the limited range of movement afforded by the remote controller and the deficient visual-proprioceptive correspondence that results from the replication of only rotational hand movements. Additionally, Labster employs a guidance system that keeps the agent on a pre-defined path and prevents agents from making mistakes. This is done by preventing the execution of actions and making objects manipulable only when needed. For instance, a pipette cannot be picked up if the current task requires the use of a microplate. This eliminates the potential for exploration and suggests that agency can only be experienced through triggering actions and making choices such as selecting the correct pipette or setting the values for a measurement.

Comparatively, HoloLAB Champions does not only require agents to actively engage with the virtual environment to perform experiments, with the support for a full range of motion and the use of controllers that detect touch and pressure, interactions can also be performed directly rather than distally, and they involve physical activity such as approaching objects, manipulating them, and adjusting their body posture for a better viewpoint. Furthermore, the less restrictive design allowed for exploration and experimentation which can account for the increased feeling of agency that participants reported during the pilot studies.

5.2.3 **Movement.**

The third and last category of affordances of immersive virtual reality HMDs concerns movement. This is defined by the pervasiveness of embodied interaction in the virtual environment, which could include locomotion, body posture, and gesture.

In the case of locomotion, only HoloLAB Champions can support it physically as the experience is presented through an HMD with rotational and positional tracking capabilities. Unlike Labster, which was designed to be experienced whilst seated or standing in a fixed position and in which locomotion is performed by teleportation, HoloLAB Champions allows agents to move and walk freely within a pre-defined space. However, due to the layout of the workspace which wraps around agents, it is never necessary to take more than a step or two in any given direction. Nevertheless, supporting the kind of positional movement that allows locomotion to take place, also enables agents to perform changes in posture and to directly interact with objects by moving their arms and hands, which can have direct implications for perception and eliciting the illusion of agency and presence.

Figure 5.6 illustrates how body posture enables more natural forms of engagement with the environment. In the image, the participant is seen taking a step back and bending down to have a closer look at a beaker. As shown on the left image, the perspective shift resulting from the change in the agent’s posture allows him to observe the meniscus and appraise whether he poured the right volume of the chemical substance.

Although Labster does not support positional movement due to hardware limitations, its support for rotational movement allows agents to look around from a fixed position. This constitutes a change in perspective, albeit constrained in comparison to what is possible with HoloLAB Champions, and it does not imply a change in posture.

Figure 5.6*. Locomotion in HoloLAB Champions (Schell Games, 2018).

Similarly, this applies to the remote controller which can detect rotational movements of the wrist to select objects to interact. Labster compensates for this limitation in two ways, the virtual hands can extend beyond the position of the body to perform a task distally, thus creating a temporary proprioceptive disconnection, or objects can be brought closer to agents and positioned at an angle that would not require changes in posture. For instance, when picking up a pipette, the virtual hand holds it vertically and farther away if the next step is to add a tip, whereas it is held at an angle and closer to the agents' eyes if it is required to set a measuring value.

Lastly, concerning gesture. Although Labster does not support the performance of physical gestures by agents, the virtual hands perform the movements that are associated with the manipulation of laboratory equipment. Comparatively, HoloLAB Champions requires that agents perform tasks physically and directly either with one or both hands. Rather than being symbolic, the gestures that agents carry out in this experience involve natural hand movements required for the manipulation of objects such as a grabbing motion when picking up glassware, pinching with two fingers to use scoops to measure powdered substances, and a shaking motion to combine substances in a flask, all of which is enabled by the controllers.

iVR systems that use controllers, typically require that these be held at all times and that buttons be pressed to initiate a task. However, the controllers used in this study have sensors that detect touch and pressure from individual fingers, thus allowing for the kinds of gestures described above to be performed. In that sense, grabbing a virtual object is done by grabbing the controller, and dropping an object requires releasing the controller. As this would require letting go, the controllers incorporate a strap mechanism that keeps them securely attached to the agent's hands, thus preventing them from falling when the hands are fully open and eliminating the need for them to be continuously held (see Figure 5.7).

Figure 5.7*. Screen capture illustrating the use of the Valve Index controllers in HoloLAB Champions (Schell Games, 2018).

Based on the discussion above, it is evident that gestural interaction in immersive virtual environments comprises two dimensions, the physical movement or gesture, and the visual simulation that reproduces such movement in the virtual environment. This constitutes an interrelationship that is instantiated through the congruency of a movement or gesture.

5.3 Gestural congruency.

As discussed in Section 3.3, gestural interfaces often require hand movements to be mediated by technology like touchscreens, cameras, or controllers. These types of peripherals read the physical gestures and interpret their meaning so that the system can perform the behaviour assigned to them. Moreover, they allow for the replication of the gestures through visual representations such as virtual hands and enable touch and haptic feedback. In that sense, the virtual environment is experienced through tools that become an extension of the body. This is a notion defined as the materiality of an interface by Xambó (2015).

Due to the capabilities and limitations of different iVR systems, physical hand movements cannot always be synchronously replicated. In that sense, agents could perform movements that are not simulated by the virtual hands, or the virtual hands could perform movements that agents have not physically executed. This constitutes a visual-proprioceptive disconnect resulting from the lack of gestural congruency.

In the context of learning environments, congruency is understood as the resemblance between the physical gesture and the conceptual or procedural content to be learnt (Segal, 2011; Black et al., 2012). Applied to immersive virtual reality, it was observed during the pilot studies that congruency designates two conditions: (1) the synchronous reproduction of the physical gesture through a visual representation in the VE, and (2) the way in which such physical gesture maps to the learned domain.

The first form of gestural congruency can be observed in Labster as the hardware is not capable of tracking the agent's positional movements. In this case, the system addresses that limitation by assuming and simulating movements in the VE through the employment of virtual hands. Figure 5.8 shows the participant pointing towards the top section of a pipette with the controller and pressing on the trackpad to select one of the arrows. This action triggers a simulation where the thumb on the virtual hand executes a flicking motion to turn the dial on the pipette and set the amount to be measured.

Figure 5.8*. Illustration of embodied congruency of gestures in Labster (2018).

Whilst the gentle movement of the participant's wrist to align the pointer is not congruent with the simulated action of the hand/fingers rotating the plunger of the pipette, the simulated action is congruent with the procedural content concerning how a pipette is operated. In that sense, although there cannot be congruency between the physical and virtual movements, there can be congruency between the virtual gesture and the content.

The second form of gestural congruency can be observed in HoloLAB Champions. Figure 5.9 shows a participant shaking the controller in his right hand. Although there is no visual representation of his hands in the VE, the shape, magnitude, and directionality of the gesture can be observed through the synchronous shaking of the flask. The movement of the flask and the substance inside it match the swirling motion of the participant’s hand, and these are congruently mapped to the content concerning mixing substances. This constitutes what Johnson (1987) defines as an image schema.

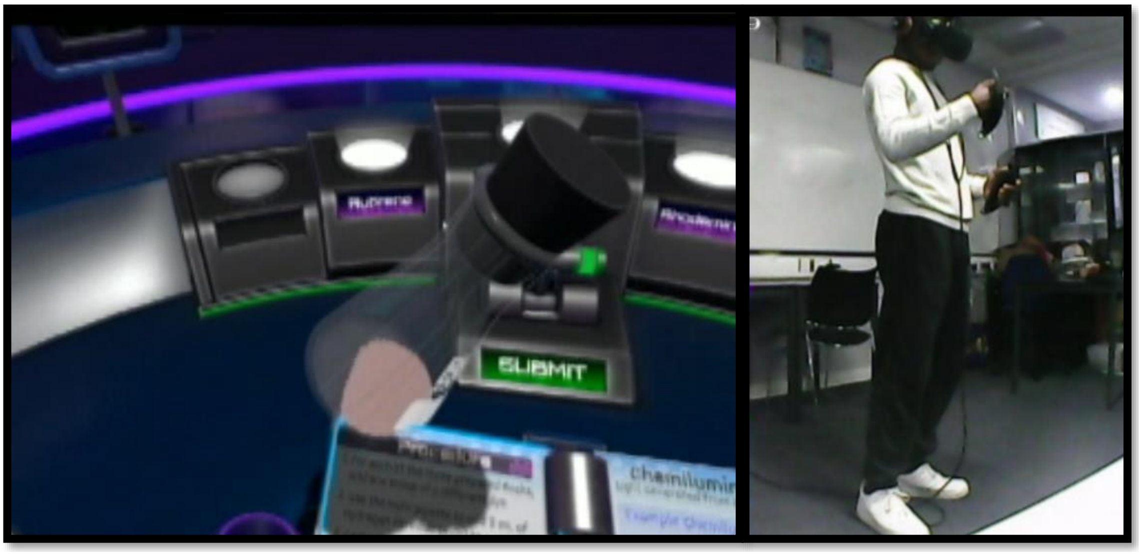


Figure 5.9*. Illustration of embodied congruency of gestures in HoloLAB Champions (Schell Games, 2018).

As discussed in Section 3.3, image schemata consist of representations of sensory-motor interactions that structure understanding (Johnson, 1987). In that sense, they can provide a framework for the assessment of the congruency of gesture.

Different authors recognise different types of image schemata (Johnson, 1987; Hampe, 2005). Hurtienne and Israel (2007), for instance, list over fifty types that could be used as patterns for tangible user interfaces, thus providing a foundation for the assessment of congruency between the visual gestural representation and the content to be learnt. Taking some of those schemata as a basis, Table 5.3 and Table 5.4 classify the different gestural movements that the virtual environments used in this research. These include posture, locomotion, and gesture.

Table 5.3. Mapping of gestural interactions in Labster.

Gestural interactions in Labster													
Spatial relation	**Gestural movement**	**Groups:** Measuring	Weighing	Pouring	Shaking / Mixing	Moving / Placing	Lifting / lowering	Pushing / Pulling	Changing viewpoint	Organising	Reaching	Navigating	**Examples of enactment**
		Image schemata per group: (Draw) up / down (level)	Add / remove	In / Out	Side / round / up / down	Left / right / front / back	Up / down	Forward / backward	Turn / tilt / bend	Pick up / move / drop	Forward / high / low	Rotate / Walk / Teleport	
Proximal	Button pressing	✓				✓		✓			✓	✓	*Setting measurements on the micropipette. *Drawing and releasing substances. *Picking up and dropping laboratory equipment. *Summoning the tablet. *Operating the centrifuge and computer.
	Pointing and clicking	✓				✓		✓			✓	✓	
	Tapping and dragging	N/A											
	Grasping and moving	N/A											
	Twisting, tilting								✓				*Looking around to identify instruments and do experiments or in reaction when the virtual assistant speaks. *Hand twist to direct the pointer.

Immediate	Leaning	N/A											
Immediate	Bending	N/A											
Immediate	Throwing	N/A											
Distal	Walking (steps)	N/A											
Distal	Teleporting											✓	*Moving between workstations (done through point and click gestures).
Distal	Distant manipulation							✓			✓		*Bringing objects closer such as the BHL model in the laboratory (done through point and click gestures).

Table 5.4. Mapping of gestural interactions in HoloLAB Champions.

Gestural interactions in HoloLAB Champions													
Spatial relation	Gestural movement	Groups											Examples of enactment
		Measuring	Weighing	Pouring	Shaking / Mixing	Moving / Placing	Lifting / lowering	Pushing / Pulling	Changing viewpoint	Organising	Reaching	Navigating	
		Image schemata per group											
		(Draw) up / down (level)	Add / remove	In / Out	Side / round / up / down	Left / right / front / back	Up / down	Forward / backward	Turn / tilt / bend	Pick up / move / drop	Forward / high / low	Rotate / Walk / Teleport	
Proximal	Button pressing	N/A											
Proximal	Pointing and clicking	N/A											
Proximal	Tapping and dragging	✓											*Drawing and releasing a substance with the pipette by tapping on touchpad.

	Grasping and moving	✓	✓	✓	✓	✓	✓	✓	✓	✓			*Holding laboratory equipment to move it in any direction or perform a task. *Operating submission lever. *Turning manipulatives to see them from different angles.
	Twisting, tilting	✓	✓	✓	✓								*Any action involving the rotational movement of the head or hands.
Immediate	Leaning					✓		✓	✓	✓	✓		*Reaching the respawn handle or areas in the back of the workstation such as the submission pedestals.
	Bending								✓		✓		*Change of body posture to pick up laboratory equipment from the floor. *Change of posture to change viewpoint.
	Throwing							✓					*Parabolic movement of the arm to fling laboratory equipment.
Distal	Walking (steps)					✓			✓	✓	✓	✓	*Any task requiring taking steps from one side of the workbench to the other.
	Teleporting	N/A											
	Distant manipulation	N/A											

The gestural movements listed in both tables are organised according to their spatial relation from the agent. That is, whether they are performed in close proximity to the body (proximal), they require changing postures or extending the arms as if reaching out for something (immediate), or they take place away from the body or require locomotion / teleportation (distal). Each of those gestural movements is then mapped to one or more of the eleven groups of image schemata. For example, in Labster, a tilting or twisting gesture is mapped to the image schemata for tilting, bending, and turning in the changing viewpoint group, whereas the same gesture is mapped to the measuring, weighing, pouring, and shaking / mixing groups in HoloLAB Champions.

The mapping presented in the tables above provides a basis for the assessment of the congruency between gestural movements and conceptual and procedural content in the virtual environments. As such, it conforms part of the framework for the analysis of conversational gestures in Chapter 9.

Chapter summary

This chapter looked at three questions guiding the exploratory work that preceded the main empirical study. The following is a summary of the main findings corresponding to each question:

- What are the features of immersive virtual reality technology?

These are organised into two groups attending to the mode of representation they support: (1) audio-visual features include computing and graphical processing, as well as properties of the screen such as size, type, shape, refresh rate, resolution, and field of view; and (2) kinetic, tactile-kinaesthetic features involve the tracking system, input devices employed, the types of interaction these enable, support for locomotion, and the type of setup for the experiences.

- What sensory-motor affordances can the features of an iVR system enable?

Based on the analysis of current iVR HMDs and a review of the literature, three affordances have been identified: (1) the sense of presence, which includes eliciting the illusion of being in a place and that what is happening is plausible; (2) the sense of embodiment, which involves experiencing self-location, owning the virtual body, and the illusion of control or agency over it; and (3) movement, which comprises locomotion, changes in body posture, and interaction through gesture, all of which are enabled by the degree of embodiment of an iVR system (not to be confused with the sense of embodiment which is a perceptual state).

The first two affordances, the sense of presence (see Section 3.4.1) and the sense of embodiment (see Section 3.5), constitute perceptual states that can be achieved from the moment agents put on the headset. Due to the surrounding nature of iVR technology, visual and auditory stimuli envelop users making them believe that the virtual environment is a new reality in which they find themselves. Although these illusions can be temporarily lost, it was found that agents employ assimilation mechanisms to re-establish the perception of this new reality (see Section 7.2). The last group of affordances, however, are defined in this research as the degree of embodiment of an iVR system (see Section 3.2.1 and Section 10.2.7). This term should not be confused with the sense of embodiment. The degree of embodiment of an iVR system constitutes an objective property of the hardware and entails the level of support for bodily forms of engagement. This can include whether walking is possible, or if agents can move their hands or use their fingers. Due to the inextricable integration of hardware and software, the notion of embodiment also includes how those properties translate into forms of interaction or are simulated in the virtual environment such as the use of hand gestures, the replication of movements by the embodied avatar, changes in viewpoint through body posture, and mechanisms for locomotion.

- How can embodied interactions be congruently mapped to conceptual and procedural content in an educational virtual environment?

A framework is proposed mapping the congruency between gestural movements and image schemata when interfacing with immersive virtual environments. Whilst such movements describe gestures and changes in posture that agents can perform, image schemata constitute abstract representations of sensory-motor engagement with the world that structure experience.

Chapter 6: Comparing learning gains between study conditions

Chapter overview

This chapter addresses the first research question explored in the empirical study, namely how does participants' learning about science differ between low- and high-end immersive virtual reality systems as evidenced by test scores, interviews, and observations?

This chapter analyses pre-, post-, and delayed test scores to measure learning gains in the school interventions. Data stems from the low- and high-end iVR conditions (i.e., Labster and HoloLAB Champions, respectively) and it is compared across study groups (i.e., within-subject, and between-groups). Findings from quantitative data are further complemented with qualitative data stemming from interviews and observations.

Three testing points were carried out as part of the main empirical study. These aimed to assess conceptual and procedural understandings about chemistry with which participants engaged during the school interventions. Although each intervention used a separate iVR experience (i.e., HoloLAB Champions and Labster), there were aspects that both shared, thus allowing to draw comparisons regarding the variables of study (see Table 4.1):

- Virtual environments. Both conditions required participants to carry out experiments in virtual chemistry laboratories.
- Thematic content: Although the environments had dissimilar goals which were driven by the topic of each experience, virtual environments revolved around creating and manipulating chemical substances.
- Conceptual knowledge. The activities in both environments involved participants learning about chemical reactions, choosing the appropriate instruments to measure substances, and the notion of scaling measurements.
- Procedural knowledge. The tasks that participants were required to do in both experiences involved the appropriate handling and use of laboratory equipment like pipettes, and the procedures to measure substances more precisely.
- Degree of agency. Within the limitations in interaction mechanics and support for movement, both environments afforded participants a high level of agency and control over virtual objects.
- Pedagogies. Despite differences in freedom of exploration, both environments follow a constructivist approach and introduce content and tasks progressively to scaffold learning.
- Viewpoint. Both virtual environments position the participants in a first-person perspective with full control of the viewpoint.

A mode detailed account of the similarities and differences between the iVR experiences used during interventions can be found in Section 4.2.4 and a descriptive matrix of each virtual laboratory can be found in Appendices B.2 and B.3 which detail affordances, educational aims and outcomes, as well as the type of content they present and how gestural interactions are mapped to them.

The pre-test had the purpose of acting as the baseline from which learning gains could be measured. The post-test, which was administered immediately after every session, had the purpose of measuring learning gains. Lastly, the delayed test, which was administered online at an average of 43 days[23] after the last intervention, had the aim of looking at how well participants were able to retain new procedural and conceptual knowledge (see Section 4.3.1 for an in-depth overview of the testing approach followed and how tests were designed for each intervention).

In the low-end iVR condition, tests focused on learning how to choose the correct pipette and tips, how to set the correct amount to be measured, and the appropriate pipetting technique when performing a Bradford Assay (see Appendix C.3). Comparatively, in the high-end iVR condition, tests focused on how well participants understood concepts such as mass, volume, units of measurement, how to read a meniscus, the identification of laboratory equipment, and its use (see Appendix C.4).

As detailed in Section 4.3.1, some participants were given form A of the battery of tests in each condition (N = 21), whilst others were given form B (N = 20). Table 6.1 shows the final random allocation of each type of test per study condition. It is important to note that this table shows data points reflecting the number of participations and not the number of participants. Although 27 secondary school students participated in the study, those who took part in the group following a within-subject design contributed with double the amount of data to the study as a result of receiving both interventions. This amounted to 41 data points as reported in Table 6.1.

Table 6.1. Distribution of test forms.

Virtual environment	Study condition	Number of participations according to test form		
		Pre/Post-test A	Pre/Post-test B	Delayed test
Labster	Low-end iVR	10	9	19
HoloLAB Champions	High-end iVR	11	11	22
			Total	41

[23] This was obtained by determining the exact number of days elapsed from each participant's last intervention to the moment they took the delayed test (N = 41). The number of Elapsed days ranged from 7 to 89 (M = 42.5, SD = 22.5).

6.1 Comparing findings from pre-, post-, and delayed tests in the low-end and high-end iVR conditions across experimental groups.

This section looks at results from statistical analysis comparing mean test scores (pre-, post-, and delayed tests) from participants in the two study conditions (low- and high-end iVR), across experimental groups (within-subject design and between-groups design). First, experimental groups were looked at to determine whether mean test scores differed between them, thus suggesting that participating in one or both interventions could have an effect in measured learning. This particularly concerns test scores from participants in the group following a within-subject design as they received both interventions (Labster and HoloLAB Champions) (see Section 4.2.4 and Table 4.5 for an overview of the underlying goals, assumptions, and affordances of each virtual environment).

Descriptive statistics (see Table 6.2) show increases in mean test scores from pre-test to post-test in both study conditions (low- and high-end iVR), across experimental groups (within-subject and between-groups). On the other hand, increases in mean test scores from post-test to delayed test were observed in all, but one case, the low-end iVR condition following the between-groups design where the mean score decreased from 69.9 to 63.20. This could suggest that participants in this combination of experimental group and study condition were only able to retain new knowledge in the short term. It is important to note, however, that splitting the cohort to analyse this subgroup brings the number of participations down to 5. As a result, this decrease in test scores could be explained by two factors: (1) the small number of data points in the subsample; and (2) the number of elapsed days between post-test and delayed test, which was corroborated with a significant Spearman's correlation test, r_s (5) = .900, p = .037. It must be noted, however, that when looking at the full cohort regardless of experimental group, mean test scores increase across the board. This suggests that the observed decrease does not make a significant impact in the overall study.

As observed in Table 6.2, not only did test scores increased from pre-test to post-test, and from post-test to delayed test, but generally, test scores seem more elevated in the high-end iVR condition than the low-end iVR condition. This is suggestive of the former intervention being more successful at supporting participants' learning, thus bringing about increased learning gains over time. Furthermore, these results are consistent with those observed in the presence questionnaire, which could be indicative of a correlation between participant's reported sense of presence and their test scores (see Section 7.1).

Table 6.2. Descriptive statistics from study conditions across experimental groups.

Descriptive statistics of test scores in low- and high-end iVR conditions across experimental groups							
Independent variable	**Experimental groups**	**M (SD)**		**Mean differences**		**N**	
		Low-end iVR	**High-end iVR**	**Low-end iVR**	**High-end iVR**	**Low-end iVR**	**High-end iVR**
Pre-test scores	Within-subject design	61.14 (20.78)	74.14 (23.99)	**13.72**	8.86	14	14
	Between-groups design	45.60 (25.24)	40.87 (23.32)	**24**	2.75	5	8
	Full cohort	**57.05 (22.42)**	**62.05 (28.39)**	**16.42**	**6.64**	**19**	**22**
Post-test scores	Within-subject design	74.86 (23.66)	83.00 (19.24)	4.14	2.93	14	14
	Between-groups design	**69.60** (24.10)	71.25 (23.47)	-6.4	10.63	5	8
	Full cohort	**73.47 (23.22)**	**78.73 (21.13)**	**1.38**	**5.72**	**19**	**22**
Delayed test scores	Within-subjects design	79.00 (10.86)	85.93 (12.50)	**17.86**	**11.79**	14	14
	Between-groups design	**63.20** (12.70)	83.25 (19.18)	**17.6**	**13.38**	5	8
	Full cohort	**74.84 (13.12)**	**84.95 (14.87)**	**17.79**	**12.36**	**19**	**22**

Another observation regarding the above, is that irrespective of study condition, participants allocated to the group following a within-subject design obtained higher test scores in subsequent testing points (post- and delayed test) than those allocated to the group following a between-groups design. This could have happened because participants who only took part in a single intervention and who had no previous experience with an iVR system may have found this experience more challenging, thus impacting their performance as they had to split their attention between the content and making sense of how the VE operated as suggested by Participant 27:

> […] Sometimes I had trouble with the mechanics... where you have to hold, keep your hand out sometimes, and I'm so used to have... having... I knew this is a video game, I'm so used to pressing a button, that's why when I grab something, I always press the trigger button because I'm so used to holding that one. (P27-HiVR)

In that way, having to figure out the interaction mechanics of the virtual environments could have reduced the attention that participants paid to the educational content. Comparatively, by taking part in two interventions, participants in the group following a within-subject design had the first intervention to learn interaction mechanics and gain confidence. As a result, when they took part in the second intervention, they potentially had a clearer idea of what to expect regarding the virtual environment and all the components of the session such as the tests and interview. That way, participants would be less likely to feel nervous or anxious by the presence of the researcher or for taking part in the study the second time.

Additionally, although the session started with a very brief tutorial regarding the use of the hardware and how to navigate the VE, this was not comprehensive due to time constrains. Resultingly, participants in the low-end iVR condition may have experienced a steeper learning curve regarding the navigation of the VE. This could happen because they had to split their attention between learning how to use the guiding system (i.e., the virtual tablet), and learning how to use the controller to navigate and interact with manipulatives, all whilst adjusting to the limitations of a space that only supported 3DoF of movement as suggested by Participant 15:

> When I couldn't workout with like... getting the liquid into the micro dish, I kept on just like reaching out and clicking towards it or just like reaching towards it thinking something was going to happen because I... I was like, I didn't know what to do. Or like with the tablet, I kept looking down and reaching it and I would be like, oh no! I have to click it because I could always see the corner of it a bit, then I'd always go to… right go and grab it up. (P15-LiVR)

To explore these observations further, two repeated measures ANOVA tests were performed comparing the effect of the experimental groups on test scores. Results show a statistically significant difference in mean test scores in both the low-end iVR condition, $F(2, 34) = 7.02$, $p = .003$, as well as the high-end iVR condition, $F(2, 40) = 25.36$, $p < .001$.[24] This is indicative that the higher test scores observed in the within-subject group compared to the between-groups group could be explained by participants acquiring new knowledge in the first intervention which helped them improve their performance in the second intervention.

[24] Several tests were performed to verify the assumptions for the repeated measures analysis of variance (ANOVA) (see Appendix C.6). Results indicate that data in only two of the twelve subsamples stemming from both study conditions do not follow a normal distribution. Furthermore, the assumption of sphericity has not been violated in any of them. Resultingly, it was decided to carry on with repeated measures ANOVAs as this type of test is robust enough for results not to be affected by the minor violations of normality given that the remaining assumptions have been met.

Post hoc pairwise comparisons[25] using the Bonferroni adjustment reveal that mean test score differences between pre-test (57.05) and post-test (73.47) in the low-end iVR condition are significant ($p = .023$). This is similarly observed between mean scores differences in the pre-test (57.05) and delayed-test (74.84, $p = .003$). However, there are no significant mean score differences between post-test (43.47) and delayed test (74.84, $p = .999$). Similar findings were revealed in the high-end iVR condition where mean test score differences between pre-test (62.05) and post-test (78.73) are significant ($p = .005$), as well as those between pre-test (62.05) and delayed test (84.95, $p = .001$). However, mean scores between post-test (78.73) and delayed test are not significant ($p = .219$).

Having considered all the findings discussed above, taking the pre-test as a baseline from which to measure learning gains in the post- and delayed tests could be problematic under three scenarios: (1) if participating in one intervention had an effect on the second intervention among participants in the within-subject group; (2) if the content of the pre-test for HoloLAB Champions was easier for students to know empirically compared to that in the pre-test for Labster; and (3) in the case of familiarity with the concepts and procedures if these had previously been covered in school, particularly among participants in years 10, 12, and 13 who were overrepresented in the cohort (see Table 7.1).

Although the points above could have acted as confounders and results cannot be fully unconfounded, ANCOVA tests have been performed to control for the pre-test in each condition as a covariate. All assumptions for the ANCOVA tests have been met and the tests have been performed without between-subjects factors. That is, the data were not split by experimental group (between-groups design or within-subject design), and it was analysed as a full dataset. Results for the low-end iVR condition, $F(1, 17) = .782$, $p = .389$, indicate that differences between post- and delayed test mean scores are not significant (see Table 6.2 for descriptive statistics), which corroborates previously reported pairwise comparisons. This demonstrates that even when controlling for the pre-test as a possible confounder, the observed increases in measured learning are still not statistically significant (see Figure 6.1). In contrast, results for the high-end iVR condition, $F(1, 20) = 5.660$, $p = .027$, indicate that differences in mean scores between post- and delayed test are significant when controlling for

[25] It is important to note that unlike the ANOVA test, these pairwise comparisons were performed without splitting the dataset by experimental group. Using the full dataset allowed to increase the number of data points in the low-end iVR condition (N = 19) and high-end iVR condition (N = 22).

pre-test as a confounder, thus suggesting that at least in this condition: (1) the baseline measurement set by the pre-test was influenced by previously knowledge; (2) observed learning gains are statistically significant (see Figure 6.1); and (3) such learning gains were maintained after several weeks.

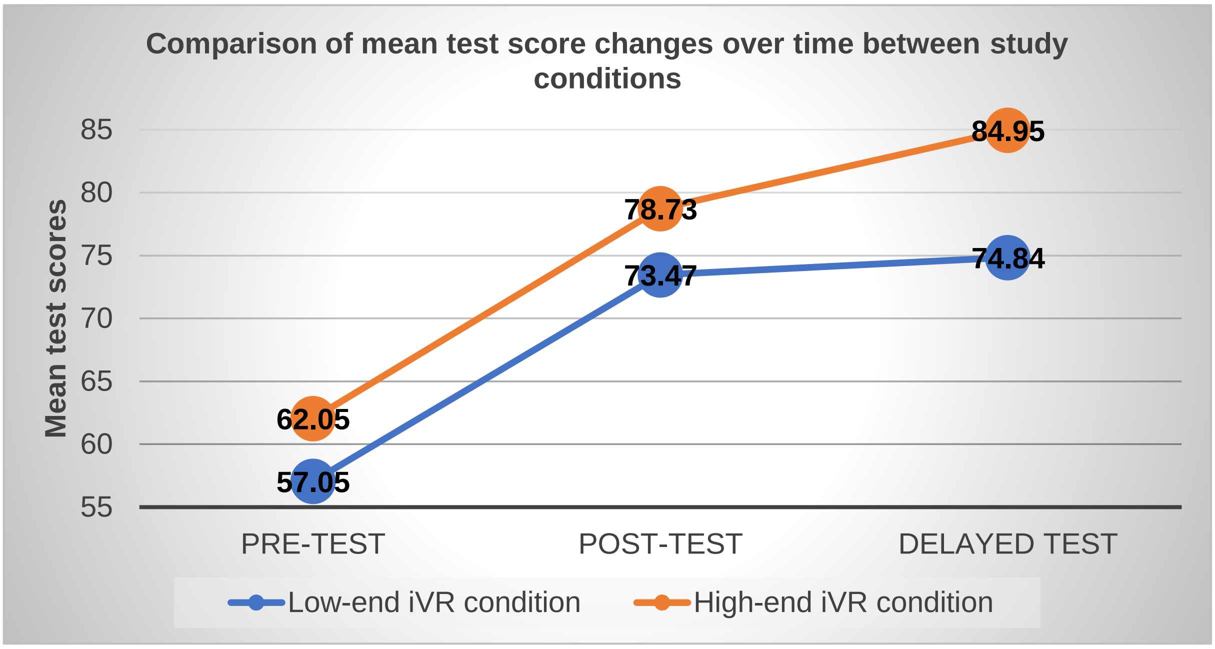


Figure 6.1. Mean test score changes over time in the study condition across experimental groups.

6.2 Exploring relationships with gender, year of schooling and number of elapsed days for the delayed test

In the case of Labster in the low-end iVR condition, results from Pearson's correlation tests show that pre-test mean scores, $W(19) = 958$, $p = .533$, have no significant correlation with gender $r(19) = .147$, $p = .547$, or year of schooling, $r(19) = .331$, $p = .166$. Similarly, results from the delayed-test, $W(22) = .972$, $p = .819$, show no significant correlation with gender, $r(19) = .284$, $p = .238$, or with the number of elapsed days between the last intervention and the delayed testing point, $W(19) = 899$, $p = .046$, $r_s(19) = .111$, $p = .650$. However, there is a strong positive correlation between delayed test mean scores and year of schooling, $r(19) = .678$, $p = .001$ (see Figure 6.2). Lastly, results from Spearman's correlation tests[26] show that post-test mean scores, $W(19) = .888$, $p = .029$, have no significant correlations with gender, $r_s(19) = .029$, $p = .905$, or year of schooling, $r_s(19) = .281$, $p = .249$.

[26] Spearman's correlation test is a non-parametric test used when data are not normally distributed.

Whilst the positive correlation between delayed test scores and year of schooling suggests that participants in later years were able to recall new knowledge 43 days later compared to the rest of the cohort, this is not an unexpected finding considering that earlier years are under- or not represented in the sample (see Figure 6.2). Alternatively, these results could indicate that content in Labster may have been too complex for younger participants.

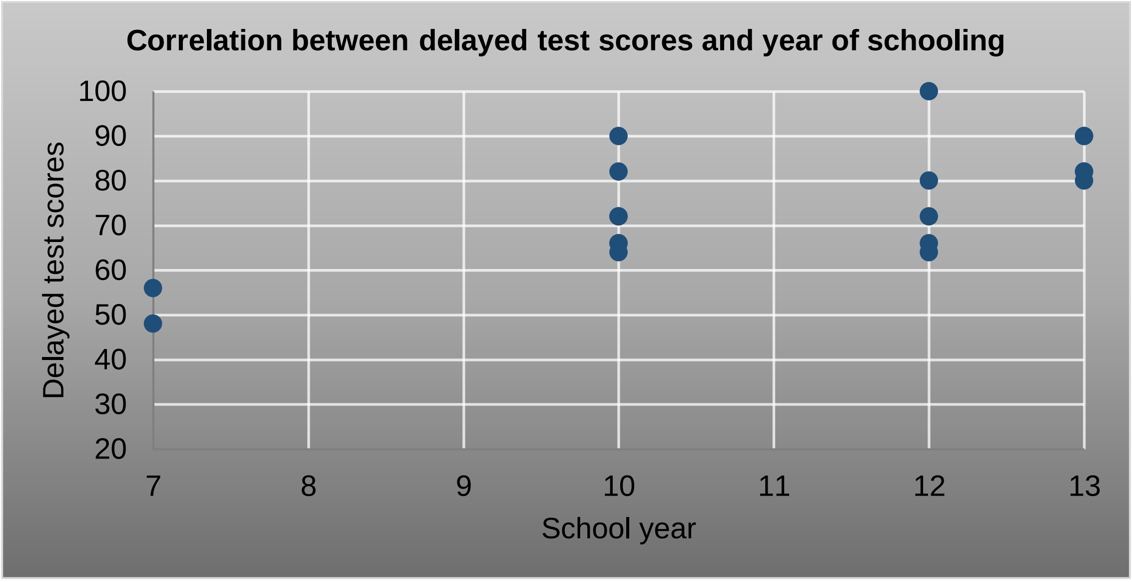


Figure 6.2. Scatter plot showing the correlation between delayed-test mean scores and year of schooling for Labster in the low-end iVR condition.

Concerning HoloLAB Champions in the high-end iVR condition, results from Spearman's correlation tests show that there is no significant correlation between pre-test mean scores, $W(22) = .911$, $p = .050$, and gender $r_s(22) = .007$, $p = .975$. However, there is a strong positive correlation with year of schooling, $r_s(22) = .710$, $p < .001$ (see Figure 6.3).

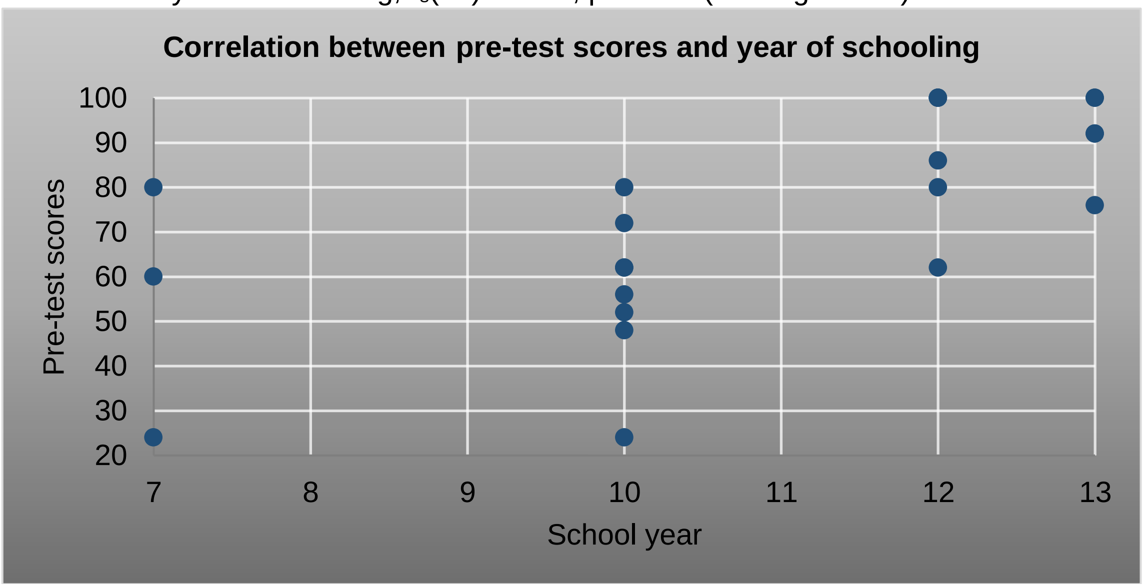


Figure 6.3. Scatter plot showing the correlation between pre-test mean scores and year of schooling for the high-end iVR condition.

Similar to previous findings, the above indicates that participants in higher years of schooling obtained better test scores compared to those in earlier years. However, participants from years 7-9 were also under- or not represented in the sample (see Figure 6.3). Moreover, as these data stem from pre-tests, it is likely that participants in later years were already familiar with the content.

Results from Spearman's correlation tests show a weak, non-significant, negative correlation between post-test mean scores, $W(22) = .848$, $p = .003$, and gender, $r_s(22) = -.110$, $p = .624$, and a strong positive correlation with year of schooling, $r_s(22) = .775$, $p < .001$ (see Figure 6.4). Similar to previous findings, this could be explained by participants in later years being familiar with the content and by the composition of the sample being mostly from years 10, 12, and 13. Lastly, results from Pearson's correlation test show no correlation between delayed test mean scores, $W(22) = .917$, $p = .065$, and gender, $r(22) = .068$, $p = .763$, or with the number of elapsed days between the last intervention and the delayed test, $r(22) = .201$, $p = .371$. However, as with the pre- and post-test mean scores, there is a strong positive correlation with year of schooling, $r(22) = .704$, $p < .001$ (see Figure 6.5) which can be explained by the same factors (i.e., base knowledge and representation in the sample).

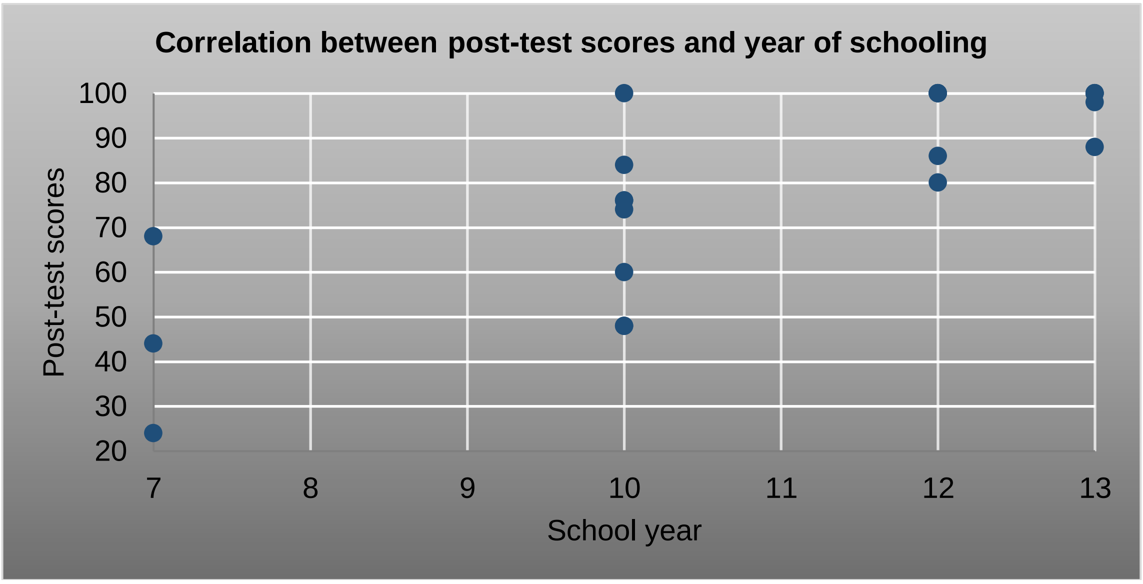


Figure 6.4. Scatter plot showing the correlation between post-test mean scores and year of schooling for the high-end iVR condition.

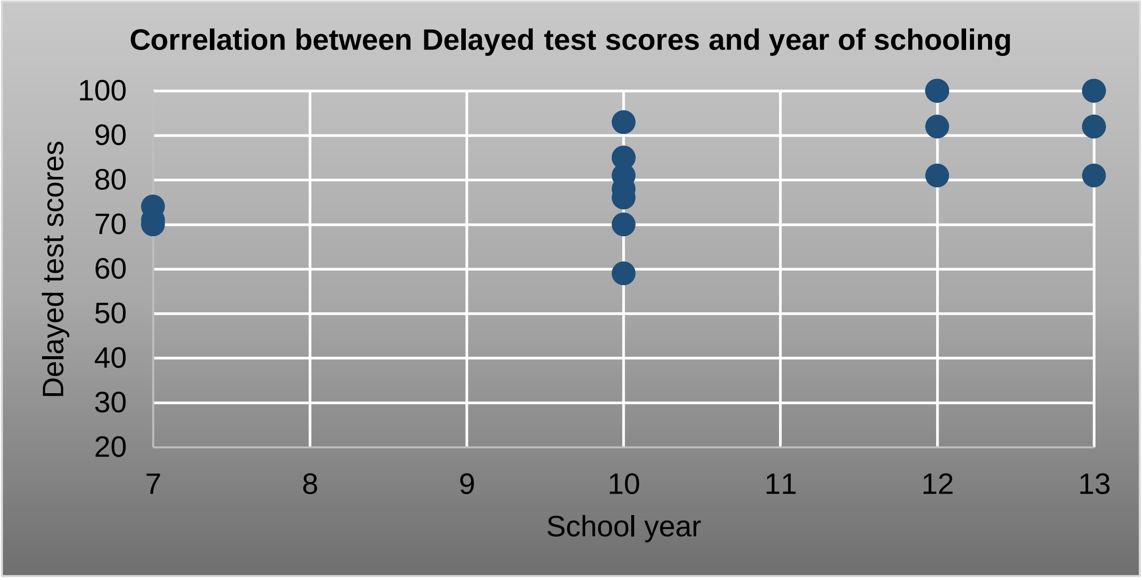


Figure 6.5. Scatter plot showing the correlation between delayed mean test scores and year of schooling for the high-end iVR condition.

6.3 Learning through immersive virtual reality environments.

During interviews, participants touched on different ways in which they made sense of the virtual environments and how they understood the content that was presented as part of the experiments. These discussions highlighted how certain affordances of the two types of iVR systems could support learning.

6.3.1 Learning by doing.

As discussed in Section 5.2, the iVR systems afforded participants forms of engagement with the VE that not only required active participation, but in the case of the high-end iVR system, also direct physical engagement[27]. This was instantiated in the participants' body language when they described the tasks they performed during experiments. Figure 6.6 illustrates participant 10 describing a portion of the experiment involving measuring a powdered substance. His gestural movement not only resembles the way he was holding the controller, but it also reflects his spatial position in the VE and replicates the directionality of the motion by twisting the wrist inwards demonstrating how he used the scoop.

[27] Time on task was kept at 40 minutes for both interventions. However, due to the experiences being self-paced, not every participant reached the end.

The above is congruent with previous findings that this type of direct manipulation or direct interaction allowed participants to successfully generate an observed anatomical structure (Jang et al., 2017). The study by Jang et al. (2017) was particularly focused on comparing the performance of medical students with different spatial abilities which were assessed using the Mental Rotation Test (MRT) by Vandenberg and Kuse (1978), and the Building Memory Test of spatial ability (BMT) developed by Ekstrom et al. (1976). As reported by Jang et al. (2017), results indicate that participants with low spatial abilities seemed to benefit the most from the direct manipulation of objects in the virtual environment. Although this research did not look at spatial abilities, the differences in gesturing observed across participants in the study like Participant 10 highlight a potential line for further enquiry in the field.

Figure 6.6. Composite image showing gestural congruency across recordings of body language during interview, the visual of the VE, and the physical performance.

After describing the task, Participant 10 reflected on the reason for his gestures. His explanation not only signals how he is mimicking the actions as he remembers them, but he points out how he probably would not be gesturing if he had not performed the task himself:

> Because my hands are remembering what they did and it's connecting to what I'm saying as well, but if it was like, if I just watched it or read it or something, I would not be able to do that as well because it's not like I'm remembering what I'm doing. (P10-HiVR)

This quote denotes the way Participant 10 grounded the notion of measuring through gesture. As shown in Figure 6.6, his gestures encapsulate kinetic tactile-kinaesthetic affordances of the iVR system. These affordances are instantiated in three ways: (1) spatial awareness through the positioning of the participant's body and hands which matched his actions during the intervention; (2) procedural understanding of a task as it demonstrates picking up a scoop, drawing the substance from a beaker, and moving over the substance to new glassware; and (3) the physical act of holding an invisible scoop as if mediated by the controller, thus denoting the perception of touch. This highlights the underlying notion explored in this research concerning the role of the body in shaping conceptual and procedural understandings which is looked at in more depth in Chapter 9. In that sense, Participant 10's gestures here instantiate an embodied cognitive process (see Section 3.2.1). However, the degree to which his body can be used is limited by the affordances of the system as all forms of interaction and movement are mediated by technology in virtual reality environments.

Similar to the previous example, Participant 15 below discusses the significance of physical engagement during the experiments and learning from doing rather than watching:

> […] it's all just the way you learn, doing things yourself because watching it, you got a rough idea, but you don't do it yourself, so you don't put it into muscle memory for... it's just hard to understand it when you're only watching it, whereas when I was doing it myself, I could sort of like work things out as I went along and I sort of understood more what was happening […] because when we first, like in year 7 when we first start using pipettes and stuff, I would like squeeze it too much, […] or like pouring beakers, I'd always go way too far because I was so used to pouring like cups of tea and stuff which are so much heavier, whereas now when I'm in the science lab, I know that things will be like this, I wouldn't have to pour as much […] (P15-HiVR)

Participant 15 argues here that by physically performing the tasks, she can "work things out as I went along," which refers to experimentation and trial and error. In that sense, this reflects how the high-end iVR system allowed participants to make mistakes and perform experiments at their own pace, both of which are discussed in the following sections.

6.3.2 Risks and consequences of behaviour.

Another emerging theme during interviews was the simulation of risks despite the absence of real consequences. Virtual reality can allow students to learn about the importance of observing security measures and following protocols in the laboratory whilst safely experiencing the consequences of not observing them. As pointed out by Participant 12, the virtual environment is "[…] less dangerous as well because you never know if you can break something in a lab, whereas this one [HoloLAB Champions], even if you break it, it's not real" (P12-HiVR). Furthermore, as suggested by Participant 10, by simulating risky behaviour and their consequences, the VE contributed to creating a sense of agency and making students feel responsible for what happened in it:

> It was similar with the kind of risk that was there. Like if I let go of something it would fall, it wasn't like someone was holding it for me, so the risks... the hazards were not as real, but you could feel the things vibrating and fall on the floor, it just felt like the risk was there... I don't know how to describe it... It felt... it had vibrations, so it felt like I was doing it in real life. (P10-HiVR)

This sense of responsibility suggests that participants not only owned the failures in the progression of the experiments, but also their successes. Furthermore, this suggests that by simulating risks and consequences, it can be possible to promote learning through exploration and trial and error which, as indicated by Participant 10, would take away the anxiety and potential for harm or destruction of a physical laboratory:

> […] usually in an experiment I don't like taking part, I like watching from afar because I feel like I can make mistakes, but with this, it makes you like room to make mistakes and you can start again without having caused any destruction. (P10-HiVR)

6.3.3 Making mistakes and scaffolding learning.

The virtual laboratories used in this study were structured around small tasks that built from one another. That is, they were designed to progressively increase in complexity to scaffold learning. In the case of HoloLAB Champions, the virtual environment supported free exploration, albeit with some guidance that was not too intrusive. This made trial and error a key component of learning in the virtual laboratory and "[…] if you make mistakes, then you can improve from that. You know what you did wrong, instead of just watching it" (P18-HiVR). By providing a space for more open exploration, testing, and discovery, the VE allowed participants the opportunity to build a better understanding of the aspects that led to mistakes and how better to solve them. As argued by Participant 13, this could be central to learning:

> […] I personally think you don't learn as much if you aren't allowed to make mistakes. And like I said, the first couple of levels, I made mistakes and I learned from them, learnt what I did wrong and fixed it, in a video, you're watching it and you go, OK I need to do that, if you do something wrong, you're like... what did I do wrong? but like that, it told me what I did wrong. If you spilt or got the wrong amount of liquid, you have to take the beaker down to re-measure [...] (P13-HiVR)

Making mistakes in HoloLAB Champions did not only impede progression and provided control for the achievement of the aims of the VR experience, and promoted problem-based learning, as students had to find a solution to their mistakes. This is not something that is widely implemented or encouraged in science practicals in schools, mainly due to the risks that the improper use of certain substances can pose. However, as this intervention demonstrated, iVR technology can provide a safe space for such a strategy to be used.

Labster, on the other hand, did not encourage exploration, and trial and error were not part of its design. These simply took place as the result of participants attempting to do something that was not permitted such as picking up the wrong pipette, drawing the wrong substance, or operating instrumentation that was not necessary for the current task.

> Well, I couldn't do the wrong thing, it wouldn't allow me... basically it wouldn't allow me like if... let's say I didn't replace the tip, it wouldn't allow me to actually put something in with the contamination wise, I had to do it properly, it wouldn't let me not do it wrong. […] It did tell me that... oh you're doing a mistake, but that kind of does help and not because instead of going all the way to the end and finding out you made a mistake, it kind of wastes time, but it then, it also shows you how you shouldn't really make it. It's more impactful towards the end. (P08-LiVR)

As pointed out by Participant 08, the guidance system in Labster would signal a mistake, but it would not allow them to perform the action, nor would it simulate the consequences of such action. Whilst this kept the focus of the experience on the outcome of the experiment and provided a more carefully scaffolded learning environment, it also stripped away the possibility for students to understand why they made a mistake, figure out the correct procedure, and get a better understanding of the experiment.

Although both virtual laboratories employed scaffolded learning techniques to present their content, the approaches were different. Labster presented students with a laboratory desk filled with equipment and guided them step by step on how to perform a pipetting procedure progressively using that equipment. Later, they were asked to repeat the same process without guidance to finish a serial dilution. HoloLAB Champions, on the other hand, asked students to engage in repetition drills performing simple individual tasks such as measuring, transferring, weighing, mixing, or scaling substances. With each task, the equipment on the workbench changed to only accommodate what was needed and the laboratory techniques that were practiced were later applied by students in a more complex experiment.

> Oh, this is interesting because... it's cool, we get all the equipment at once, whereas here [HoloLAB Champions] step by step they will cheer for you and then after... you have to press the submit lever, you wouldn't get that in real life, would you? In real life you have to get all the equipment gathered at once and then follow everything step by step, that's what we do in like biology, chemistry, physics practicals, we get all the equipment and then like do what we have to do, like all the instructions step by step, whereas this one, they would give you a little bit of equipment and they will tell you like 3 steps, as you press the submit lever, they'll cheer for you, have a few jokes and then they'll put more equipment, and then more equipment, and then more steps. (P14-HiVR)

Participant 14 touches on the potential of the technology to support learning differently from traditional school practicals where the number of tasks to be performed and equipment to be used could be overwhelming. This is particularly important when students are not properly guided in the conduction of experiments, nor given the opportunity to develop procedural skills that they can apply on their own. Although HoloLAB Champions included a guidance system, this was more passive as it would not tell students what to do at every step. Guidance was provided in a book with instructions for the procedure, diagrams illustrating how to use laboratory equipment, and theory about the substances being used.

6.3.4 **Collaboration.**

Finally, another important point raised in the interviews is the potential for collaborative work which neither of the virtual laboratories supported. Interestingly, it was not a feature that was requested or even wished by some participants in the study. When asked whether they would have preferred to do the activities with another person, they drew comparisons to their school practicals where often they did not get to do the experiments themselves because they had to split the tasks with the rest of their peers as described by Participant 21:

> Um no because then you get to do everything, you do every step so it's cool. If you work with someone, one person would be doing like one step, you do the next step, so you miss parts out, but this way, you're doing it fully. And you kind of have someone because they're talking in your ear, but not literally working. (P21-LiVR)

One of the defining features of immersive virtual reality is the isolation the headset and headphones create from external visual and auditory stimuli which has two implications. On the one hand, such isolation prevents users from maintaining communication or doing collaborative work with people who are not wearing a headset. On the other hand, it helps in guiding students' perception toward the experience's aims by blocking external factors that could impact their attention.

As pointed out by Johnson-Glenberg (2017) there is a need for a platform in education where students can use HMDs in a collaborative manner, not only in the sense that they can easily access experiences as a community, but a platform that is capable of bringing multiple students into the same virtual environment so they can see each other, communicate with each other, and work together. Although there has been some progress in that regard with platforms like Engage, to a great extent, commercial educational iVR software is rarely designed to support multiple simultaneous users.

Chapter summary

This chapter looked at pre-, post-, and delayed test scores measuring learning gains from participants in the school interventions. Findings were compared between low- and high-end iVR conditions across study groups (i.e., within-subject and between-groups designs). The following is a summary of the main findings in response to the research question guiding this empirical work, namely how does students' learning about science differ between low- and high-end immersive virtual reality systems as evidenced by test scores, interviews, and observations? A detailed discussion of the implications of such findings is presented in Section 10.2.1):

- Results from the statistical analysis indicate increases in mean test scores from pre-test to post-test, and from post-test to delayed test in both study conditions across experimental groups. This suggests that both interventions were successful in supporting learning gains regardless of the mode of delivery.
- Only participants in the low-end iVR condition following the between-groups design saw decreased delayed test mean scores at a level below the post-test. A Spearman's test confirmed that this decrease was correlated to the elapsed time between intervention and delayed test. Whilst this might suggest that students in this condition were more likely to forget the newly acquired knowledge, the small increase in mean delayed test scores observed in the group following the within-subject design, could be interpreted as an indication that the small sample could be at least partially responsible for the effect.
- Results from two repeated measures ANOVA tests indicate a strong statistically significant difference in mean test scores between the low- and high-end iVR conditions across experimental groups. This indicates that participants in the within-subject groups performed better than those following the between-groups design, which could be explained by the sample size difference or some effect in which the first intervention boosted performance in the second, thus bringing overall mean scores higher.
- There is a strong positive correlation between delayed test mean scores and year of schooling. This could be explained by the composition of the sample as there was higher representation from key stages 4 and 5 where students have familiarity with a

wider range of laboratory techniques, thus increasing the likelihood that they were familiar with the content.

- Based on results from post hoc paired samples t-test, significant mean score increases were observed in the low-end iVR condition from pre-test to post-test and from pre-test to delayed test. This suggests that Labster was successful in promoting learning during the intervention, as well as in the retention of that knowledge in a period that ranged from 7 to 89 days (N = 41, M = 42.5, SD = 22.5). Comparatively, results in the high-end iVR condition show significant mean score increases only from pre-test to delayed test. This suggests that although HoloLAB Champions was also successful in bringing about immediate learning gains, knowledge retention 43 days after the last intervention was more significant.
- Data from observations of interviews suggests that support for embodied forms of interaction, such as gestural movements that simulate how objects are manipulated in the real world, provide the opportunity for the development of motor control, spatial awareness, and procedural skills.
- Data from interviews suggests that simulating risky behaviour and its consequences could contribute to the way students experience agency and to their sense of responsibility for their actions and the outcomes of the experiments.
- Data from observations and interviews suggests that designing an environment that implements scaffolding techniques and supports embodied exploration, discovery, problem solving, and making mistakes could allow students to get a clearer understanding of the subject matter and its underlying processes.

Chapter 7: Exploring the experience of presence

Chapter overview

This chapter discusses the first portion of the findings concerning the second research question for the main empirical study, namely in what ways can free movement and embodied interaction impact how participants experience presence, hand ownership, and agency in low- and high-end iVR systems?

The findings discussed in this chapter concern the sense of presence and stem from the immersive virtual reality presence questionnaire (iVRPQ) and the thematic analysis of interview data. Findings concerning the notions of hand ownership and agency are presented in Chapter 8 as these constitute dimensions of the sense of embodiment, a separate affordance of iVR systems.

Slater and Sanchez-Vives (2014) conceptualise the notion of presence as the elicitation of two perceptual dimensions: the illusion of being in a place and the illusion that what is being experienced is plausible or really happening. This suggests that (1) the sense of presence is not only subjective to every individual and how they experience the world through their senses, but that (2) it is also context-dependent.

Being a qualia, the former cannot be directly measured (Slater, 2009). However, the behavioural and perceptual effects of the latter can act as indicators of the elicitation of presence, thus providing a more holistic view of how participants experienced presence in both study conditions. Such indicators were explored through the iVRPQ and during interviews, of which findings are presented in the following sections.

7.1 Comparing experiences of presence as measured by the iVRPQ.

As detailed in Section 4.3.2, one of the methods employed to explore the perception of presence was the immersive virtual reality presence questionnaire (iVRPQ), which consists of 14 items reporting agreement using a Likert scale (see Appendix C.5). Descriptive statistics of a sample comprised of 41 data points indicate that participants in the high-end iVR condition (HoloLAB Champions) experienced higher levels of presence (N = 22, M = 3.95, SD = 0.54) with a minimum usual value of 3.07 and a maximum of 4.71. This contrasts to participants in the low-end iVR condition (Labster) (N = 19, M = 3.18, SD = 0.74) reporting a minimum usual value of 1.57, and a maximum of 3.93. This kind of spread in response values is notable because it is indicative of participants experiencing various degrees of presence, potentially due to external factors temporarily breaking the illusion.

Table 7.1. Representation of participants by year of schooling, age, and gender.

Participants per year of schooling, age, and gender									
School	Year 7 (Key Stage 3) 11-12 years old		Year 10 (Key Stage 4) 14 years old		Year 12 (Key Stage 5) 16-17 years old		Year 13 (Key Stage 5) 17-18 years old		Total participant
	Female	Male	Female	Male	Female	Male	Female	Male	
A			4	4			4	2	14
B					4	4			8
C	2	3							5
	5		8		8		6		27

To complement the descriptive statistics above, the association between presence mean scores and the two study conditions was explored. Results of a Spearman's rho and eta tests[28] show a moderate negative correlation, $r_s(41) = -.47$, $p = .002$, $\eta^2 = .270$. This indicates that participants reported having experienced higher presence in the high-end iVR condition than in the low-end iVR condition (see Figure 7.1).

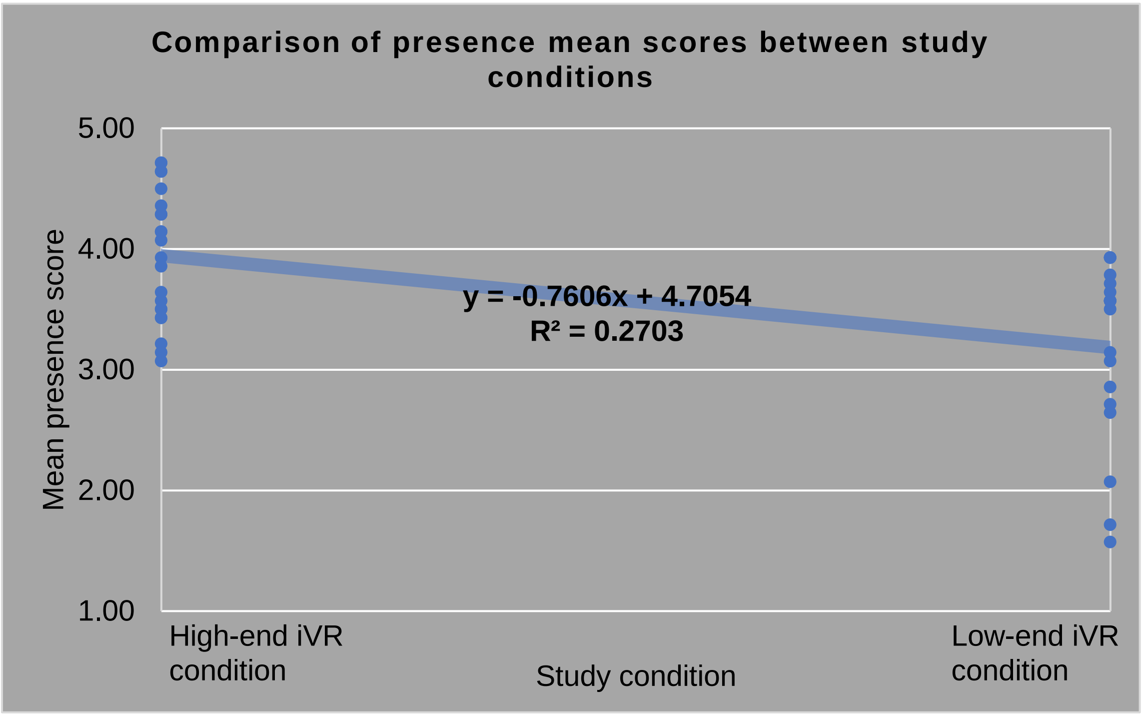


Figure 7.1. Scatterplot comparing presence mean scores between study conditions.

Although presence mean scores in the high-end iVR condition are concentrated in the high tier of the scale, scores in the low-end iVR condition show more spread. This could be indicative of participants being able to maintain a strong sense of presence in the former condition, and such illusion being occasionally broken in the latter, which was also observed with the minimum and maximum values in the descriptive statistics. The mean difference between both conditions is $M = 0.76$ with a proportion of variance of $R^2 = .27$. This suggests that 27% of the variance in the presence mean scores can be explained by the study conditions.

[28] Non-parametric tests have been used here because it was found that the sample does not follow a normal distribution.

Similar to pre-, post-, and delayed test results (see Section 6.2), the association of responses to the iVRPQ were looked at in relation to year of schooling and gender. The distribution of participants can be observed in Table 7.1. The resulting sample is comprised of 14 female participants and 13 male participants, their ages range from 11 to 18 years, and there is representation from years 7, 10, 12 and 13; that is, each of the key stages that comprise secondary school education in the United Kingdom[29].

Spearman's rho and eta value tests were performed to look at potential relationships between presence mean scores and gender. Results show that there is no association between the two in the full dataset, $r_s(41) = .05$, $p = .778$, $\eta^2 < .001$, or only considering cases from the high-end iVR condition, $r_s(22) = .07$, $p = .751$, $\eta^2 = .006$, or the low-end iVR condition, $r_s(19) = -.01$, $p = .969$, $\eta^2 = .016$. This indicates that the illusion of presence was similarly perceived by female and male participants and there are no potential differences in responses according to gender worth exploring in this data.

Participants' perception of presence in the virtual laboratories in relation to year of schooling was also examined. Results of a Spearman's rho test show that there is a non-significant weak association between year of schooling and mean presence scores, both in the full dataset, $r_s(41) = .18$, $p = .269$, and the individual study conditions, high-end iVR condition $r_s(22) = .23$, $p = .309$ and low-end iVR condition $r_s(19) = .24$, $p = .324$. This indicates that the weak associations found may be explained by chance.

In order to compare mean ranks in both study conditions (Low- and High iVR) across experimental groups (within-subject and between-groups designs), Mann-Whitney U tests were performed. In the case of the high-end iVR condition (see Figure 7.3)[30], whilst the median and mean ranks seem to suggest that presence scores are higher in the group following the within-subject design ($N = 14$, $Mdn = 4.04$, Mean rank = 12.61), compared to the group following the between-groups design ($N = 8$, $Mdn = 3.79$, Mean rank = 9.56), $U = 40.5$, $p = .297$, $r = .23$, the p-value indicates that the differences between both groups are not significant.

[29] This does not include Scotland where the levels and structure of the education system are different.
[30] For the tests verifying the assumptions for the Mann-Whitney U test see Section C.5.3.

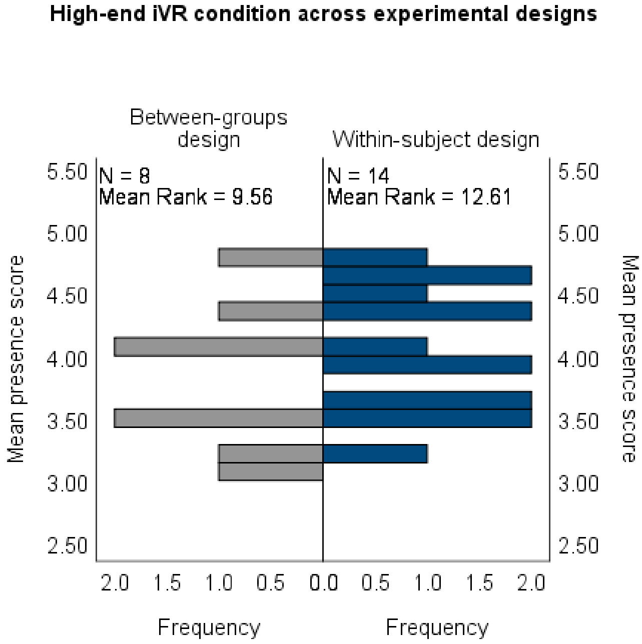


Figure 7.3. Distribution of presence scores for the high-end iVR condition across experimental groups.

Similarly, a Mann-Whitney U test was carried out to analyse the distribution of presence mean ranks in the low-end iVR condition across experimental groups (see Figure 7.2). Results indicate that presence scores are higher in the group following the within-subject design (N = 14, Mdn = 3.57, Mean rank = 9.93), compared to the group following the between-groups design (N = 5, Mdn = 3.50, Mean rank = 10.20), U = 36.0, p = 1.0, r = .021. However, the differences between both groups are small and non-significant.

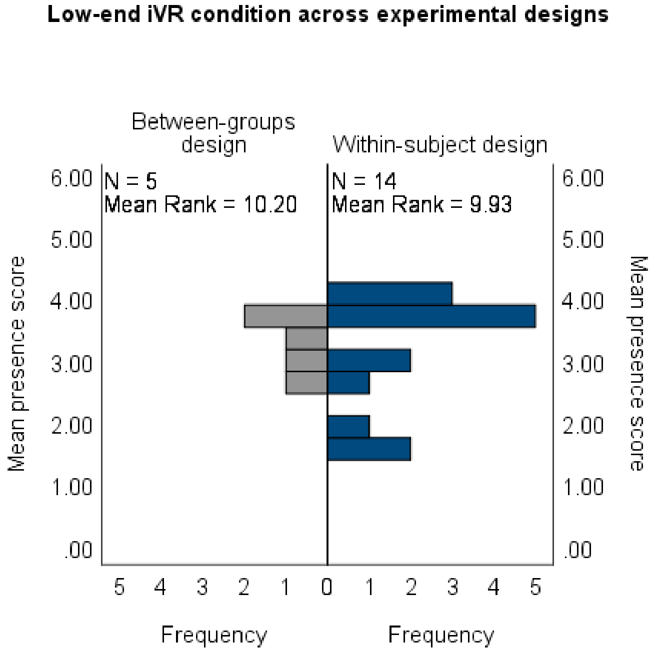


Figure 7.2. Distribution of presence scores for the low-end iVR condition across experimental groups.

Based on the test results for both study conditions above, it is not possible to reject the null hypotheses that the median differences between the experimental groups are similar. This implies that the type of experimental design had no effect on presence scores.

A final aspect explored in relation to presence mean scores was the differences between study conditions across the pathways comprising the experimental groups. Wilcoxon Signed-Rank tests were performed for pathways 1 and 2 which followed a within-subjects design, and a Mann-Whitney U test was performed for pathways 3 and 4 which followed a between-groups design.

When the low-end iVR condition was administered first and the high-end iVR condition second (Pathway 1), participants reported higher presence scores in the latter condition (N = 8, Mdn = 4.43) with 6 positive differences than in the former (N = 8, Mdn = 3.61) with one negative difference, Z = 2.13, p = .033, r = .75 (see Figure 7.4).

Differences in presence mean scores between study conditions in Pathway 1

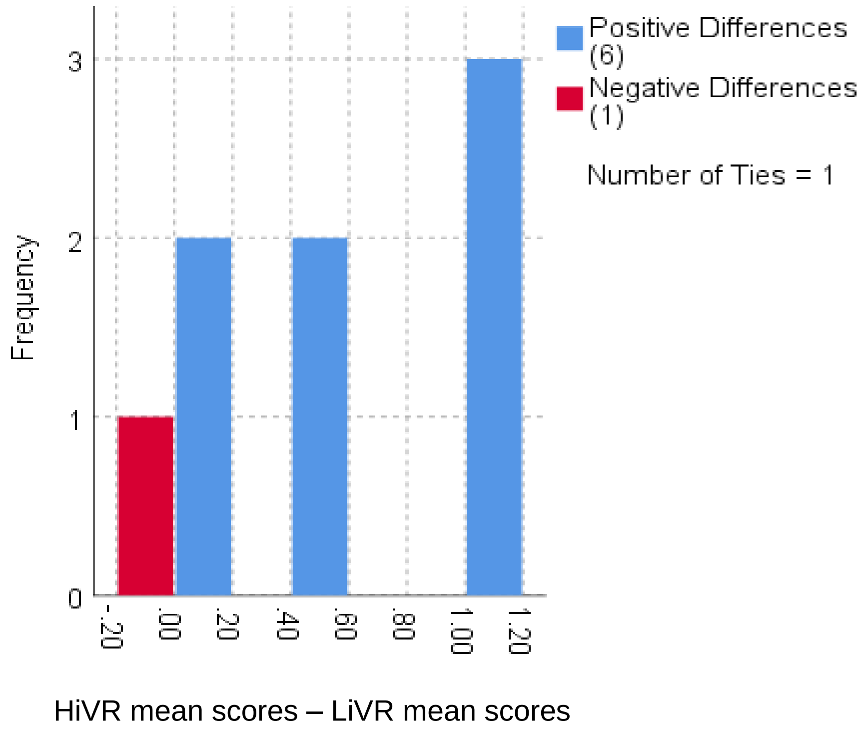


Figure 7.4. Distribution of presence mean scores across study conditions in Pathway 1 (within-subject design).

When the high-end iVR condition was administered first and the low-end iVR condition second (Pathway 2), presence scores were higher in the former condition (N = 6, Mdn = 3.72) with 6 negative differences than in the latter (N = 6, Mdn = 2.39) with zero positive differences, Z = 2.20, p = .028, r = .90 (see Figure 7.5).

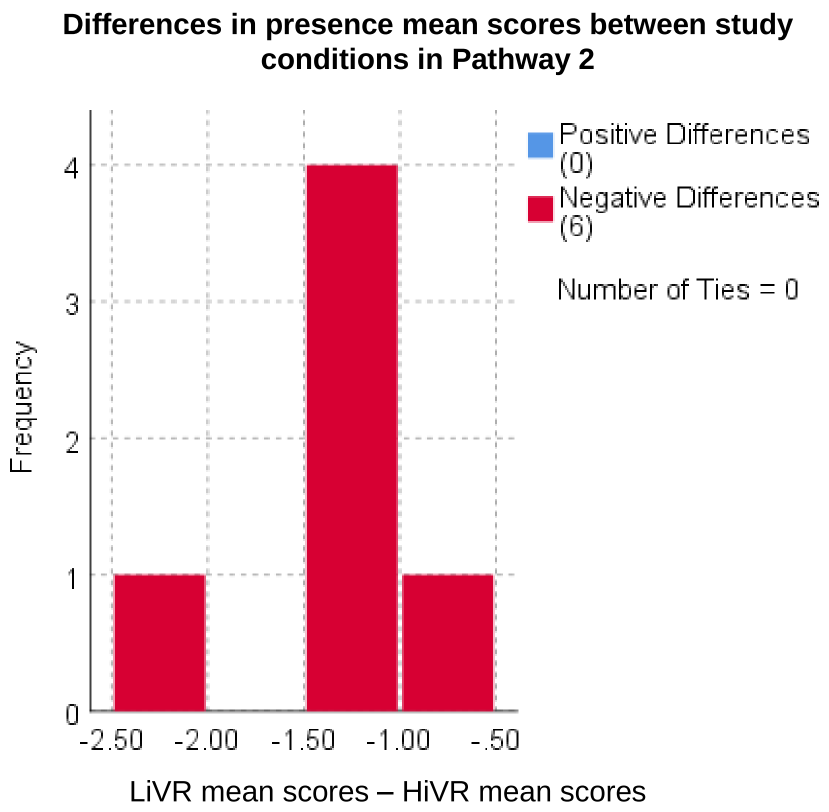


Figure 7.5. Distribution of presence mean scores across study conditions in Pathway 2 (within-subject design).

At a 95% confidence level, the null hypothesis that the median of differences between both interventions is equal to zero can be rejected for both pathways. This is consistent with previous findings (see Figure 7.1) showing that participants reported having experienced higher levels of presence in the high-end iVR condition. Interestingly, this also suggests a potential anchoring effect.

Concerning the distribution of presence scores in the group following a between-groups design, the median and mean ranks in the high-end iVR condition (N = 8, Mdn = 3.79, Mean rank = 8.00) also indicate higher presence scores than those in the low-end iVR condition (N = 5, Mdn = 3.50, Mean rank = 5.40), U = 12.0, p = .284, r = .33 (see Figure 7.6).

Whilst the above differences seem to be considerable, they are not significant. Resultingly, there is not enough evidence to reject the null hypothesis that presence scores are similar which contrasts with the findings from pathways 1 and 2. These differences support the notion that the order of interventions in the group following a within-subjects design had an effect in how presence was perceived by participants, thus suggesting the existence of bias in responses from the presence questionnaire stemming from the second intervention.

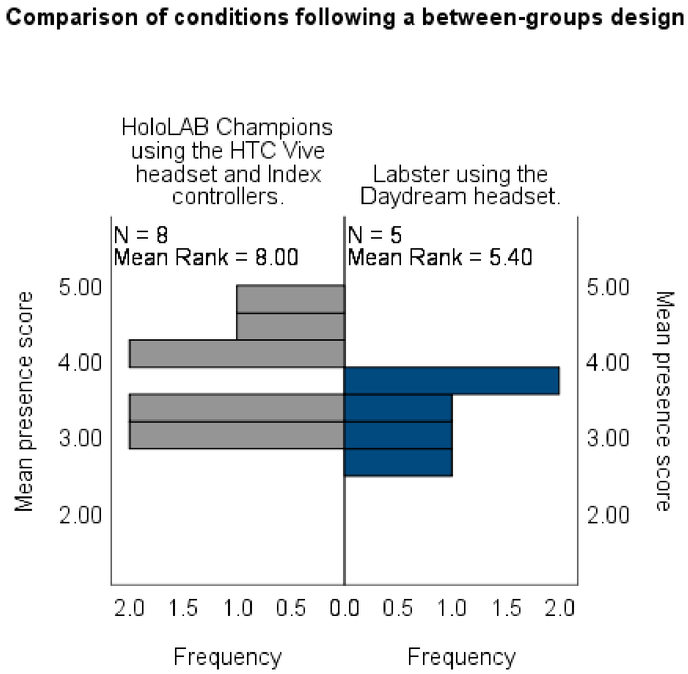


Figure 7.6. Distribution of presence scores across study conditions following a between-groups design.

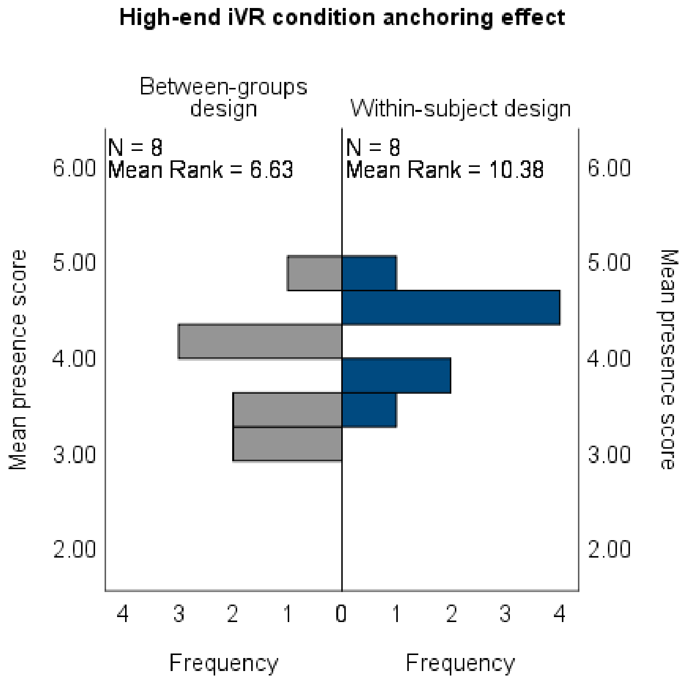


Figure 7.7. Distribution of presence scores for the high-end iVR condition across interventions (excluding responses from condition as a first intervention).

To further test the bias described above, Mann-Whitney U tests were performed. These allowed to compare presence scores between both experimental designs as initial observations in the dataset, particularly of items 1, 5, 6, 7, 8, 10, and 13 in the questionnaire, suggested that responses in the low-end iVR condition were lower when this was administered second (Pathway 2). Inversely, responses from the high-end iVR condition seemed to be higher than average when this intervention took place second (Pathway 1). Results from the high-end iVR condition (see Figure 7.7 above) indicate that there are considerable differences between the two groups: within-subject design (N = 8, Mdn = 4.43, Mean rank = 10.38) and between-groups design (N = 8, Mdn = 3.79, Mean rank = 6.63). However, these differences are not significant due to the small number of data points resulting from creating the subsample for analysis, U = 17.0, p = .130, r = .40.

Comparatively, results from the low-end iVR condition (see Figure 7.8) also show a considerable difference in median and mean ranks between both groups: within-subject design (N = 6, Mdn = 2.39, Mean rank = 4.17) and between-groups design (N = 5, Mdn = 3.50, Mean rank = 8.20). These differences are also not significant, U = 26.0, p = .052 (asymptotic p = .045), r = .61.

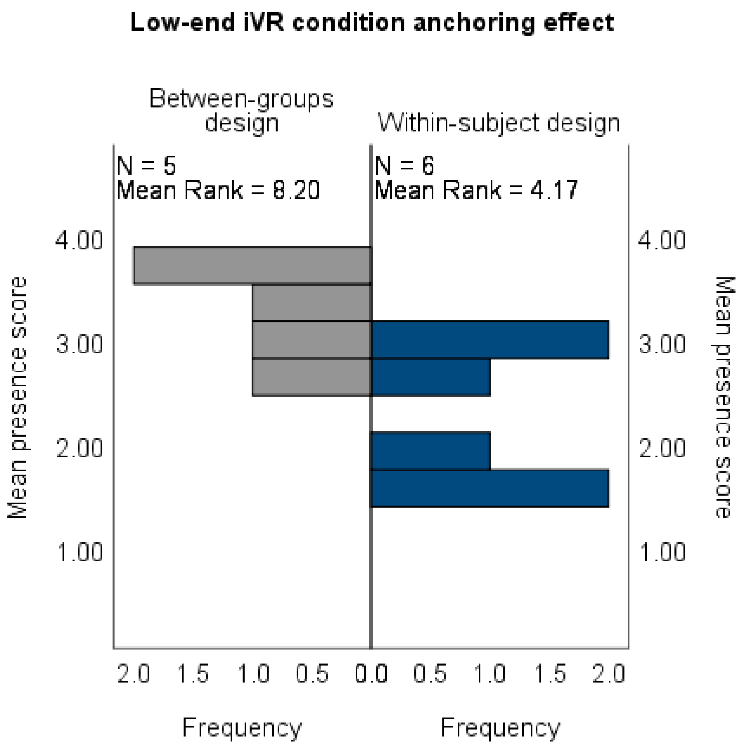


Figure 7.8. Distribution of presence scores for the low-end iVR condition across interventions (excluding responses from condition as a first intervention).

Resultingly, although there is not enough evidence to support the notion that the perception of presence was affected by the order of the interventions, the significant asymptotic p-value in the low-end iVR condition suggests that a larger sample might show different results. This could constitute a potential avenue of enquiry for future work.

The following sections discuss the implications of the findings from each of the items of the iVRPQ. These are presented attending to the themes identified in the interviews.

7.2 Visuo-proprioceptive congruency between the real and the virtual.

Slater and Sanchez-Vives (2014) argued that a sense of presence can be achieved by evoking a feeling of being self-located in a space (i.e., place illusion), and that such space and what happens within it is believable (i.e., plausibility illusion). This conception implies two basic assumptions: (1) the possibility of being perceptually surrounded by a virtual environment, and (2) accepting the rules and conditions of that environment as plausible, thus eliciting appropriate responses from agents.

Concerning the first assumption, by covering the agents' field of view with the virtual environment, it was possible to create some degree of detachment from reality. As reflected by Participant 02's quote, doing this could elicit a perceptual state of self-location in the VE, "It [HoloLAB Champions] felt like I was actually in the game compared to the last one [Labster] […]" (P02-HiVR). However, the fact that both systems involved HMDs and the participant experienced presence differently suggests that other factors had an effect in evoking this perception. Although HMDs commonly achieve this through visual and auditory stimuli, it is hypothesized that touch, proprioception, and support for movement may also play an important role as described by Participant 21:

> [The controllers felt] not fully my hands because obviously it wasn't a hand, but when you're not looking at them and just kind of using them, kind of because you're literally... like to grab something, you have to grab it, so it kind of feels like that, but I wouldn't be...can be like yeah, these are my hands, you know what I mean? (P21-HiVR)

The statement above suggests that Participant 21 had to conciliate conflicting stimuli between what was seen and felt, between virtual and real. As a result, perceived presence had to be adjusted according to the congruency of visuo-proprioceptive stimuli.

Controllers can provide a sense of touch in relation to virtual objects as these allow participants to physically perceive something in their hands. However, they can also create a visual and tactile disconnect in the absence of a visual representation. As argued by Argelaguet et al. (2016) visuo-proprioceptive correlations can influence the illusion of being self-located in the space, and as suggested by Participant 16, it also contributed to the feeling of realness of the VE:

> It was just like… because I was putting my hand out to move things, that gave me like the sense of it being real, but then because I was using the controller, that made me think it's not that real. So, it was kind of like both in a way. (P16-HiVR)

The second assumption for the elicitation of presence consists in participants assuming a perceptual state where sensory-motor stimuli in the VE are prioritized over conscious knowledge. In that sense, participants could feel present or self-located in the virtual environment if it behaved according to expectations of reality. Although such expectations could concern sounds, the look of the space, and how things behaved, as suggested by Participant 06, they were more notable in regard to touch due to incongruent perceptual stimuli:

> […] The only thing that I didn't necessarily liked [sic] feeling was like when I grabbed an object, I was expecting to hold it as if I was actually grabbing it in real life […] (P06-HiVR)

By involving touch through the controllers in the high-end iVR condition, virtual objects could be perceived as physical or tangible. However, as suggested in the quote above, that could bring about incongruencies between visual and proprioceptive stimuli that had the potential of breaking the illusion of presence such as the perception of weight and the shape of such objects.

As suggested by Participant 17, congruency was not limited to visuo-proprioceptive stimuli, other modes could also break the illusion of presence by making more evident the divide between virtual and real, as is the case with external auditory stimuli:

> […] I could hear things outside and that just made me more aware of what I was holding and the actual reality, the real world. And looking at my hand, my virtual hand, I wasn't holding anything, but I could feel that I was holding something... the other one, the other hand with the iPad, it was the same thing, but just the other way around. (P17-LiVR)

Participant 17 highlights the fragility of place illusion as the incongruency of the visual and auditory modes can draw attention to other aspects such as behaviour and the perception of touch. In that sense, feeling the weight and shape of the controllers, but having no visual representation constitutes an incongruency that is comparable to having a virtual representation of the hands holding an object without the physical perception of such object.

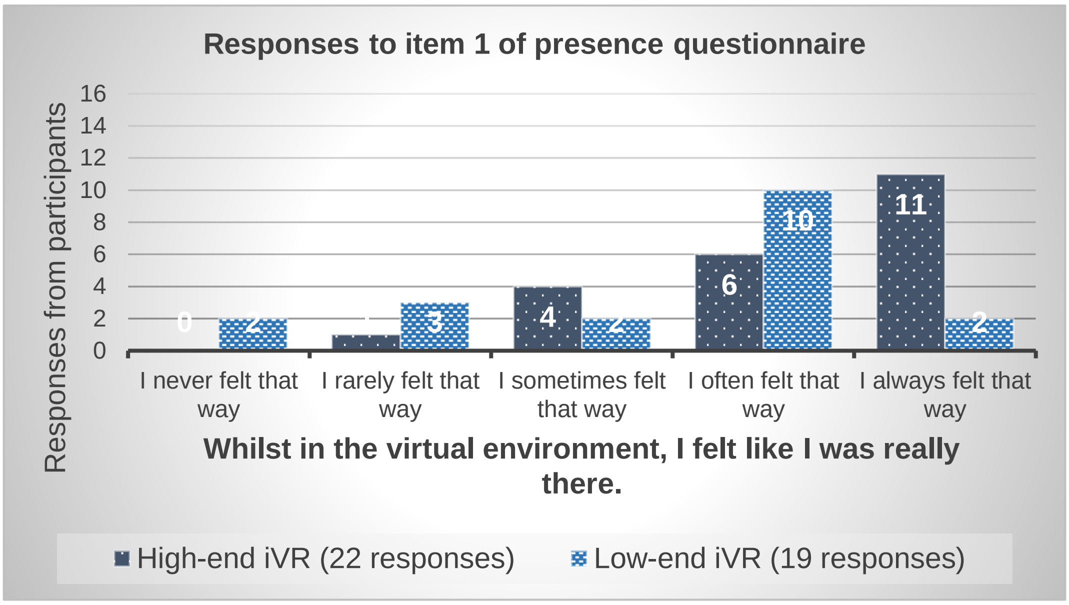


Figure 7.9. Comparison of frequencies for item 1 of the presence questionnaire.

The distinctive ways in which perceptual indicators of presence were experienced by participants were also reflected in the responses to some of the items in the iVRPQ. For instance, results from item 1 enquiring whether participants felt self-located in the virtual environment indicate a higher perception of bodily presence in the high-end iVR condition (M = 4.23) than the low-end iVR condition (M = 3.37) (see Figure 7.9). Contrastingly, results from item 4, which asked whether participants felt like they were not inside the virtual environment, indicate that only sixteen participants in the high-end iVR condition (M = 3.91) and eight in the low-end iVR condition (M = 3.16) “rarely” or “never” felt they were not bodily present in the virtual laboratory (see Figure 7.10).

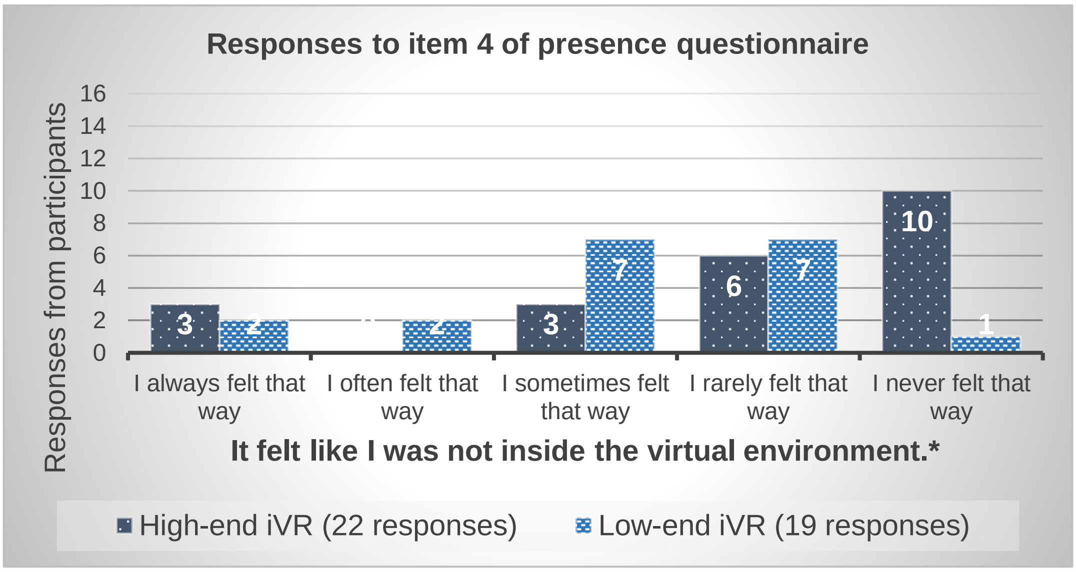


Figure 7.10. Comparison of frequencies for item 4 of the presence questionnaire.

A closer look at the full dataset revealed that seven responses for this item directly contradict participant responses in item 1, which suggests they exhibited response sets. Furthermore, the higher concentration of responses in the middle point of the scale (six responses in item 1 and ten in item 4) indicates there were moments when the illusion of being present was temporarily broken by external stimuli. As described by Participant 04, “[…] the only thing that made me remember that I was in here was the cables on the floor, but that was it, because... yeah, it's immersive” (P04-HiVR).

Another cause of visuo-proprioceptive incongruency stemmed from participants attempting behaviour that was not supported by the iVR system, particularly when it concerned translational movements as explained by Participant 02:

> There's one part where it said to go to the other workstation and I kept looking around trying to find where it was and I started walking for a little bit, but then I remembered. (P02-LiVR)

In this scenario in Labster, Participant 02 encountered visuo-proprioceptive incongruency when their physical movements were not replicated in the virtual space, making it seem like the VE moved with them as if attached to their head. Whilst this could break the perception of being situated in the VE, reverting to a standing position could re-establish it.

The above is congruent with Slater’s (2009) assertion that place illusion is conditional as it “is bound by a particular set of valid actions that support perception and effectual action” (p. 3552). In these cases, Participant 04 and Participant 02 could maintain a feeling of self-location in the VE despite perceiving external stimuli, or not seeing their behaviour being replicated. This suggests that the sense of presence could be re-established either by mending the sensory-motor incongruency that broke the illusion, or by assimilating the new conditions and eventually accepting them as real and plausible within the limits of that virtual environment.

Concerning the latter, as discussed by Participant 17, s/he adjusted his/her expectations of the VE in the high-end iVR condition to the point that the audience of brains, the floating camera, and the holographic commentator in HoloLAB Champions became plausible within that space. This seemed to have happened not because those aspects were congruent with reality, but because they were cohesive with each other and the rest of the virtual environment, “Everything was a bit weird, the people, the audience, but I kind of got used to it later. It matched the environment” (P17-HiVR). In that sense, elements that once stood out and threatened the sense of presence now contribute to it once their plausibility had been established and accepted.

As illustrated by participant 10 and Participant 13, the condition discussed above was not limited to aesthetics, embodied interaction such as the gestural movements in HoloLAB Champions and the point-and-click motion in Labster could also be assimilated:

> The interaction was very realistic, it felt like what I have done in school before. It was a bit hard at first to get used to the holding on tight, to know that you've got it and then letting go to... once you've learnt that it's like second... you just know to do it, you don't have to think about doing it before you do it. (P10-HiVR)
>
> […] the first time, I tried to do it [approaching objects], but from then on, I realised... I took it as a game where you click. My hand, it was like it could only move in there… and there… and there… and there [signalling wrist rotation]. (P13-LiVR)

This is a notion that is consistent with theories of brain plasticity (Kolb and Whishaw, 1998; Gamma, 2021) which suggest that experience could shape brain structures. In that sense, it is suggested that continuous use and mastery of the mechanisms for interaction in both virtual experiences could allow agents to assimilate the incongruent sensory-motor stimuli, thus minimising their impact on the elicitation of the sense of presence.

Another example of the assimilation to the new conditions of the VE can be observed in the interrelationship between hand presence, virtual representations, and visuo-proprioceptive congruency. Results from item 6 in the questionnaire exploring whether participants felt that their hands and/or body were in the virtual environment show a strong difference in responses between conditions. 91% of responses in the high-end iVR group (M = 4.05) indicate participants experienced sometimes, often, or always feeling that their physical body and hands were inside the virtual laboratories. In contrast, only 58% of responses in the low-end iVR condition (M = 2.79) indicate similar agreement (see Figure 7.11).

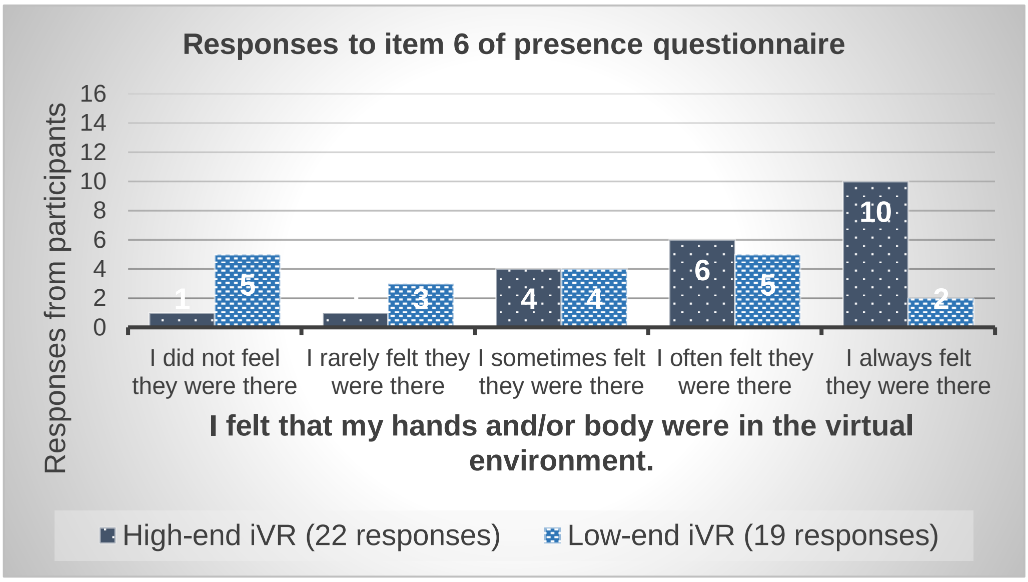


Figure 7.11. Comparison of frequencies for item 6 of the presence questionnaire.

Data from interviews suggests that participants attributed the illusion of hand and body presence to being able to feel and see their hand movements replicated inside the virtual laboratory (visuo-proprioceptive congruency), “you do stuff with your hands; you can pick things up. It felt a bit more real than just using the controller... than just using the pointer” (P02-HiVR). As described by Participant 20, this is particularly evident in the high-end iVR condition where the dual controllers could not only track the position of the participants’ hands, but also the sensors on them allowed for gestural interactions such as grabbing or pinching, thus making the manipulation of objects more natural than pressing buttons.

> Because it just... basically because... it technically is my hand in a way because wherever I moved my hand, my actual hand outside of virtual reality, the move in the virtual reality would move in the same direction, and say I need to grab it, it would still grab the thing, so it felt like my hands. (P20-HiVR)

Interestingly, despite not providing agents with virtual hands, but rather virtual controllers, HoloLAB Champions induced higher hand presence on participants, “[…] I didn't really find myself looking down at it [the controller]. I just... it felt normal to just reach out and grab something” (P18-HiVR). This suggests that congruent embodied interactions and visuo-proprioceptive synchronicity have a more prominent role in creating and sustaining the illusion of hand presence than the realistic visual representation of hands such as that in Labster. This is corroborated by the literature as it has been reported that evoking a stronger sense of bodily awareness is dependent on action, touch, and proprioception (Tsakiris, Prabhu and Haggard, 2006). Furthermore, it is through synchronous visuo-tactile stimulation that a sense of ownership (see Slater, Perez-Marcos, et al., 2009; Perez-Marcos, Sanchez-Vives and Slater, 2012) and agency (see Argelaguet et al., 2016) can be induced more effectively, thus allowing for agents to perceive the virtual controllers as their hands.

7.3 The VE becoming the dominant reality.

Another emerging theme describing how embodied interaction and movement shaped the perception of presence consists in being able to surrender to the perceptuomotor stimuli of the virtual environment despite awareness of an external reality to the VE, “everything was normal like in the real world, but in your head like what's happening is happening” (P26-HiVR).

For some participants this was achieved through visual or auditory cues, as they were the dominant modalities in both interventions, “I had a lot of freedom because I didn't really see reality, so I felt like I had the whole place to myself” (P24-HiVR). Interestingly, it was observed that one indicator of a participant's strong sense of presence was their lack of awareness of some of the sensory-motor contingencies that they experienced:

> Oh, I zoned out. I didn't even once think about my hands or my legs, or anything, I was just standing the whole time. I was more focused in what I was doing and the fact that I was getting this out... it felt like real life. I didn't focus like, you know... I didn't have time to focus on my legs and my hands because I had an instruction to do. So, it didn't really distract me like my legs and my hands are like disconnected, I could do everything normally. (P14-LiVR)

This psychological state corresponds to what was previously described as a perceptual response to the immersiveness of a system. Although immersive systems are not capable of replicating reality to the fullest extent, the aim is to approach a level of resemblance with each of the main modes involved (i.e., visual, auditory, touch) to make stimuli in the VE plausible. In that way, rather than becoming the focus of attention, things like the representation of hands, external sounds, or incongruencies in proprioception could become imperceptible:

> Towards the end I kind of got immersed in it a bit, when I was holding the conical flask, I would hold it towards the top rather than the bottom which is more like a bubble, more in like the slender part on the top, and the beaker. I held it like as if it was a larger object, and with the measuring cylinder, it was like gently as well to get more accurate as I would do in the lab. (P06-HiVR)

The statement from Participant 06 above attests to the plausibility of what was happening in the VE and to the believability of it as a space where the participant felt self-located. This degree of assimilation to the conditions of the experience is better illustrated when behaviour in the VE elicits a physical response from agents as with Participant 24, "[…] if I wanted to grab something that I was afraid that it might spill, I had to move back a bit until I leave a bit of space between me and the beaker, […] I thought it actually might spill on me, so I'd move it back" (P24-HiVR).

It is important to note that Participant 24 was able to physically react to the environment because the system used in the high-end iVR condition afforded such behaviour. Moreover, his/her reaction was the result of awareness that the system could dynamically simulate such outcome. In that sense, the iVR system provided sensory-motor stimuli and forms of engagement, but more importantly, it was capable of responding to input from the participant by simulating appropriate actions such as a substance spilling if a flask was moved abruptly or glassware breaking if knocked over.

Despite knowledge that the VE was computer-generated, it is proposed that the embodied engagement that participants were afforded in the high-end IVR condition, contributed to its believability, thus temporarily allowing it to become the dominant reality as illustrated by participants' reactions such as stepping back so a virtual substance does not spill on them, or moving the hand away when glassware broke.

Some of the items in the iVRPQ enquired about this balance between the conscious and unconscious awareness of stimuli, as well as the experience of having moments when participants found themselves so invested in the virtual environment that it became dominant enough to sustain the illusion of presence.

Item 7 explored whether without trying, the participant was aware of things happening outside of the virtual environment like sounds, the temperature of the room, other people, the headset, controller(s), or cables. Findings from the statistical analysis for this item indicate that participants were rarely or completely unaware of what was happening in the physical environment. This represented 68% of the responses in the high-end iVR condition (M = 3.95) and 47% of the responses in the low-end iVR condition (M = 3.00) (see Figure 7.12).

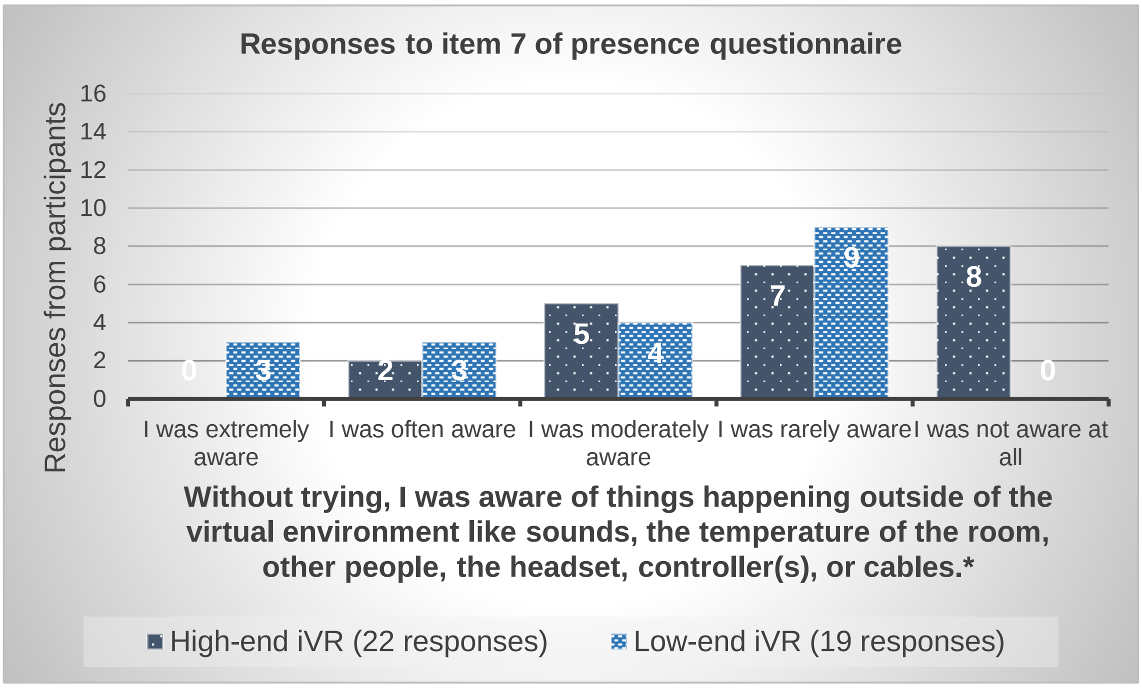


Figure 7.12. Comparison of frequencies for item 7 of the presence questionnaire.

The distribution of responses suggests that, overall, participants experienced a high degree of isolation from reality. While the findings from the high-end iVR condition fall within expectations due to the use of headphones that blocked out outside noise in addition to the visual isolation provided by the headset, responses in the low-end iVR condition deviate from those expectations.

It is particularly notable that nine out of the nineteen responses in the low-end iVR condition indicate that participants were rarely aware of external factors, considering they did not wear headphones. However, this is congruent with the notion discussed earlier regarding how participants could become perceptually absorbed by the sensory-motor stimuli in the VE that external stimuli were blocked out. An example of this is how some participants described their perception of presence in terms of their interactions with the VE and hand ownership, "Not really, not with that one [Labster]. This one [HoloLAB Champions] felt more realistic" (P16-HiVR). "[Labster] felt real, but not that real because […] it's just the click of a button […] I felt like my hand was sort of there but wasn't really there. I felt restricted, get what I'm saying?" (P11-LiVR)

Surrendering to the sensory experience of the virtual environment and, as a result, becoming less aware of what makes it virtual constitutes an indicator of presence (Schubert, Friedmann and Regenbrecht, 2001). However, when the conflicting stimuli stemming from both domains, the virtual and the real, cannot be conciliated or suppressed, the illusion of presence cannot be achieved. For instance, for Participant 01, the visual aesthetic of HoloLAB Champions became the source of the main disconnect from reality:

> Because of the actual game setting, that's when I felt like, I mean obviously, I knew I wasn't there, but I felt like if it was an actual science lab, then I would have thought I was there, but because it was like the actual animations and like the feeling, that's why I didn't feel I was there. (P01-HiVR)

Results from item 8 enquiring whether participants completely or mostly forgot about the real world when they were in the virtual environment. In the high-end iVR condition ($M = 4.05$, $SD = 1.05$), 86% of responses indicate that participants sometimes, often, or always forgot about the physical environment during interventions, compared to 74% in the low-end iVR condition ($M = 2.95$, $SD = 1.18$) who reported the same (see Figure 7.13). Both the high scores and relatively small differences between conditions were expected due to both VR systems being immersive. Results from an independent samples t-test indicate that the differences in mean scores are significant, $t(39) = 3.16$, $p = .003$, $d = 1.11$.

Interestingly, in some cases, awareness of the artificiality of the environment was intentional as agents actively attempted to test the fidelity of the simulation, "I know it sounds kind of sadistic, but I did kind of smashed a glass on purpose to see if it would mirror that, and it did." (P06-HiVR). Whilst this constitutes a conscious attempt at breaking the illusion of presence, it does not guarantee it, as incongruencies only emerge when the system is stressed beyond its capabilities. That is, when an action is performed, but it cannot be simulated by the system such as when attempting to walk or physically approach an object in an environment that does not support positional movements like Labster.

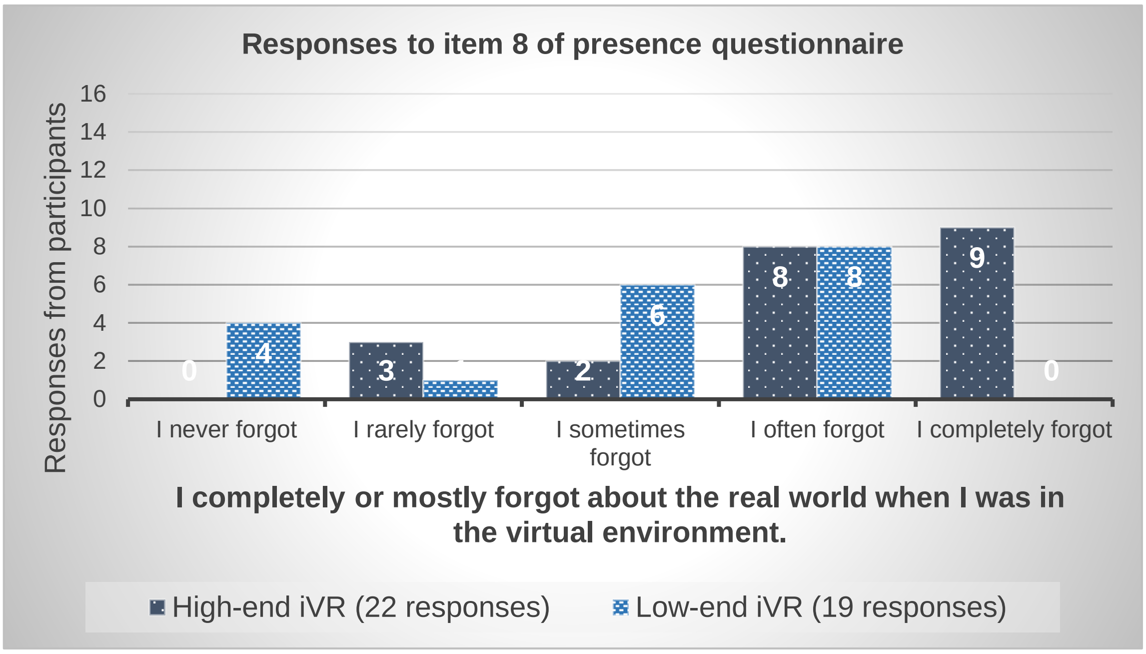


Figure 7.13. Comparison of frequencies for item 8 of the presence questionnaire.

7.4 The VE meeting expectations.

A final theme that was identified concerning the experience of presence consists in how embodied interaction and movement shaped participants' expectations of the VE. For instance, when using laboratory glassware, it is expected to have a certain shape, be graduated, and translucid; when letting go of an object, it is expected to fall and possibly break due to the effect of gravity; or when moving a container with liquid inside, the liquid is expected to shift and possibly spill.

> I think it was great, I think the gravity of it all, so when I tested it out, I got... at the end of one of the practicals, I grabbed a spoon and then chucked it... and the way it throws and like if I wanted to put it down, I could just drop it and it would like drop, of course if it was glass it would break, but even if I wanted to pick it up and I moved it too far that way, this beaker and it spills because it was too fast, so it was very realistic with the movements and the gravity and all. (P13-HiVR)

As described by Participant 13 above, the virtual environment is deemed realistic or believable if there is congruency between expectations of behaviour based on reality and the simulations in the VE. This is what Slater (2009) defines as plausibility illusion, "the illusion that what is apparently happening, is really happening (even though you know for sure that it is not)" (p. 3553).

Some of the items in the iVRPQ looked at participants expectations of the realness of the virtual environment. Responses to item 11, which enquires whether the virtual world looked realistic, indicate agreement on eleven counts in the high-end iVR condition (M = 3.18) in contrast to only four in the low-end iVR condition (M = 2.74) (see Figure 7.14).

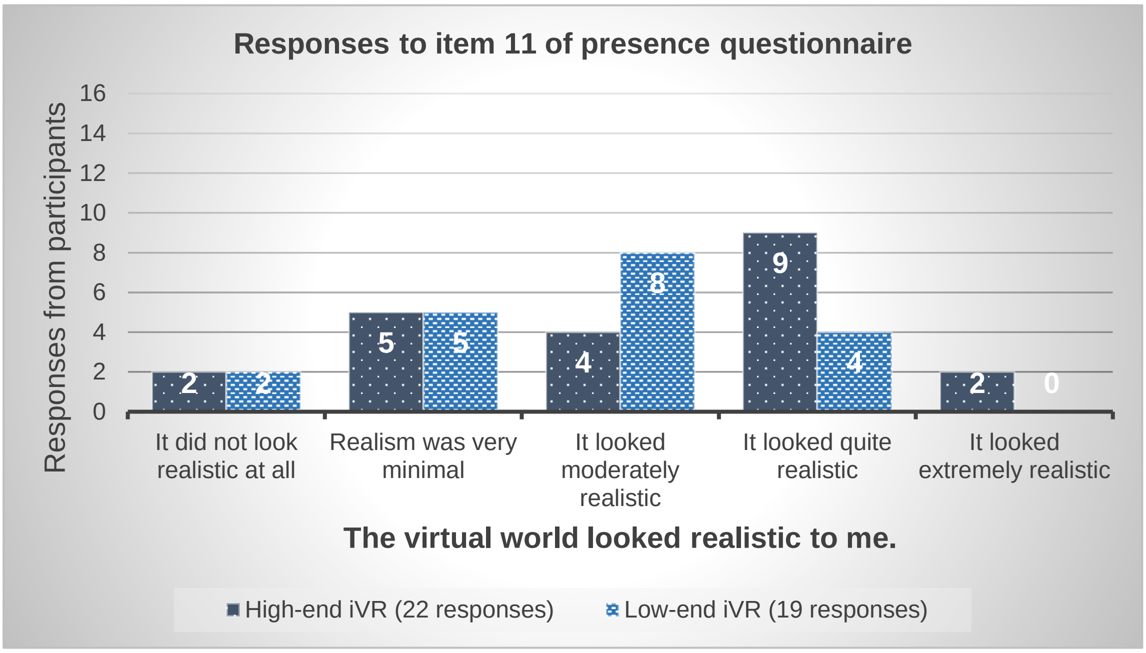


Figure 7.14. Comparison of frequencies for item 11 of the presence questionnaire.

Whilst the small difference between mean scores suggests that the virtual laboratories in both interventions looked realistic to participants, stylistically they were considerably different. Whilst Labster more closely resembled a real laboratory, HoloLAB Champions had a more cartoon-like visual style. These results suggest that the congruency between the VE with what would be expected in a real laboratory do not only reside on the visual mode. As pointed out by Participant 22, interactions, and feedback from the VE also contribute to its perception of realness:

> That one's obviously more realistic [HoloLAB Champions], you can still spill stuff and break stuff. You have to be aware of where you're placing stuff to be aware of your safety, whereas this one [Labster], you can actually stop being aware of your safety because it did stuff for you, but this one [Labster] still made you… you had to wear a lab coat and stuff, and the gloves. It would check for the pipette tips, make sure it's not contaminated, so that is all quite similar to what we do in school, we have to make sure everything is as accurate as you can make it. And with the other one [HoloLAB Champions], with all the different readings you have to take and the different scales. I guess, in this [Labster], you have different pipettes, but in the other one [HoloLAB Champions], you had different spatulas and ways of weighing stuff out, that's quite accurate as well. In chemistry we have to make sure we reduce the uncertainty of it, so that one's quite similar [HoloLAB Champions] because you have to measure them and make sure which one would be the best ones to use. (P22-LiVR)

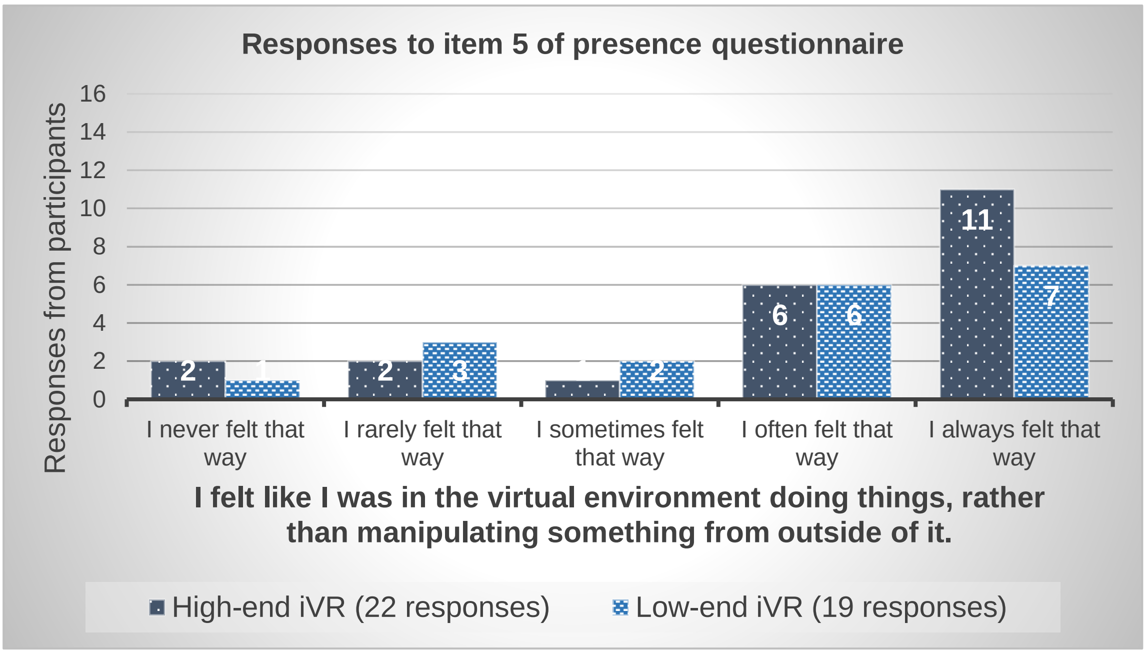


Figure 7.15. Comparison of frequencies for item 5 of the presence questionnaire.

A similar effect can be observed in responses to item 5, which enquires whether participants felt like they were in the virtual environment doing things, rather than manipulating something from outside of it. 82% of the responses in the high-end iVR condition (M = 4.00) indicate that participants sometimes, often, or always experienced feeling like they were carrying out the experiments from within the virtual laboratories, rather than as externally. In contrast, only 79% of responses from the low-end iVR condition (M = 3.79) indicate the same (see Figure 7.15).

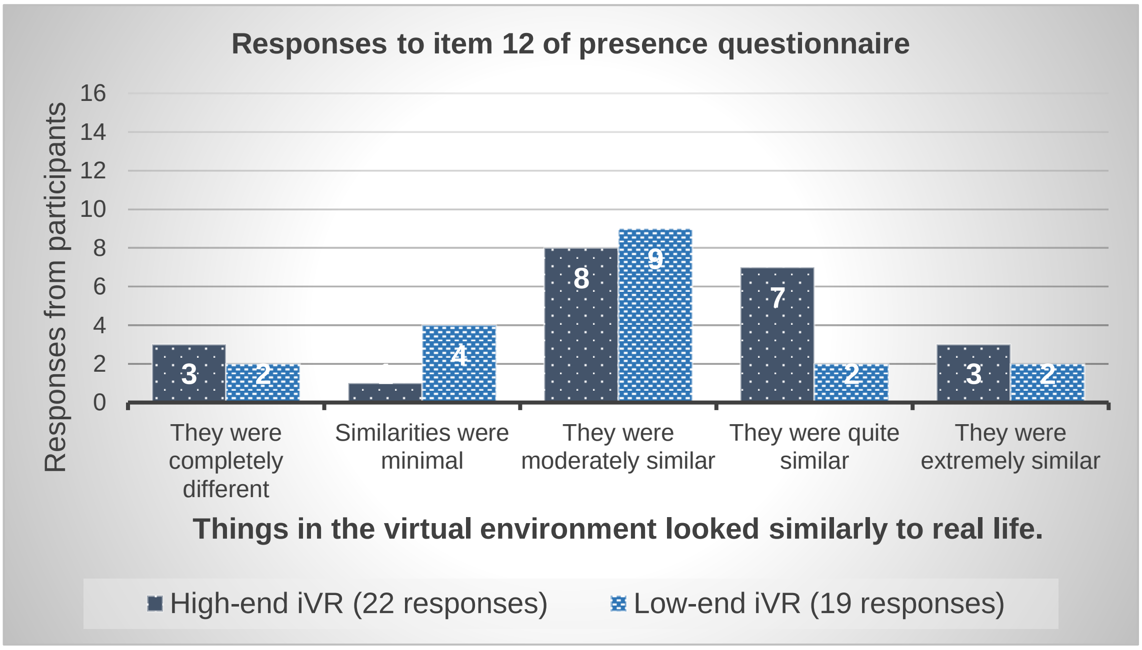


Figure 7.16. Comparison of frequencies for item 12 of the presence questionnaire.

Comparatively, with respect to item 12, which asks whether things in the virtual environment looked similar to real life, it was observed that the highest number of responses concentrate around the middle section of the scale for both the high-end iVR condition (M = 3.27, SD = 1.202) and the low-end iVR condition (M = 2.89, SD = 1.100). 46% of responses in the former indicate that participants perceived objects in the virtual laboratories as “quite” or “extremely” like reality. In contrast, only 21% of responses in the latter condition indicated something similar (see Figure 7.16). Results from an independent samples t-test indicate that these differences are not significant, t(39) = 1.04, p = .303, d = 1.16.

These small differences in mean scores and the spread of responses across conditions are suggestive of conflicting ideas concerning the expectation of realness of the virtual environments. For instance, Participant 04 highlights how whilst manipulatives could be qualified as real and congruent visually, there were other aspects in the VE that evidenced its virtual nature:

> Obviously, colours are different. It's more like sci-fi, is that a word for it? like more... yeah although the beakers and the flasks and the scale were all the same, the surroundings are what make you aware that you're not in reality. (P04-HiVR)

In that respect, HoloLAB Champions, by being designed in a visual style that is reminiscent of children’s cartoons with saturated colours and unrealistic characters, gave participants a science fiction feeling, “everything was a bit weird, the people... the audience, but I kind of got used to it later... it matched the environment” (P17-HiVR). The laboratory equipment, on the other hand, was perceived with a higher level of realism despite its cartoony colours. This was in part due to being shaped and proportioned like real instrumentation, but also, as pointed out by Participant 13, due to how these behaved or reacted to being manipulated such as moving and spilling the substance inside when moved too hastily, wobbling when placed in an uneven surface, making clicking sounds when knocked against other glassware, etc.:

> I'd say it's similar [the level of realism between both virtual laboratories], the measuring, and the scientific is great, everything is similar. It's like cheating around it to do... you can't just type this amount, you have to measure it, so it's realistic that side of it... it's realistic about when you mix it or you react to what happened and what actually does happen, I think it's realistic... and the way you can move around, you pick stuff up and you can literally just move it away and if you knock something, which I did twice, it would wobble, but it wouldn't just knock it out of the way, it would wobble. So, it's pretty aware about what it was in real life if I was in the lab doing it. (P13-HiVR)

On that note, responses to item 13, which enquires whether things in the virtual environment behaved like participants would expect them to if they were real, show a wide distribution of responses for both conditions. 64% of responses in the high-end iVR condition (M = 3.86) indicate participants considered that manipulatives in the virtual laboratories behaved almost or extremely like they would expect them to, whilst 63% of responses in the low-end iVR condition (M = 3.47) indicate a similar perception (see Figure 7.17).

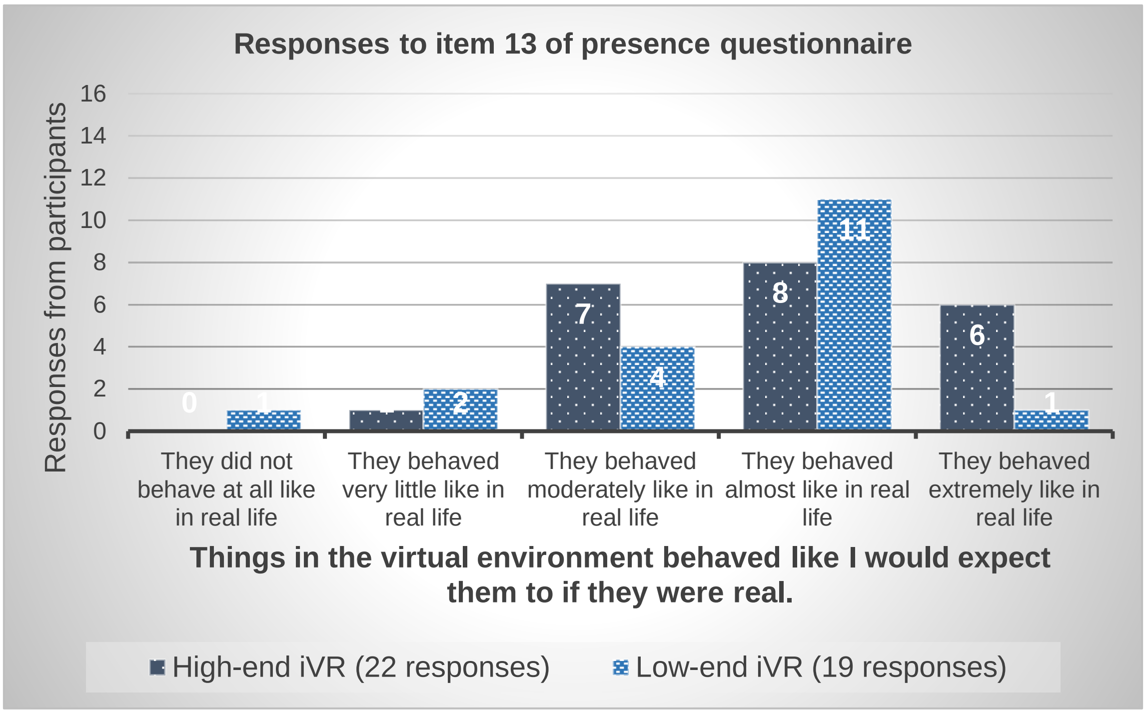


Figure 7.17. Comparison of frequencies for item 13 of the presence questionnaire.

The above implies that both systems performed in similar terms according to participants' expectations. During interviews, however, more nuanced responses were provided. As discussed by Participant 13, one of the expectations with Labster was that more natural interaction be supported, “I wanted to interact more because it was just clicking and clicking. I wanted it more immersive and more understanding if you naturally react to something” (P13-LiVR).

In the case of HoloLAB Champions, when some incongruencies or behaviour outside expectations were encountered, “[…] it's not really natural for you to shove a spoon through a flask to get it out, but I noticed that you could do that” (P08-HiVR), these provided new opportunities for engagement as participants re-adjusted expectations of how the space worked and encouraged them to try new things even if they were not congruent with reality. Participant 09 describes these expectations:

> Well, you reach out to touch things usually. At the beginning, I didn't realise that you could go through stuff so I was using it [a scoop and beaker] as I was in real life, carefully moving stuff around, but then I realised I could use the spoon to go through glassware which made it easier to see things. (P09-HiVR)

Another type of expectation concerns touch. As pointed out by Participant 16, they experienced a disconnect between virtually holding an object and the tactile perception of holding the physical controllers:

> It was just like, because I was putting my hand out to move things, that gave me like the sense of it being real, but then because I was using the controller, that made me think it's not that real. So, it was kind of like both in a way. (P16-HiVR)

As previously discussed, the incongruency between visuo-proprioceptive stimuli could happen in two directions, particularly with Labster where participants could see the virtual hands perform tasks and move around the space but feel their physical hands not moving. Alternatively, if they attempted to perform hand movements, these could be felt, but not visually replicated in the VE.

Another consideration regarding touch is the feeling of constantly holding a controller, which in the case of the high-end iVR condition, it was not necessarily an issue. The Index Controllers used during the intervention had a strap mechanism that allowed two things: (1) participants could have their hands open as a default position, thus eliminating the feeling of holding a physical object at all times, and (2) a grabbing motion by holding the controllers which was only necessary when picking up objects. This, coupled with the haptic feedback of the controllers, provided the perception of physically touching the virtual objects, with the caveat that the shape or weight perceived through touch would not necessarily match the visual mode.

Lastly, there were also expectations concerning embodied interaction and movement. Participants reported experiencing less restrictions in HoloLAB Champions in the high-end iVR condition, “it was a bit more interactive; I think. I think that's the word. It felt like I was actually in the game compared to the last one and it was pretty good.” (P02-HiVR). As indicated by Participant 02, the increased level of interaction contributed to the perception of presence as participants had more freedom of movement, which more closely resembled reality. As suggested by Participant 09, this reduced the gap between the virtual simulation and reality.

> I could go anywhere unless an actual real wall [was] there. That's how I felt, I could pick up anything, I could go through whatever, nothing was really stuck in the virtual world rather than the physical world. (P09-HiVR)

In that sense, an environment where manipulatives behave and can be interacted according to expectations may be able to offset the effect of being surrounded by a virtual environment that may look too artificial, “that one [HoloLAB Champions], it felt more realistic, even though it was more cartoony, it felt realistic. […] It's because that one [HoloLAB Champions] was more realistic because it felt more realistic […] (P13-HiVR). Furthermore, it was observed that once participants understood the limitations of each of the experiences, they were able to adjust their expectations of what they could do in the VEs. By doing so, participants were less likely to engage in behaviour that would create sensory-motor incongruencies like walking, approaching objects, or attempting to interact with certain elements in the space. In that sense, if participants did not engage in such behaviour, incongruencies would not emerge, and the sense of presence could more easily be maintained.

The findings discussed in this chapter are consistent with the assertion that “the more senses a media environment activates in its users the more likely it is that the receivers will feel like they ‘are’ in the environment” (Wirth et al., 2007, p. 496). More significantly, they suggest that agents construct a mental representation of the virtual environment which they need to constantly evaluate and adjust from an egocentric frame of reference in order to maintain a sense of presence.

Chapter summary

This chapter discussed results from the analysis of the immersive virtual reality presence questionnaire (iVRPQ) and interviews concerning how free movement and embodied interaction shaped participants' experience of presence in both iVR environments during the school interventions. The following is a summary of the main findings:

- Results from statistical analysis indicate that participants in the high-end iVR condition experienced a stronger sense of presence (N = 22, M = 3.95, SD = 0.54) than those in the low-end iVR condition (N = 19, M = 3.18, SD = 0.74) regardless of gender, year of schooling, and experimental group.
- Results from Spearman's rho and eta tests show a moderate negative correlation between presence mean scores and study conditions, $r_s(41) = -.47$, $p = .002$, $\eta^2 = .270$, which corroborates the finding above. A proportion of variance of $R^2 = .27$ indicates that 27% of the variance in the presence mean scores can be explained by the study conditions. Furthermore, the spread of mean scores in the low-end iVR condition shown in Figure 7.1 suggests that participants were not able to maintain a constant sense of presence throughout the intervention.
- When looking at presence mean scores in the pathways for participation across experimental groups, results suggested the existence of anchoring bias among responses. This consists in participants judging their perceived sense of presence taking the first intervention as the basis and giving higher or lower scores than the average during the second one. Results from Mann-Whitney U tests performed for the high-end iVR condition, U = 17.0, p = .130, r = .40, and low-end iVR condition, U = 26.0, p = .052 (asymptotic p = .045), r = .61, show no significant differences, most likely due to the small number of data points resulting from splitting the dataset for this particular analysis. Although the anchoring effect could not be corroborated, the significant asymptotic value in the low-end iVR condition suggests that such bias could potentially be observed had the sample been larger.
- It was observed that one of the ways in which embodied interaction and movement shaped participants' sense of presence was through the congruency of sensory-motor stimuli between the VE and reality. This concerns the synchronicity between the feeling of a movement being made and the visual of the virtual simulation of that movement

(i.e., visuo-proprioceptive congruency), as well as the appropriate representation of visuals and the simulation of behaviour and sound. Furthermore, by integrating touch through controllers that do not need to be continuously held, this notion of congruency extends to the expectation of physical properties of objects in the VE such as their weight and shape. Based on these findings, it is proposed that whilst the sense of presence can be broken by incongruent sensory-motor stimuli, it can be re-established by reverting or stopping the condition that broke the illusion, or by assimilating the condition and accepting it as plausible within that space.

- Another way in which embodied interaction and movement were observed to influence the sense of presence was by reinforcing the believability of the VE, which would allow it to become the dominant reality or source of stimuli. It was observed that iVR systems required to provide agents with sensory-motor stimuli and they also had to be capable of reacting dynamically to input from agents. In that sense, the more immersive the system, the greater its potential to support more modes to achieve this. For instance, the simulation of mistakes such as breaking glassware and spilling substances, which requires the tracking of movement and hand gestures, reinforces the notion that actions have consequences in the VE, thus making it more believable.
- A final observation concerning how embodied interaction and movement shaped the perception of presence was that they could act as mechanisms to adjust perceptual expectations of the VE. This included the visuo-proprioceptive disconnect of not having virtual hands whilst performing hand movements aimed at interaction, the tactile perception of holding a controller, the increased freedom of movement to perform actions in the iVR condition, and the re-evaluation of how certain manipulatives worked such as the ability to put a scoop through glassware. It is suggested that this readjustment of expectations allowed participants to accept the plausibility of the new conditions so they would stop being perceived as incongruencies that negatively impacted the perception of presence. Furthermore, through this readjustment of expectations, participants would no longer find the need to engage in behaviour that is not supported and that could break the illusion of presence.

Chapter 8: Exploring the perceptions of hand ownership and agency

Chapter overview

This chapter discusses findings related to RQ2; namely in what ways can free movement and embodied interaction impact how participants experience presence, hand ownership, and agency in low- and high-end iVR systems?

This chapter focuses on findings around two dimensions of the sense of embodiment: hand ownership and agency, stemming from thematic analysis of interview data and observations made during the school interventions.

The following sections explore how free movement, including gestural interaction and locomotion could shape participants' experience of hand ownership and agency, both of which constitute dimensions of the sense of embodiment (Kilteni, Groten and Slater, 2012; Galvan Debarba et al., 2017).

8.1 Constrained active engagement.

Through the observation of participants during interventions and based on responses from interviews, it was found that freedom of movement such as hand gestures and locomotion were instrumental to how experiments were conducted and how participants interacted with the virtual environments.

Unlike the senses of presence and body ownership, locomotion and free movement are not illusions, these constitute affordances that only iVR technology with 6DoF tracking systems can support (see Section 2.1.3). As pointed out by Participant 09, the influence of these on the perception of agency represents one of the most consequential differences between the two iVR experiences used in the school interventions:

> The other lab [Labster], I think it was weird because as I've said before, you can't really move around, so if you have to go somewhere, you have to click a button and it just... I think it gives you the same amount of control, you just don't feel like you have that much control. (P09HiVR)

Although both virtual environments may have offered the same amount of control to users, they felt perceptually different, partly due to the limitations on free movement and the mechanisms employed for interaction which, as suggested by Participant 07, could feel crippling in the low-end iVR condition:

> I think I tried to move... wanted to move to the other side of the lab to see how it was like, because I was looking around and I couldn't do anything, I was stuck in that position. (P07-LiVR)

Participant 05 describes how, despite the differences in how embodied interaction and movement were enabled by both virtual environments, these gave participants the capacity to be in control of what was happening by allowing them to initiate behaviour, rather than responding to automatic actions performed by the system:

> Well, I wasn't really moving around, but I could turn around and look at other things and if I wanted to click on something else, it would kind of remind you how to do it a bit, but you could still do what you wanted. (P05-LiVR)

This highlights two important distinctions, the first consists in how capacity for movement could enhance or limit interaction as this could range from point-and-click behaviour to metaphoric gestures and more natural gestural movements such as grabbing, pinching, throwing, or releasing. The second distinction relates to what Participant 05 described as the ability to "do what you wanted." Regardless of the level of support for movement and the mechanisms employed for interaction, both of the virtual environments required the active engagement of participants to carry out the experiments:

> [In] this one [HoloLAB Champions] you actually do the experiments, [in] that one [Labster], you kind of point towards it and press a button which will pour the liquid, so I think it makes it not as interactive and educational like in schools if we're doing it. […] I felt completely... like I could do the steps in whatever order I wanted [in HoloLAB Champions], so I felt completely in control, and they highlight repercussions like breaking stuff if you dropped it, it was very realistic. (P05-HiVR)

Here, Participant 05 describes how simply pressing buttons on the controller in Labster felt "not as interactive and educational" despite this environment being relatively as interactive as HoloLAB Champions in terms of the ability to initiate actions with virtual objects. In contrast, Participant 05 describes experiencing a feeling of control in HoloLAB Champions due to the ability to perform the experiments at their own pace. Furthermore, the experience was deemed "realistic" due to the simulation of consequences in response to self-initiated actions such as breaking or dropping glassware.

As described by Participant 10, free movement in relation to the body was supported in the high-end iVR condition through the ability to lean and take steps in any direction, bend down, or make slight adjustments to the position of the head and body to get a better view of laboratory equipment and substances:

> […] I tried crouching down and reaching out to my face, but I think reaching out to my face was a bit better than crouching down and looking it from the table [the liquid in glassware], but it did feel like it was... I don't think it was moving [the liquid], I was holding it to my face. (P10-HiVR)

In relation to interactivity, as illustrated by Participants 09 and 10, free movement was supported through the ability to reach for manipulatives in a more natural manner such as using a grabbing or pinching gesture, and the possibility to directly move objects in the environment when carrying out the experiments:

> I just prefer it [HoloLAB Champions] in the sense of holding stuff and not just clicking a button, you can actually reach, you reach out to hold stuff, it was more realistic and comfortable […] (P09-HiVR)

> […] I could change the amount. I could move things around. I could place them [the lab equipment] in a way, organise my... organise the table the way I wanted it to be. (P10-HiVR)

In contrast, Labster, by not being able to replicate any movements other than rotation, gave participants a feeling of reduced agency and realism, which Participant 10 discusses as:

> […] it [HoloLAB Champions] just gives you that real life experience, like you're doing it yourself, even though in the second option [Labster] you would still be able to choose options. [In

> HoloLAB Champions] you are directly... your hand movements are doing what needs to be done, so it's more realistic to what you're doing in real life. (P10-HiVR)

Ultimately, systems with a higher degree of immersiveness will integrate modes of representation (see Kress, 2014) in a way that is closer to reality than less immersive ones. However, being a simulation, virtual environments will always feel constrained in some way. As suggested by these findings, the ability to move and directly interact with objects could contribute to a stronger feeling of realism and that the environments and the actions taking place could be plausible. However, limitations on the participants' capacity to perform those actions impacted such perception and their experience of agency. Interestingly, participants reported a stronger sense of agency when they were able to directly manipulate objects and move them freely in the space as opposed to when there was a high level of control over such objects, but this was exerted distally and without the capacity for direct manipulation and free movement.

The above is consistent with previous findings in relation to the elicitation of presence (see Chapter 7, Figure 7.15), and align with the work of Sato and Yasuda (2005) who concluded that the mechanisms controlling movement could influence the sense of agency as it is impacted by discrepancies between predicted and actual sensory consequences. Examples of these are the synchronous replication of hand and body movements in the virtual environments and the simulation of responsive behaviour such as seeing an object move when interacting with it, or a substance sloshing inside glassware when being manipulated.

8.2 Mediating interaction.

VR technology mostly relies on visual and auditory stimuli to immerse users in their computer-generated environments. However, touch through tactile interfaces or input devices has become one of the most prominent aspects looked at in research due to their potential to significantly impact the experiences that VR technology can offer. Gloves, controllers, exoskeletons, or gesture recognition cannot fully convey a sense of weight, volume, temperature, force, texture, or even the shape of the object being held. Nevertheless, mechanisms for interaction such as these make it possible to more naturally simulate the manner in which objects are manipulated or interacted with by tracking the motion of the hands and even individual fingers, thus allowing for grabbing, pointing, and pinching gestures to be used.

The technology in the controllers used in this study played an important role in shaping the nature of the interactions that the VEs could support. As described by Participant 14, the low-end iVR condition used a single controller only capable of 3DoF of rotational movement:

> That one [the Daydream View 2 system and remote], I felt like I was… more restrictions compared to that [the Vive system and Index controllers] because, first of all, you had one controller, right? whereas that we had 2 controllers, so... it's why we can hold like... because that one [the Daydream View 2 system and remote] you had a remote, it was touchscreen… like touch sensitive and stuff, but it was not as, you know... hold things, move it here and drop this thing, you know; whereas that [the Daydream View 2 system and remote] you had to do it with the remote control and use the button instead of you doing it yourself and moving yourself. (P14-HiVR)

As described by Participant 14, the discrepancies between input devices in both conditions were immediately perceptible, not only because of the shape, size, and number of controllers, but by the way each afforded interactions. Support for only 3DoF of movement with the remote controller used in the low-end iVR condition limited interactions. As described by Participant 03, these were reduced to pointing and clicking as the system could only sense and replicate the rotation of the participant's wrist:

> Well, I couldn't really use my hands, I had to press the pointer, so I just pointed at an object and clicked a button which would make the virtual hand pick it up […] (P03-LiVR)

Thus, whenever movements were performed, these had to be virtually simulated and done automatically for the participants without the implication of physical hand gestures or motions:

> Yeah, but they [the virtual hands] were... like you aren't really using them yourself, only the left one that holds the iPad, but even then, you have to click with your right hand. It was a.... It wasn't... you couldn't really control them […] P19-LiVR)

Comparatively, the high-end iVR condition used dual controllers capable of providing not only 6DoF of rotational and translational movement, but also finger tracking which made it possible for virtual manipulatives to be interacted through grabbing and pinching gestures that did not require button pressing. As suggested by Participant 18, these forms of embodied engagement such as adjustments in body posture and gestural movements expanded the possibilities for interaction in the high-end iVR condition:

> So, we used the controllers, so we had to open our hands to grab something and then close, so yes, similar to the actions we would take it normally. Sometimes, I found myself moving in positions to grab something. So yeah, it was good. (P18-HiVR)

Involving these natural forms of engagement with the VE meant that participants did not have to learn interaction mechanics or metaphoric gestures, thus making the experience more intuitive, "it wasn't challenging the way I interacted because I'd say it was realistic, so it's just real life" (P10-HiVR). As argued by Segal (2011), this could reduce cognitive load and improve performance. Furthermore, it was expected that at least subtle movement such as changes in posture to get closer to an object would be supported, as argued by Participant 05:

> [...] when I was using the remote, I would go a bit closer to it [the pipette]. Yeah, I wouldn't be trying to reach out, I just kind of leaned towards it, like I'd turn my head towards where it was or turn all my body. (P05-LiVR)

This highlights the ways in which the body directly supports perception and interaction in these types of systems and how preventing movement could be restricting, thus making other limitations more perceptible:

> It felt very simple, it's very precise which I liked, it was very precise and coherent in that... the only thing that I didn't necessarily liked [sic] feeling was when I grabbed an object, I was expecting to hold it as if I was actually grabbing it in real life […] (P06-HiVR)

As suggested by Participant 06 above, just as the opportunities for engagement could make the environment feel simple, precise, and realistic, being mediated by physical input devices (i.e., the controllers) also could make those actions feel less reactive and intuitive. For instance, in the low-end iVR condition, participants used a single hand to make selections. Actions, however, were only simulated by the virtual hands. In contrast, as described by Participant 02, physical and simulated actions could be carried out with both hands simultaneously in the high-end iVR condition:

> There was a point when I was holding the beaker full of the solid and I was holding the spoon and I was putting it in at the same time [in HoloLAB Champions]. In the other one [Labster], because you've got only one controller, you can't really do that, you have to put it down, you have to... it's all one handed, it doesn't feel natural. (P02-HiVR)

Interestingly, even when two-handed operation was possible, there were participants who would still engage with the manipulatives exclusively with one hand, “I just... I don't know, I guess I forgot that I could use my other hand” (P04-HiVR). This behaviour was particularly notable as it was not exhibited exclusively by participants who had previously taken part in the low-end iVR condition, which suggests this was not the result of an ordering effect. Moreover, even when participants had been reminded that two-handed manipulation was possible, they often reverted to using only one hand later in the experience:

> No, I kind of had to consciously remember that I had my left hand there, so most of the time when I was in the experience, I forgot it was there and I was just using my right hand. (P09-HiVR)

Although it is common for participants to have a dominant hand and for that to be reflected in the way they engaged with the virtual environment, there were situations where two-handed manipulation would have made more sense. One instance of this concerns transferring substances between flasks or scooping powders out of a beaker, where the glassware can be held with one hand and tilted to allow for an easier insertion and retrieval of a scoop with minimal spillage. This is described by Participant 22 as unintentional behaviour:

> I honestly don't know, I might have started using only my right hand, but I didn't think to do anything about it, I was just using my right hand. […] When we got to the mass bit, then I realised I hadn't used my left hand at all, but I just didn't do anything about it. (P22-HiVR)

In some respects, this behaviour could be seen as a self-imposed barrier that could prevent participants from experiencing a higher degree of presence or perform the experiments faster and more efficiently by not causing glassware to be knocked over, to break, or substances to spill. This could also suggest that participants were subconsciously aware that the VE was an artificial space that had limitations and they behaved cautiously and less confidently as a result. Alternatively, this behaviour could be an effect of the participants' engagement with other technologies that are predominately operated with one hand such as smartphones and tablets.

Finally, it is important to note that both virtual environments were designed so that participants would carry out and learn appropriate practices that correspond to physical wet laboratories. Interactions in Labster, for instance, were constrained so that participants could not engage in divergent behaviour or attempt inappropriate tasks, thus ensuring they would follow and learn the appropriate method to conduct an experiment or to use laboratory equipment. Most significantly, this behaviour was simulated at the command of the participants, but not actually carried out by them. In contrast, HoloLAB Champions required that participants perform the tasks themselves which opened the door for alternative behaviour and mistakes to be made. However, this was addressed by penalising participants when something was done wrong, and by sectioning the experience and requiring participants to submit a solution, which could only be achieved by following the appropriate method.

As per the strategies described above, it can be argued that both virtual environments fostered practices that could be transferred to the real world such as pouring, taring, measuring, transferring, and mixing substances, as well as the use of laboratory equipment like pipettes. Despite the limitations brought about by the mediation of interaction and movement, immersive virtual reality technologies like these could be capable of delivering practical and safe environments for the development of procedural skills and the grounding of conceptual understandings (see Chapter 9).

8.2.1 The impact of interaction on the perception of hand ownership.

The relationship that participants experienced between their bodies, particularly their hands, and the VE was also significantly impacted by the controllers used in both study conditions. Two main issues were identified that directly affected the perception of hand presence and ownership. Firstly, the presence or absence of a visual representation of the participants' hands. While the low-end iVR condition incorporated virtual hands, these were not able to move in synchrony with the participants' which hindered how they were perceived.

On the other hand, although the high-end iVR condition was capable of replicating hand movements and supporting grabbing or pinching gestures, participants could only see a model of controllers in the place of their hands in the VE. As observed by Participant 21, this caused its own set of challenges when it came to sustaining the illusion of hand presence and ownership:

> [The controllers felt] not fully my hands because obviously it [sic] wasn't a hand, but when you're not looking at them and just kind of using them, kind of because you're literally... like to grab something, you have to grab it, so it kind of feels like that, but I wouldn't be...can be like yeah these are my hands, you know what I mean? (P21-HiVR)

A second challenge stemming from the use of controllers and their capabilities concerned the disconnect experienced between what participants saw and what they felt, "because it was kind of like, you saw it. This [Labster]... visually, it felt like those were mine, but in... physically, like to touch, it felt like it was mine in this one [HoloLAB Champions)" (P21-HiVR). Participant 21 is making a distinction between both interventions, one where interaction was mostly visual, and the other where it was primarily experienced through the mode of touch.

Two further issues were observed in relation to the potential to sustain the illusion of hand presence and particularly, hand ownership. One of them concerns the tactile feeling of grabbing the controller and of pressing buttons, and the other, the sense of proprioception.

Regarding the first issue, in the low-end iVR condition, where Labster was used, the left virtual hand would always hold a virtual tablet, but that sensation could not be replicated physically as there was no left controller to hold:

> For starters it [the virtual hand] didn't look like my hand, and also, I could feel my hand moving when I was... I think it was the right hand that was holding stuff, but then I could feel my right hand clicking the buttons and moving it around. There was [sic] bits where I felt like it was my hand, like I was controlling it, because if I would turn like that, the hand would also move, so then it kind of felt like it, but most of the time I'd be doing stuff, so I'd be over here and then that hand would just be there. (P03-LiVR)

As pointed out by Participant 03 above, the single right-handed controller implemented could only provide the tactile feeling of pressing a button regardless of what the virtual hand was doing or holding. Moreover, as evidenced by the quote by Participant 17, touch was experienced bidirectionally. The combination of visual and touch could introduce discordant stimuli when there is a disconnect between both modalities such as when holding a virtual object, but the shape of the controller is felt instead. Alternatively, this can happen when a virtual action such as lifting glassware from a table is done by the physical pressing of a button. Inversely, the absence of paired stimuli can also be a point of incongruency. For instance, as illustrated by Participant 17, when the sense of touch is being engaged by the feeling of holding a physical controller, but this is not supported by the visual mode if the virtual hand is not holding anything:

> […] looking at my hand, my virtual hand, I wasn't holding anything, but I could feel that I was holding something... the other one, the other hand with the iPad, it was the same thing, but just the other way around. (P17-LiVR)

Regarding the sense of proprioception, this was directly tied to the type of iVR technology used in the interventions. In the high-end iVR condition, the same tracking system that supported locomotion was responsible for making sure that hand movements were replicated. This reinforced the sense of ownership of the virtual controllers because they were always positioned in the same perceived physical location as the participants' physical hands. In the low-end iVR condition, however, such tracking system could only replicate the rotation of one of the participants' hands. This created a disconnect between the visual mode and the participants' sense of proprioception, particularly when performing tasks requiring moving the hands and arms away from the body:

> There were bits where if I was over here and then I had to... I don't know, throw something in the bin, I'd click on the bin and then it wouldn't be my hand that was moving towards the bin, my hand would be here and the [virtual] hand over there, it's just going like that and putting it in the bin. (P03-LiVR)

Participant 03 makes an important distinction that was voiced recurrently regarding the low-end iVR condition. Hand ownership was experienced momentarily and was dependent on the congruency between the visual mode and proprioception. When the participants positioned their hands in the same place as the virtual hands and did not perform any movements, they experienced a feeling that their hands were theirs. However, when they had to move their hands and this was not simulated in the VE or when the virtual hands performed an action and they did not physically move their hands, it created a disconnect that broke the illusion of hand ownership.

Derived from the above, incongruencies between the sense of proprioception and the visual mode created a feeling of detachment from the virtual hands, “I just thought they were there, not that they belonged to someone, just they're there and I just accepted it and kind of moved on” (P09-HiVR). Of course, these effects were not pervasive across conditions. To some participants like Participant 02, the visual mode was not as important as their attention was not always on their hands, but rather on the manipulatives and what they could do with them:

> They [the controllers] didn't look like my hands, but I still felt like they were my hands because I was using the physical controllers with my hands, but not... [I] didn't have to see my hands in the game to know they were my hands. (P02-HiVR)

This is suggestive of proprioception having a much stronger effect on realising the illusion of hand presence and ownership and this was achieved through congruent movement, or lack thereof. Although the VR system in the low-end iVR condition could not replicate positional hand movements, the virtual hands could still elicit a sense of proprioception as long as no physical or virtual movements were performed. Similarly, the high-end iVR condition, albeit with virtual controllers instead of hands, maintained the participants’ sense of proprioception by faithfully matching their physical hands and arm movements in the VE, as was the case with Participant 14:

> Oh, I felt like my hand was here alongside the controller because literally as I move my hand, the controller moves with my hand... I was moving my feet or moving to this place, my whole body like, you know... Even the virtual and the real world connects [sic] so both things will move to that area... so it felt a lot more... because this one [Labster], I thought that, oh it did kind of feel real, but you know, restricted. Again, you have to sit or standing. (P14-HiVR)

Furthermore, in the case of HoloLAB Champions, even when the visual disconnect was still perceptible, the sense of touch was strong enough for participants like Participant 08 to maintain the partial illusion that their hands were truly there, although not necessarily that they belonged to them:

> I did not think they were my hands. At one point, I went like that with the holes [demonstrating with the hands at eye level] and looked through, because it's like they were my hands, but not […] I knew they weren't my hands, but I knew they were my hands in this virtual space, so it was sort of in between. (P08-HiVR)

Another example of such visual disconnect is how the virtual controllers were only visible when they were not holding manipulatives. A blue hue would appear around objects to signal they were being virtually touched, and then the controllers would disappear as soon as the participant grabbed them (see Figure 8.1). Although this was a design feature thought to allow unobstructed views of the objects instead of them being attached to the end of a virtual controller or blocked by the virtual hands, participants still found themselves able to maintain the sense of proprioception due to the replication of their hand movements, even if visually it looked like the objects were floating in the air as described by Participant 22:

> Yeah, but then I think the little blue outline made it a bit easier to kind of assume where your hands would be. […] It was really strange because I was holding something, picking it up and you use your fingers as you would normally do and you kind of feel the same things, but then can't physically see your hand moving, and you can't see the controller moving, you're just seeing something still, and you know you moved your fingers to do something […] (P22-HiVR)

Figure 8.1. Visual of virtual controller when touching and object (left) vs. holding it (right) (Schell Games, 2018).

By opening the possibilities for interaction using hand gestures, the controllers in the high-end iVR condition evoked not only a higher sense of hand presence, but also of ownership which Participants 10 and 12 describe below:

> Yeah, I think... I felt like my hand was actually there because this one [HoloLAB Champions] is like, when you open your hand, you can grab it [an object]. So, it felt like I was actually holding the substance and when I let go, it would just stop. […] Yeah, I thought they were my hands even though I couldn't see it. (P12-HiVR)

> […] I could do similar things that I could do with my hands like letting go, holding on tight, grabbing things, moving them around in a way I would normally... they were just in my hand. (P10-HiVR)

This is in direct contrast to the perception elicited by the controller in Labster where presence was achieved, albeit without assuming ownership of the virtual hands which "[…] you couldn't really control them, and on that one [HoloLAB Champions], even though you had controllers, they still felt like hands" (P19-LiVR). Instead, in this condition, the use of the virtual hands was often described as a feeling of control elicited through an avatar. As argued by Participant 03, this happened regardless of whether that avatar was perceived as an external entity over which they exerted control, or one they embodied.

> Yeah, it felt like I was controlling a robot. So, I was in control, but it never felt like this is my hand moving. […] It didn't actually feel that weird because it wasn't my hand, like I knew the whole time I could feel that that wasn't my hand, I knew I could control it and everything, so I felt like I was there, I felt like I was controlling it, but throughout all of that, it didn't feel like my hand, so when it moved over there, it didn't feel weird, like why is my hand doing that? because it was more, I'm making the robot's hand move over there, so it was fine. (P03-LiVR)

Participant 21 points out that attributing interactions to an alternate entity eliminated the perception that they were expected to physically approach an object, reach out, or get closer.

> Um, I don't know, at that point I guess I felt kind of like I was just telling someone to do something, so by pointing and clicking kind of then, I didn't have to come over there... I didn't feel like I had to go up to... I didn't have to reach my own arm out because it was something else doing it. You know what I mean? it felt like I was kind of like... it's kind of like a robot. With the iPad as well, it felt like it wasn't my own body, it was just a machine there. If I clicked it, it would come up for me [...] (P21-LiVR)

Furthermore, these statements evidence how hand ownership was linked to proprioception as "[…] with certain actions like with the pipette and when it's there, when it's close to you with the pipette, it was like it's yours […]" (P21-LiVR). However, when the virtual hands moved away from the body to carry out an action, the illusion was more difficult to maintain, and that's when some participants made sense of the condition by attributing the observed behaviour to "a robot." This eliminated the disconnect and normalised the behaviour as the observed action no longer needed to be congruent with the participants' actions as these were not being self-attributed, "you kind of get used to it as well. It just feels normal, that's the reality of it, that's what you have to do." (P21-LiVR)

All these findings indicate that the controllers offered more natural forms of interaction. Those interactions sustained the perception of hand presence, and the conjunction of the two, coupled with the sense of proprioception elicited a feeling of hand ownership. However, these are just the underpinnings to achieving a stronger sense of agency over what was happening in the virtual environments. As posited earlier, from the standpoint of being the agent of change in the VEs, both virtual laboratories required a similar amount of active engagement from participants.

8.2.2 **Experiencing agency through embodied interactions.**

The sense of agency is generally understood as the wilful intention of motor control (Blanke and Metzinger, 2009). That is, the self-attribution that a certain behaviour originated in the self. This has two implications: firstly, that participants identified themselves as the ones executing the actions, regardless of whether these were performed with conscious intent or not; and secondly, that participants experienced being the cause of such behaviour. This of course does not only concern body movements but extends to interacting with the environment and having a certain degree of control over what happens in it.

As discussed in more depth in Section 3.5.3, the notion of agency accommodates two aspects. The first of these concerns the objective level of control over the virtual body and the environment. This is measured by the degree of movement and interactivity that is afforded by a system as it integrates an agent's body. Furthermore, it also concerns the interactability of the environment and the feedback loop created by these agent-environment dynamics. In that sense, an agent's behaviour can influence or change the environment, which is interpreted as feedback from the initial action; subsequently, this can cause a behavioural response from the agent, thus closing the loop.

The second aspect refers to the subjective notion of agency as a perceptual state which is explored in this section. From this perspective, agency is seen as constitutive of the sense of embodiment (see Section 10.2.5) and it is defined by the perception of control over the virtual body and over the virtual environment regardless of the actual level of physical control being afforded. As it is discussed below, a low perception of agency can be experienced even when the iVR system affords agents high levels of control over the environment. This seemed to be influenced by the level of agency experienced over the body, thus reflecting the tactile-kinaesthetic and affective nature of agency (Sheets-Johnstone, 2000).

Based on interview data and observations, it was found that more so than the sense of ownership, eliciting a sense of agency was partially predicated on visuo-proprioceptive congruency. That is, the correspondence between the behaviour observed in the virtual environment and the actions carried out by participants contributed to the illusion that such behaviour was self-originated. There were instances, however, when such illusion was not realised or was broken, particularly in the low-end iVR condition. Interestingly, as discussed in the previous section, some participants employed a mechanism that helped them rationalise incongruencies between visual and motor modalities, namely attributing the behaviour to a separate entity over which they had control (i.e., a robot or an avatar).

On the one hand, feeling bodily present or experiencing the illusion of owning the virtual hands allowed participants to perceptually attribute behaviour to the self, "it made it a bit more easier [sic] for me to understand and I felt like I was in control of it instead of someone else doing it for me" (P12-HiVR). On the other hand, a diminished or absent sense of ownership resulted in detachment from the observed behaviour, thus minimising the feeling of being in control of what was happening, “I think it's just the feeling of not directly touching something or moving it around and just waiting for someone else to do it for you” (P09-HiVR). A similar sentiment is described by Participant 11:

> The fact that... obviously it's virtual so you can't really feel anything properly, but it felt like everything was done for me, like when... like using the pipette it was just too easy, like more than how it would be in real life is what I'm trying to say. […] I felt like I was told what to do. So, I felt like they were controlling me, I wasn't controlling it, if you get what I'm trying to say. (P11-LiVR)

As discussed during interviews, this was offset by attributing behaviour to a separate entity of which participants were in control as suggested by Participant 22:

> […] I felt kind of like I was just telling someone to do something, so by pointing and clicking kind of then, I didn't have to come over there... I didn't feel like I had to go up to... I didn't have to reach my own arm out because it was something else doing it. You know what I mean? it felt like I was kind of like... it's kind of like a robot. With the iPad as well, it felt like it wasn't my own body, it was just a machine there. If I clicked it, it would come up for me [...] (P21-LiVR)

In that sense, observing the virtual hands perform an action that the participant has not physically carried out would not create a break in the sense of agency despite not experiencing a feeling of ownership. This is because some, like Participant 03, rationalised the action as ordered or triggered by them, but performed by someone else:

> Yeah, it felt like I was controlling a robot. So, I was in control, but it never felt like this is my hand moving. […] so, when it moved over there, it didn't feel weird, like why is my hand doing that? because it was more: I'm making the robot's hand move over there, so it was fine. (P03-LiVR)

This contrasts to the high-end iVR condition where the direct interaction with manipulatives was supported and participants' behaviour was replicated as described by Participant 10:

> It felt like I was actually grabbing on to things that I was holding down like that. […] I think there was a high level of control because if I let go of stuff, it would fall, it wasn't like... it didn't feel like someone else was doing it for me, it felt like I was actually... I had control of what was going on, I could change the amount, I could move things around, I could place them in a way, organise my... organise the table the way I wanted it to be. (P10-HiVR)

In this instance, there was congruency across different sensory-motor affordances of the iVR setup: (a) the visual feedback of the surrounding virtual environment; (b) the illusion of realistic interaction with manipulatives; and (c) full control over what was happening, as supported by the ability to move, grab, let go of things, and organise the workspace as desired, which Participant 14 describes as:

> I had quite a lot of freedom, the fact that I could actually stretch something, hold it, take here and then, you know, release that substance into that container. It felt, in my opinion, it felt like pretty much real life because you know, you have to literally… the controller, you had both controllers in your hand, and you had to hold it, they felt like you were actually doing that specific thing. (P14-HiVR)

As a result, and as posited by Tsakiris, Schütz-Bosbach, and Gallagher (2007), experiencing ownership is a prerequisite for experiencing agency. However, it is not necessary to elicit a sense of agency to experience ownership, such is the case with involuntary movements.

An example of this can be found in the low-end iVR condition which Participant 07 discusses below. Despite Labster requiring the active involvement of participants, they experienced reduced agency compared to the high-end iVR condition due to the strict guidance system dictating what and when things could be interacted, the impossibility to make mistakes and the lack of support for free exploration:

> Sometimes when I would do something, it prompt me to be like... make sure you empty the contents of the pipette before you press a new one in, and that's when I thought that I wasn't in control because in real life, if I did that, there would be a consequence, and in the virtual reality, there really wasn't a consequence, it was just the prompt letting me know that I shouldn't do that. (P07-LiVR)

Additionally, participants identified the potential of iVR technology to provide spaces where dangerous tasks could be performed safely and the pressure of consequences when making mistakes could be eliminated, “it's less dangerous as well because you never know if you can break something in a lab, whereas this one [HoloLAB Champions], even if you break it, it's not real” (P12-HiVR). This is also highlighted by Participant 10 who describes the relevance of providing opportunities for learning through trial and error, exploration, and simulating the consequences of actions:

> […] If I'm using my hands a lot, usually in an experiment I don't like taking part, I like watching from afar because I feel like I can make mistakes, but with this, it makes you like room to make mistakes and you can start again without having caused any destruction. (P10-HiVR)

Furthermore, as reported by participants in the high-end iVR condition like Participant 10 below, whilst the simulation of virtual consequences such as the breaking of glassware or spilling of a substance contributed to eliciting a sense of responsibility for behaviour in the VE, the integration of congruent embodied interactions also prompted a sense of responsibility for the appropriate conduction of the experiments and the achievement of the desired outcomes:

> […] it just helps you understand how important it is to be accurate with the equipment. I felt like... with more control you feel more responsible for what you're doing... I think if you're watching someone else you wouldn't be able to understand the importance of making sure you keep everything the same or making sure you use let's say one spoon for one thing and another spoon for another thing, and just being able to do it yourself feels... you feel more responsible for what you're doing because it's like you're more aware of what's going on because it's like I'm doing this, if I put the wrong amount or something, this would give me a different result, it gives you more freedom. (P10-HiVR)

As pointed out by Participant 10, the experience in the high-end iVR condition brought about the realization that the embodied nature of interactions was an essential component of how the different aspects of the experiment were understood, which is in direct contrast to the low-end iVR condition where participants felt they had a more passive or receptive role, which Participant 01 describes:

> With a lot of things when you do it yourself, you understand it more, if that makes sense. It's like, you pick up on things a lot quicker, whereas if you just watch something and you can't experience it yourself, but you're just watching it, and you can't experience picking up and pouring it yourself, it wouldn't be the same, it wouldn't be as effective. (P01-HiVR)

Participant 02 draws a comparison between HoloLAB Champions and their school practicals in relation to the role that physically doing the experiments or engaging with the space have in shaping their understanding of content and how such content is remembered:

> […] when I'm explaining a practical, I always find it easier to… if I had done that practical, I find it easier to remember. But there's practicals that I haven't done, but I've read through, but I wouldn't be able to talk about them because I wouldn't remember […] I think it's more memorable if you're actually picking something up physically than pressing a button. I think I'd remember this one [HoloLAB Champions] better than the one that I did previously [Labster]. (P02-HiVR)

Furthermore, this notion of being the source of behaviour and physically engaging with the environment can be also implemented as a mental mechanism when the medium of presentation requires students to assume a more passive role physically as suggested by Participant 14:

> When you have like a written down practical, I still try to imagine my own self doing it. Let's say we're doing it about how to prepare a slide for onion cell, also like I remember myself peeling the epidermal tissue. I still try to remember either way, like imagining if I were doing it because, in my opinion, I feel like that's easier for me to learn. (P14-HiVR)

In summary, the arguments presented in this chapter provide compelling evidence suggesting that the senses of hand ownership and agency are influenced by sensory input, particularly the visual mode. More significantly, these perceptual states seem to be deeply nested in the same mechanisms that enable motor control in immersive virtual reality environments. As a result, embodied forms of interaction which are dependent on locomotion such as gesture and body postures seem to more significantly impact how hand ownership, and more so agency are experienced. Moreover, this provides a framework on which the potential impact of these two conditions could have on meaning making and, by extension, learning with immersive virtual reality systems as explored in the following chapters.

Chapter summary

This chapter discussed results from observations of the participants' use of two immersive virtual reality systems, as well as the analysis of interview data. The reported findings concern how free movement and embodied interaction shaped participants' experience of hand ownership and agency during the school interventions. The following is a summary of such findings:

- It was initially hypothesised that eliciting the illusion of hand ownership and a sense of agency would be dependent primarily on the visual fidelity of the VR experience. However, it was found that both of these perceptual states were more affected by incongruencies between the visual and motor modalities, such as observing the virtual hands perform an action that the participant had not carried out physically. Due to this, it was deduced that hand ownership and agency, although reinforced visually, are nested in the same mechanisms that enable motor control, namely the ability to freely move and engage with manipulatives in a direct and natural manner.
- Concerning the sense of agency, it was found that even when provided with an environment that required the active involvement of participants (Labster), thus fostering a feeling of control, limited mobility and visuo-proprioceptive congruency diminished the overall sense of agency that participants experienced. This was caused mainly by three conditions: (a) the participants' physical movements were not replicated congruently, (b) the consequences or outcomes of the participants' actions were not simulated as making mistakes was not possible, and (c) free exploration and dictating the pace of the experiments was not allowed.
- It was found that three factors influenced the elicitation of the sense of hand ownership: (a) the participants' hands being visually represented in the virtual environment, although these did not have to look like hands, (b) the replication of the participants' hands and arms movements, and (c) the congruency between those two factors including positioning and timing between the movement and the visual simulation.
- Although hand ownership and agency constitute distinctive perceptual states, it was observed that along with the sense of self-location, they conform a single cohesive experience characterised by how the body was brought into the VE.

Chapter 9: Looking at conceptual and procedural understandings

Chapter overview

This chapter looks at free movement and embodied interactions (i.e., gesture) in relation to their potential to influence students' understanding of conceptual and procedural content.

The above constitutes the third research question guiding the main empirical study. The qualitative analysis and findings presented in the following pages are based on a purposive sample of video recordings stemming from interviews with participants and their engagement with the virtual environments.

As outlined in Chapter 6, results from pre-, post-, and delayed tests showed increased scores in both study conditions. However, it was found that participants in the high-end iVR condition achieved significantly higher scores than those in the low-end iVR condition. Based on observations of participant engagement with the virtual laboratories and the analysis of interview data, it was reported that support for embodied forms of interaction can provide opportunities for the development of motor control, spatial awareness, and procedural skills.

Chapter 7 and Chapter 8 extended that work by exploring how the affordances of the iVR technology used in both study conditions could influence different aspects of a virtual reality experience. Such work was particularly concerned with the integration of touch and the congruent replication of sensory-motor stimuli that the high-end iVR condition incorporated. It was found that the perception of presence was modulated by the participants' judgement of the VE as a plausible space. Furthermore, despite describing distinct perceptual states, the illusions of hand ownership and agency were identified as being part of a single, cohesive experience.

The relevance of these findings resides in how they are underpinned by two conditions. The first of these consists in the capacity of the VE to support body movements such as changes in body posture, walking, and the movement of arms and hands. The second condition comprises the involvement of the mode of touch and support for embodied forms of interaction like grabbing, pinching, twisting, tilting, shaking, throwing, and releasing, all of which constitute natural gestures that enable the direct manipulation of objects.

Building on the work summarised above, this chapter re-examines the affordances of the iVR technology used during interventions. In doing so, it explores the potential of such affordances to influence students' understanding of the concepts and procedures with which they engaged. To do this, the following sections discuss findings from the qualitative analysis of video recordings which stem from participant interviews and their engagement with the virtual laboratories. Recordings of the latter consist of composite videos involving the physical actions performed by participants and corresponding gameplay from the VEs.

In order to create a corpus of conversational gestures, inductive coding was initially performed on every recorded interview using NVivo 12 Pro. The identified gestures were subsequently classified into themes to prepare them for analysis (see Table 9.1). However, the theoretical framework used for the analysis of gestures draws from Multimodality theory (Kress, 2010; Jewitt, 2014), with particular focus on three modes of representation: hand gestures, posture, and speech. From a multimodal approach, these forms of communication provide insights into the ways in which participants understood the virtual environments. Furthermore, as first argued in Chapter 1, they can act as a window into participants' meaning-making practices concerning the conceptual and procedural content with which they engaged during interventions. As it is discussed throughout this chapter, being mediated by technology, the way participants are allowed to use their bodies to engage with a virtual environment can shape how this is understood. This implies that embodied forms of interaction like changing the viewpoint, moving the limbs, and walking can allow users to understand a concept or procedure in a certain way by grounding it on physical properties such as the size, directionality, and spatial location of objects in relation to their own body and its position within the virtual environment. These forms of understanding the space and the concepts and procedures it presents constitute meaning-making practices.

Table 9.1. Coding scheme of video recording from interviews.

Descriptors			Number of instances per study condition		
Themes	**Codes**	**Type of gestures**	**Low-end iVR**	**High-end iVR**	**Total**
Action and movement	Indicating gradation	Metaphorics	16	6	22
	Signalling a meniscus	Deictics	1	3	4
	Use of lab equipment	Iconics	49	56	105
	Re-enactment of procedures	Iconics	31	98	129
	Describing interactions	Iconics	51	53	104
	General actions or behaviour	Iconics	63	18	81
	Locomotion	Iconics	26	10	36
Spatial awareness	Sense of space	Deictics	14	0	14
	Sense of direction	Deictics	16	5	21s
Sense of self	Sense of presence	Metaphorics	7	5	12
	Denoting proprioception	Deictics	44	35	79
Abstractions	Describing concepts or notions	Metaphorics	3	19	22
	Depicting time	Metaphorics	9	1	10
	Cause / effect	Metaphorics	1	0	1
Maths	Counting	Deictics	7	3	10
Contrast	Yes / No	Deictics	17	16	33
	Describing alternatives	Deictics	20	2	22

9.1 The body and spatial awareness

Multimodal analysis of recorded interviews with participants showed that their conversational gestures and movements denoted their sense of proprioception and depicted the virtual environments in relation to their bodies. That is, these gestures illustrated some of the ways in which embodied engagement shaped their spatial understanding of those environments and the dynamic relationship between the real and the virtual realms. This was established by the positioning of the participants' hands and how this related to their speech, and to the actions observed in the video recordings of interventions. Proprioception was established as the foundation of a gesture when it replicated a real movement that was synchronously simulated in the virtual environment, or one that simply depicted the use of a controller. On other hand, their spatial positioning in relation to the space was established as the basis of gestures and postures in those instances where these reflected the location of objects in the virtual environment based on height, distance, and right or left positioning taking the participant as the centre. Figure 9.1*[31], for instance, shows Participant 13 explaining how he is able to perceive the position of his hands regardless of whether he can see them:

> If my eyes are closed… if I rotate my wrists, it will rotate... if I put my arms like that and I close my arms and when I get them together, I just know that... if I close my eyes, I know I'm getting them there together. (P13-HiVR)

In his demonstration, Participant 13 simulates the grabbing motion used in HoloLAB Champions. In this position, the fingers of each hand rest along the body of the controllers, and the thumbs are placed on their faces. To illustrate his sense of proprioception, participant 13 rotates his hands; subsequently, he extends his arms out to each side and slowly closes them until both hands meet in

Figure 9.1*. Participant 13 describes the congruency of movements in HoloLAB Champions (Schell Games, 2018).

[31] All figures marked with an (*) portray gestures or postures that participants performed during the interventions. As these are not always clearly illustrated through still images, animated gifs have been created capturing movement. These can be found in Appendix D.

the middle in front of his chest. Interestingly, although these motions can be replicated in the virtual environment, thus suggesting that the participant is attempting to enact the visual synchronicity of those actions (physical behaviour and virtual simulation), the way he chose to position his hands does not constitute a visual depiction. Instead, this denotes his perception of touch.

HoloLAB Champions did not include a virtual representation of hands. Additionally, the experience was designed around controllers, different to the ones used during interventions. As a result, the virtual controllers in this experience did not match those physically held by participants. The above suggests that, for Participant 13, touch had a bigger impact in how he processed information. In that sense, tactile input seemed to have been codified as part of the participant's mental framework, which he later drew on to convey the notion that the virtual controllers perceptually became his hands.

Another example of the above is illustrated in Figure 9.2* where Participant 17 is shown discussing how her movements were not fully replicated in Labster, "It wouldn't show the whole movement, like grabbing... At the start, I had to grab the artificial corn, it was just the hand floating and grabbing it, nothing else." For Participant 17, interaction was surrogated to the virtual hand and not done by her directly. This is reflected in the way she refers to the hand as a third entity, thus suggesting the absence of the perception of ownership and self-location (see Wirth et al., 2007; Slater, 2009; Black et al., 2012).

Figure 9.2*. Participant 17 discusses interaction in Labster (2018).

Rather than reflecting interaction or the use of a controller, Figure 9.2* shows Participant 17 performing a type of gesture, which McNeill (1992) describes as deictic because it denotes directionality and spatial positioning. This particular arrangement illustrates the spatial configuration of the virtual environment (Labster) and how the participant's virtual hand moved towards her left to pick up the corn. It is important to note, however, that the modes of touch and gesture are absent from this gestural depiction of the environment as Labster did not support them. Thus, unlike Figure 9.1*, here the participant does not position her hands in a way that shows a grabbing gesture, nor does she move them in a way that could denote the performance of a task. Instead, her movements and gestures only indicate the direction in which the virtual hand moved and the spatial arrangement of interactable objects in relation to her visual perspective.

The contrasting representations made by both participants above reflect a common observation during interviews. When support for natural gestures involving touch is present in the virtual environment, this permeates into the depictions that participants make of it, as was the case with HoloLAB Champions. In contrast, when such support is absent, as with Labster, those representations rely more on the visual mode, thus reflecting spatial relationships, relative size, or what the virtual hand did instead.

Figure 9.3*. Participant 17 discusses the use of pipettes in Labster (2018).

Another example of deictic gestures can be observed in Figure 9.3* where Participant 17 provides details of the laboratory equipment that she had to use during the intervention. Whilst describing the pipettes, the participant points to the space in front of her and drags her finger in the air from right to left as if counting the pipettes that she is describing. Once again, the mental image of the space that her gestures denote is congruent with the spatial relations of manipulatives in the virtual environment. That is, the pipettes were presented in front of her, and they were positioned in the order that she signals with her gesture.

Comparatively, Figure 9.4* shows Participant 18 explaining how to operate a pipette whilst using what McNeil (1992) designates as iconic gestures. In this example, however, gestures are not underpinned by the tactile feeling of a controller, or the direct physical engagement with a manipulative. Instead, these gestures are based on the visual and spatial conditions of the virtual hand performing a task. Whilst describing, "I had my hand up here pointing at it, almost like holding a pipette, kind of this way," Participant 18 provides a gestural representation of the spatial position and volume of the pipette as he pretends to hold it with one hand, whilst moving his other hand up and down to convey a sense of its shape and size. This is suggestive of how in the absence of tactile feedback and movement, it is the visual mode that is primarily used as a frame of reference to make sense of the virtual environment.

Figure 9.4*. Participant 18 demonstrates the use of a pipette in Labster (2018).

Participants 06 and 04 in Figure 9.5* and Figure 9.6* respectively, also employ iconic gestures to describe behaviour during the intervention. Moreover, these gestures similarly denote the spatial arrangement of manipulatives in the virtual environments. However, unlike the previous three examples stemming from Labster where touch and direct gestural interaction were not supported, it can be observed here that gestures are more detailed.

Figure 9.5*. Participant 06 describes tactile feeling whilst holding the controllers in HoloLAB Champions (Schell Games, 2018).

For instance, Figure 9.5* shows Participant 06 describing how he felt like he was holding a scoop rather than the controller when measuring a substance, “I can actually picture me slowly turning to empty out the spoon and then with the pipette I can almost kind of feel it.” His depiction combines the visual input of holding a scoop, the tactile perception of the controller, and the replication of the precise twisting movement required to tilt the scoop and release small amounts of the substance. This was found to be consistent across participants who took part in the high-end iVR condition where touch and movement were supported. In this study condition, gestures were found to be richer and drew on the visual, tactile, proprioceptive, and kinetic modes of representation and interaction (see Table 9.1 for the list of codes and count of instances).


Figure 9.6*. Participant 04 describes a break in her sense of proprioception in HoloLAB Champions (Schell Games, 2018).

Similarly, in Figure 9.6*, Participant 04 can be seen explaining an instance when her hands and their corresponding virtual representations did not match each other’s movements, thus temporarily breaking the sense of proprioception in HoloLAB Champions, “when a beaker fell over, but didn't smash, I had to pick it up, but it [the virtual controller] was twisted, but the beaker was straight.” Her description and gestural depiction of her movements provide insights into how each mode contributed to the communicative act and complement speech. The position of Participant 04’s hands denote the special arrangement of manipulatives in the space and how they were interacted with. However, unlike the previous examples, the detail to which this is demonstrated differs due to the involvement of the modes of touch and gestural movement. In this case, although Participant 04 uses her left hand to illustrate what she is describing in speech, her right hand also assumes the same position as if holding the controller. During her explanation, Participant 04 initially performs a deictic gesture that depicts the flask falling over. This is followed by a series of iconic gestures that simulate picking up the flask, lifting it, and rotating it, thus encapsulating the visual properties of the object, the perception of movement, directionality, and spatial location, as well as evoking the tactile feedback of the interaction.

Based on these findings, it can be argued that due to the sensory-motor nature of immersive virtual environments, the gestures made by participants instantiate spatio-dynamic relationships between the different modes of representation operating at the moment of engagement. These stem from visual, tactile, proprioceptive, and kinetic input.

9.2 Subverting expectations about interaction

Mechanisms for movement and interaction constitute one of the most prominent differences between the virtual environments used in this study. Whilst Labster was capable of distal interaction and teleportation, it could not replicate the movement of participants, or the performance of gestures to interact with the virtual objects. HoloLAB Champions, on the other hand, not only required that participants performed natural gestures to interact with virtual objects, but it also enabled direct manipulation, movement, and the perception of touch through haptic controllers.

It was observed that the involvement of the modes of touch and gesture influenced participant expectations of interaction. In HoloLAB Champions, for instance, controllers perceptually assumed the role of whatever virtual object participants were holding (i.e., a scoop, flask, pipette, cylinder, weighing boat, etc.) via the performance of gestures such as grabbing, twisting, pinching, tilting, shaking, throwing, and releasing. By grabbing the controller, visual and tactile stimuli evoked the perception that what was felt in the hand was in fact the virtual object. However, this was found to influence expectations of the physical and tactile properties of such objects. As pointed out by Participant 06, "When I grabbed an object, I was expecting to hold it as if I was actually grabbing it in real life." This is illustrated in Figure 9.7* where Participant 06 simulates grabbing a flask by making a gesture depicting its shape. This gesture, however, does not only provide visual resemblance, the way McNeill (1992) conceives iconics. This gesture also instantiates action (see Streeck, 2008) which, in this case, shifts from expected to actual behaviour.

Figure 9.7*. Participant 06 describes expectations of touch in HoloLAB Champions (Schell Games, 2018).

Initially, Participant 06 demonstrates a width of the aperture of his hand that he considers congruent with the apparent size and shape of the virtual flask. He then reinforces his point by grabbing the edge of the tablet in front of him, thus adjusting the angle, position, and width of his grip. Finally, his gesture transitions to a position depicting him holding a controller, thus illustrating the discordance in tactile perception between the shape and size of the controller and the shape and size of the virtual object.

Interestingly, these types of incongruencies were more noticeable by participants like Participant 06 who engaged with HoloLAB Champions in the high-end iVR condition. Based on observational data, this can be attributed to preconceptions that participants have around touch and movement in the real world. Particularly, how the intensity and directionality of movement can affect the objects being manipulated such as substances inside glassware. Additionally, the ways in which tactile perceptions of weight, texture, rigidness, size, and shape of such objects are experienced differently when mediated by technology like controllers.

In contrast, participants who engaged with Labster in the low-end iVR condition did not report an increased level of such incongruencies. As this virtual environment did not have the capacity to support touch and movement, it was observed that participants adjusted to these conditions and generally avoided engaging in behaviour that would highlight the limitations of the technology such as waving arms or changing their body posture.

Another expectation brought about by the integration of direct, gestural interaction concerns the consequences of actions in the virtual environment. In Figure 9.8*, Participant 24 demonstrates how she physically reacted to behaviour in the VE, “If I wanted to grab something that I was afraid that it might spill, I had to move back a bit until I leave a bit of space between me and the beaker.” Participant 24 is seen here performing the grip gesture whilst getting closer to the table in front of her as a way to convey her proximity to the laboratory equipment and show how that could be an issue if she spilled one of the substances she was mixing during the experience. Despite knowledge that things in the VE could not physically harm her, Participant 24 steps away in anticipation to the potential spillage which, as argued by Slater (2009), constitutes a realistic response that indicates the assumption of the VE as plausible.

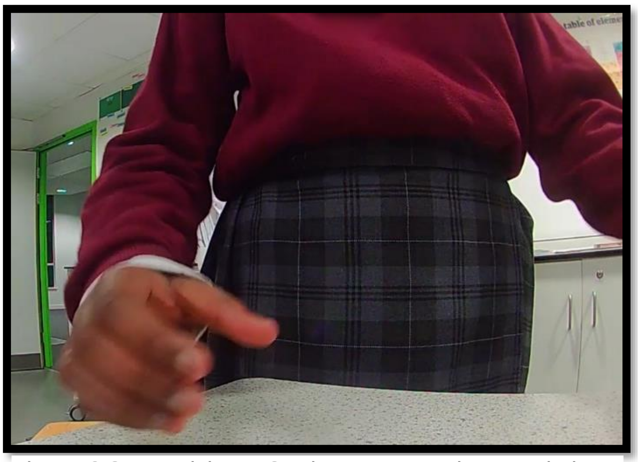


Figure 9.8*. Participant 24 demonstrates her proximity to manipulatives in HoloLAB Champions (Schell Games, 2018).

Similarly, in Figure 9.9*, Participant 13 is seen demonstrating the motion performed when moving a beaker from one side of the workstation to the other. His demonstration juxtaposes slow and fast movements using iconic gestures to illustrate the effect of the movements on the liquid substance he is pretending to hold in his hand, "even if I wanted to pick it up and I moved it too far that way, the beaker, it spills because it was too fast." Here, Participant 13 uses this demonstration to justify how he modulated his behaviour concerning interaction with manipulatives to avoid effects such as the spilling of substances as seen in Figure 9.10*.

Figure 9.9*. Participant 13 illustrates consequences of careless behaviour in HoloLAB Champions (Schell Games, 2018).

In both examples above, movement and touch caused participants to re-evaluate their assumptions about the environment itself and what could be expected from their physical interactions with it. Despite performing similar tasks, participants who engaged with Labster did not demonstrate these subversive expectations. This can be partly explained by the impossibility to make mistakes in Labster, thus eliminating the need to simulate consequences.

The findings discussed above also suggest that the mere addition of the modes of touch and movement could carry with them two types of assumptions. Firstly, that the direct manipulation of virtual objects through natural gestures could lead to the attribution of physical properties to objects such as a substance being wet. But also, that the simulation of consequences of behaviour could possibly have an impact on reality, such as the belief that it is possible to spill a virtual substance on oneself.

Figure 9.10*. Participant 13 spills a substance in HoloLAB Champions (Schell Games, 2018).

Because Labster was not capable of supporting movement nor touch congruently to the visual mode in the same way as HoloLAB Champions, this could also explain why participants in the low-end iVR condition (Labster) did not adjust their expectations of the environment, but rather adjusted their behaviour.

9.2.1 **Behavioural change**

In the case of Labster, it was observed that participants avoided the movement of their hands, arms, or body to reduce the potential to encounter incongruent perceptual stimuli such as perceiving the movement of their hand, but not seeing it replicated in the VE. However, changes in behaviour were not solely observed as a mechanism to keep incongruencies between visual, motor, and tactile stimuli from emerging. Behavioural change in HoloLAB Champions, for instance, took place in response to the adjustment of expectations that participants made because of congruent and synchronous visual, motor, and tactile stimuli. In this respect, behavioural change was found to occur under four scenarios: (a) to test the limits of the VE in relation to its capabilities to enable movement, interaction, and the effects of such interaction, (b) to avoid mistakes, (c) to correct mistakes, and (d) to naturally engage with the VE.

Figure 9.12*. Participant 13 describes the realism of interaction in HoloLAB Champions (Schell Games, 2018).

Regarding the first of those scenarios, in Figure 9.12*, Participant 13 illustrates how interaction matched his expectations of reality, thus increasing the validity of the VE, “at the end of one of the practicals, I grabbed a spoon and then chucked it... and the way it throws. And if I wanted to put it down, I could just drop it and it would drop. Of course, if it was glass it would break.” Here Participant 13 simulates picking up a scoop and throwing it, a behaviour that he performed during the intervention as an attempt to explore the interactive potential of the VE and the effect of his actions (see Figure 9.11*).

Figure 9.11*. Participant 13 throwing a scoop across the laboratory in HoloLAB Champions (Schell Games, 2018).

Trying out different things to evaluate what could be done in the VE and which objects were interactable constituted a behaviour that was observed repeatedly in HoloLAB Champions. This behaviour instantiates the way in which support for touch and movement opened a wider range of affordances for interaction and exploration.

Mistake-making constituted another source of behavioural change derived from the capacity of the VE to support touch and movement. These adjustments of behaviour were found to follow two possible functions: (a) adjusting behaviour to avoid making mistakes, or (b) adjusting behaviour to correct issues caused by mistakes. Regarding the former, in Figure 9.14*, Participant 13 employs an iconic gesture to illustrate how his movements had to be gentler to avoid the spillage of the substance, “I wasn't looking close enough to see if I was actually pouring in […] I lost a lot of points for spilling a tiny bit, but from there, I just tried to be more careful.” As observed in Figure 9.13*, Participant 13 not only modulated the intensity of his pouring gesture, but also his posture.

Figure 9.14*. Participant 13 discusses how he adjusted to the conditions of HoloLAB Champions (Schell Games, 2018).

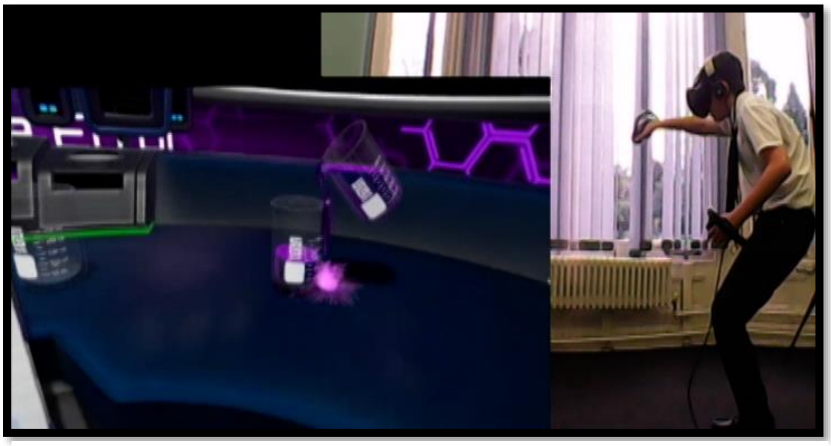


Figure 9.13*. Participant 13 transfers and spills a substance in HoloLAB Champions (Schell Games, 2018).

By leaning forward and bending down, Participant 13 managed to get a closer view, improve his perception of depth, and gauge the distance between beakers to avoid spilling all of the substance:

> I couldn't see it in my eye, but I've done it and it worked. I took it right down and tried to crouch down again and I put them next to each other just to see which one is higher, then I went and put it and I did it and it worked. (P13-HiVR)

Here, Participant 13 describes how being able to change his body posture and appreciate the meniscus in the cylinders at eye level was necessary to determine the precise volume of liquid they contained (see Figure 9.16*, and Figure 9.15*). This is depicted not only in Participant 13's hand gesture, but also in his posture as he lowers his head to enact the adjustment of his viewpoint, and in his gaze when he looks up at the imaginary scoreboard whilst describing that he lost points for spilling the substance.

Figure 9.16*. Participant 13 describes changes in body posture to engage with manipulatives in HoloLAB Champions (Schell Games, 2018).

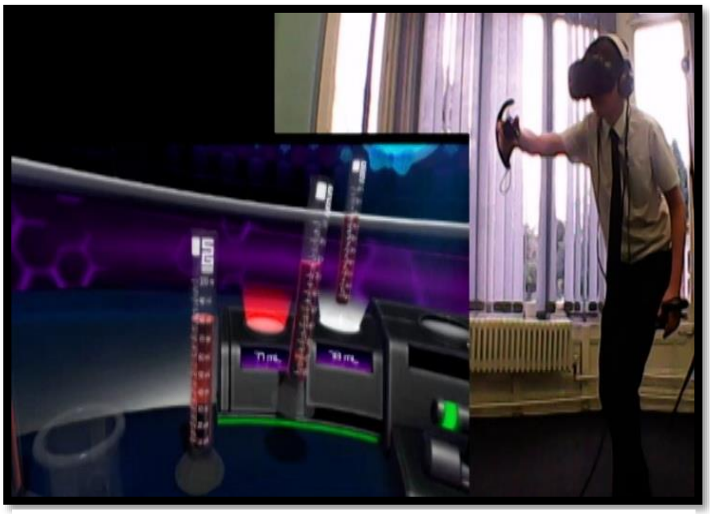


Figure 9.15*. Participant 13 comparing volumes in cylinders in HoloLAB Champions (Schell Games, 2018).

The final scenario where behavioural change was observed concerns the natural forms of physical engagement that are afforded by the VE. Figure 9.17* illustrates how Participant 13 was able to pick up scoops that fell on the floor just as he would expect in reality, "I dropped one of the spoons on the floor, I could pick it up." This allowed him to adjust his assumption about that could be done in the space, thus encouraging divergent behaviour such as when he threw away a scoop.

Figure 9.17*. Participant 13 picks up a scoop from the floor in HoloLAB Champions (Schell Games, 2018).

Based on the findings discussed in this section, it can be summarised that whilst the integration of touch and movement in immersive virtual environments could bring about more natural forms of interaction, support for these modes of representation could also come with certain expectations defined by two types of relationships: (a) between the participants' sense of proprioception and the limits to gestural interaction in the VE, and (b) between the tactile stimuli being perceived and the physical properties assumed of the virtual objects or manipulatives. This includes their perceived size, shape, weight, texture, and rigidity. Regarding the first kind of relationship, this was found to encourage behavioural change in the VE under four types of conditions: (a) to explore the capabilities of the VE in relation to touch and movement, (b) to engage with the VE through natural movement and gestures, (c) to avoid making mistakes, and (d) to mend issues caused by mistakes.

9.3 Kinetic, tactile-kinaesthetic properties of procedural and conceptual understandings

This section looks at the ways in which participants employed gestures to explain conceptual and procedural understandings and whether these differed depending on the study condition in which participants took part. Although both virtual environments used in this study introduced basic concepts around chemistry and required the performance of tasks, the balance between the two was skewed towards the latter. Additionally, active participation was a requirement for progression in both study conditions, thus making the capacity for interaction, touch, and movement the most contrasting aspects between both experiences.

Drawing from the work of Segal (2011), this research argues that gestures produced in speech can reflect the kinetic tactile-kinaesthetic properties of gestural interfaces. On that note, Segal (2011) proposes that human computer interaction (HCI) involving direct manipulation should consider three aspects of gestural interface design: (a) behavioural mapping, which the author defines as natural movements or gestures that establish cause/effect relationships and that the user would employ in a real environment; (b) conceptual mapping, which refers to the correspondence between the gesture and the virtual representation of the concept to be learnt; and (c) direct-touch input, which concerns the physical manipulation of virtual objects.

Figure 9.18* illustrates those three aspects. Here Participant 04 explains how to measure the mass of a substance whilst conceptualising the notion of taring in HoloLAB Champions:

> You get your spatula and then... well, first your, what are they called, weighing boats? on the thing... the scale... And then, is it tare? tore?... tare. Click that and reduce the weight of that. And then put your mass in to measure the mass without the weighing boat. And then, depending on how much you want, there's different spatulas, which I found out later on, and then you use those to get your accuracy. (P04-HiVR)

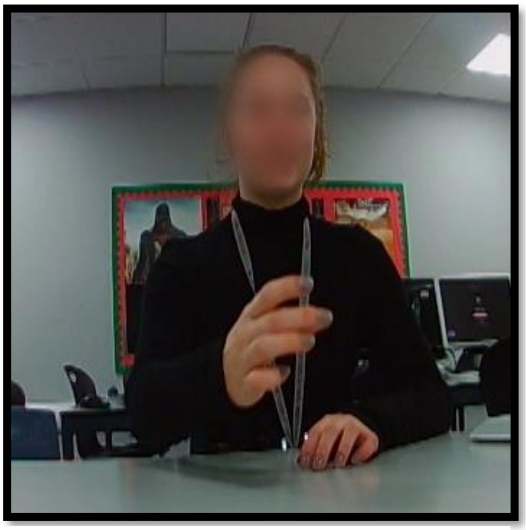


Figure 9.18*. Participant 04 conceptualising measuring mass in HoloLAB Champions (Schell Games, 2018).

Whilst describing the procedure, Participant 04 employs a series of iconic gestures that depict her behaviour in the VE. Thus, her movements are clearly mapped to tasks like placing a weighing boat on an analytical balance, pressing a button to tare it, and holding laboratory instrumentation like a scoop. These gestures, also denote touch and direct manipulation by being re-enactments of the movements Participant 04 used during the intervention. When indicating that a weighing boat must be placed on the analytical balance and the tare button pressed, Participant 04 places her hand flat mid-air as to indicate the level of a substance and lowers it whilst indicating that taring would “reduce the weight.” This metaphoric gesture, however, does not depict an action, it constitutes what Streeck (2008) defines as ceiving, a type of gesturing that communicates or is mapped to a concept. In this example, such concept is the understanding of what taring entails.

Based on the example above, gesture was observed to be co-expressive with speech and, as argued by McNeill (1992), cannot be explained in isolation from a purely kinetic standpoint. Furthermore, the findings discussed above suggest that iconic gestures enacting behaviour and denoting touch and direct manipulation can be co-expressive with ceiving as well. Although gestures are not mutually exclusive and can, for instance, act as icons and metaphors simultaneously, it was observed that gestures derived from behaviour and conceptual understandings can also be co-expressive whilst remaining distinctive. For instance, Participant 04’s use of iconic gestures to explain the procedure and metaphoric gestures to indicate a decrease in weight constitutes a single act of signification that combines concept and process through gesture. In that sense, gestures can be co-expressive with each other as well as with speech.

Another observation from the example above is how Participant 04 gave the metaphoric gesture a physical property that could be enacted, the depiction of the level of a volume. Interestingly, despite the incongruency of using the physical property of a liquid to describe a solid, the metaphor effectively conveyed the concept of taring. As proposed by Lhommet and Marsella (2014), this attribution of physical properties constitutes the grounding or mapping to concrete elements that a concept needs before being depicted through gesture.

Figure 9.19* illustrates another instance of conceptual grounding, this time in Labster. Here, Participant 08 explains the concept of a serial dilution:

> Well, you would take a part of one solution, and you would take a bit of it and that would dilute it down when you put it into the other one and you keep doing that over and over again until you have the right amount that you need. (P08-LiVR)

The grounding of the gestures shown in Figure 9.19* stems from the laboratory equipment and their spatial location. Participant 08 is seen pretending to hold a pipette with his right hand and making subtle movements up and down simulating the insertion of the pipette into test tubes to draw and release liquid from one to the next. Despite not making any mention of either type of equipment, the properties of these gestures are used to denote the notion of transfer and repetition, which are central to the idea that the concentration of a substance can be reduced with every transfer of liquid.


Figure 9.19*. Participant 08 explains what a serial dilution is in Labster (2018).

Also, it is important to note that the limited capacity for interaction in Labster is reflected in the less pronounced and simpler gestures used by Participant 08. This contrasts with the more detailed and varied gestures used by Participant 04 in the previous example. This is suggestive of how, whilst being co-expressive with speech, gestures also depict the kinetic tactile-kinaesthetic forms of interaction afforded by the virtual environments. Although both can denote conceptual mapping and some degree of behavioural mapping, only participants who took part in HoloLAB Champions showed influence from direct-touch input in their gesturing.

Figure 9.20* and Figure 9.21* below illustrate other instances of conceptual grounding. Figure 9.20* shows Participant 06 referring to the surface tension of a liquid describing how to read the level of such liquid in a cylinder, “You get to eye level with it and check that the bottom of the meniscus which is kind of the curvature that the liquid forms in the container was at the top of the line.” In this case, Participant 06 refers to the curvature produced by surface tension as the meniscus which he outlines with his index finger and traces back and forth in a virtual container that the visualizes in front of him.

Figure 9.20*. Participant 06 explains what a meniscus is in HoloLAB Champions (Schell Games, 2018).

Unlike the previous example, Participant 06’s iconic gestures depict not only behavioural and conceptual mapping by simulating movement and representing the notion of surface tension as the physical property of a line that bends. As argued by Becvar et al. (2007), this constitutes a cognitive artifact in the sense that it acts as a tool to support reasoning by more concretely representing or abstracting a concept.

Figure 9.21* also illustrates this type of concretization of an abstract concept. Here Participant 14 is seen explaining the notion of cross-contamination of a sample, “Let's say you have the tip for it. If you dip into each solution, not only will it start mixing with the others, but the accuracy wouldn't be good enough... not accuracy, I mean it would get contaminated basically.” Through her gestures, Participant 14 outlines the shapes of the pipette and the tips, she suggests the spatial location of test tubes, and uses her index fingers to denote switching from one thing to another. These concrete properties act as conceptual grounding to describe transfer and repetition which, similar to Figure 9.19*, represent central notions related to the concept of a serial dilution. Furthermore, this illustrates how a sample can get contaminated in that transfer process if the tip of the pipette is not replaced before each repetition or step.

Figure 9.21*. Participant 14 explains how a sample gets contaminated in Labster (2018).

Similar to Figure 9.19*, the gestures shown in Figure 9.21* are not behaviourally mapped or grounded on direct-touch input. This constitutes an expected outcome considering *Labster's* lack of support for gestural interaction, movement, and touch. In contrast, Figure 9.22* shows Participant 04 describing the process to measure liquid substances:

> It depends on the amount of volume of liquid that you're trying to measure, but like the usual measuring cylinder or your pipette and then you just... with the measuring cylinder you need to pour it, with the pipette you draw it out and then put it in. (P04-HiVR)

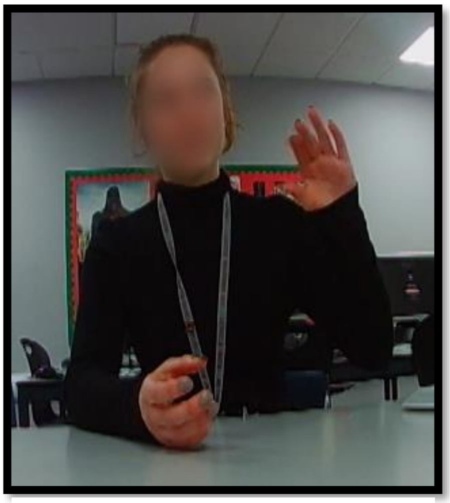


Figure 9.22*. Participant 04 explains how to measure liquid substances in HoloLAB Champions (Schell Games, 2018).

In this instance, Participant 04 uses iconic gestures to depict the shape and spatial location of a pipette and cylinders. Whilst pretending to hold them, she performs a pouring motion suggesting the transfer of liquid from one to the other. Subsequently, Participant 04 uses her left hand to enact controlling the pipette and putting it in and out of two beakers. These gestures depict direct-touch input through the way she is "holding" the laboratory instruments, as this reflects the physical positioning of her fingers whilst using the controllers. The enaction of the tasks, on the other hand, acts as behavioural mapping for the gestures. Conceptual mapping, however, is absent here as Participant 04 is describing a process, rather than an abstract concept.

Generally, the findings presented in this section reinforce the previous assertion that gestures accompanying speech could depict the kinetic tactile-kinaesthetic affordances of a virtual environment. When touch, movement, and direct manipulation are supported, as is the case with HoloLAB Champions, this could influence the ways in which participants make sense of the virtual environment, thus shaping their understanding of conceptual and procedural knowledge as demonstrated in the types of gestures and movements that they employed during interviews.

Chapter summary

The findings discussed in this chapter address the third research question guiding the empirical study. This concerns the ways in which free movement and embodied interaction shaped participants' understanding of the concepts and procedures introduced during interventions. The following is a summary of such findings:

- The gestures made by participants when discussing their engagement with the virtual environments instantiate spatio-dynamic relationships between the participants and the objects or manipulatives in them. That is, gestures were found to depict the spatial position and organization of the virtual environment using the participants' first-person-perspective as a frame of reference.
- It was found that the gestures made by participants reflected the level of support for movement, direct interaction, and touch of the iVR systems. Participants who engaged with HoloLAB Champions performed gestures that encapsulated visual, proprioceptive, and touch input. In contrast, the gestures of participants who engaged with Labster relied more on the visual mode, thus reflecting spatial relationships, relative size of objects, and the actions performed by the virtual hand.
- It was observed that the capacity for movement and touch in HoloLAB Champions caused participants to re-evaluate their assumptions about the environment and the ways in which it afforded interaction. This was instantiated in two ways during interventions: (a) through the congruency between the participants' sense of proprioception and the visual simulation of their actions, and (b) through the congruency between perceived tactile stimuli and the physical properties expected of the virtual manipulatives (i.e., size, weight, texture, shape, rigidity, wetness, corrosiveness, etc).
- The affordances of movement and direct gestural interaction in HoloLAB Champions were found to encourage behavioural change during interventions. This was demonstrated in participants' subversive behaviour which could be aimed at testing the limits of what they could do in the VE, avoiding or correcting mistakes, or simply performing tasks in a more natural way.

- Gestures were observed to be co-expressive both with speech and with other types of gestures. That is, whilst gestures could act as icons or metaphors simultaneously in support of speech, they were observed to also support other distinct types of gestures as part of a single cohesive communicative act.
- It was observed that gestures used to discuss concepts such as taring, serial dilutions, or a meniscus were given physical properties derived from the tasks that participants performed associated to these concepts. This acted as conceptual grounding for their depiction through gesture. Alternatively, gestures derived from procedures were observed to be rooted on student behaviour, and only participants who engaged with the high-end iVR condition showed signs of direct-touch input in their gesturing. This demonstrates that gestures accompanying speech could depict the kinetic tactile-kinaesthetic affordances of the virtual environments with which participants engaged, thus, to some degree, shaping their understanding of conceptual and procedural content.

Chapter 10: General discussion of findings

Chapter overview

This chapter summarises the findings stemming from the preliminary work (see Chapter 5), as well as from the main empirical study (see Chapter 6, Chapter 7, Chapter 8, and Chapter 9) and discusses their implications in relation to the field of VR and the use of these immersive technologies for education.

10.1 Preliminary work and pilot studies

The work carried out in preparation for the main empirical study involved the analysis of different types of immersive virtual reality hardware and experiences (see Chapter 5). This work was guided by three main questions looking to: (1) define the properties of different types of iVR hardware, (2) appraise how such properties could enable different opportunities for sensory-motor engagement, and (3) map the congruency of gestural movements with the conceptual and procedural content to be learnt in each iVR experience.

10.1.1 The features of immersive virtual reality technology.

Two groups of features of VR hardware have been identified in this research (see Chapter 5.1). These reflect the ways in which sensory-motor engagement is supported by different types of systems, thus distinguishing them from each other.

The first group considers computing and graphical processing, as well as audio-visual properties such as spatial audio, screen size, type, shape, resolution, refresh rate, and field of view. These are responsible for perception which, as argued by Sherman and Craig (2003), constitutes a key component of a VR experience.

The second group designates properties of the hardware that enable movement and touch. These kinetic, tactile-kinaesthetic features include the tracking system, input devices, the types of interaction these enable, support for locomotion, and the type of setup in which agents can experience the virtual environments. As reported by Slater et al. (1998), mechanisms for interaction that involve whole-body movement can increase the illusion of presence. Furthermore, interactivity and increased vividness of the virtual experience has been found to enhance learning (Kwon, 2019). This suggests that iVR systems with more robust support for movement and direct interaction could provide experiences that are closer to reality and offer more opportunities for meaning making through action and bodily engagement.

The analysis of VR hardware carried out for this research (see Chapter 2) brought into focus two concerns. Firstly, although there are signs of stabilization such as the discontinuation of low-end HMDs and the standardisation of mechanisms for interaction such as the layout of controllers, the landscape of immersive virtual reality technology remains highly fragmented which is detrimental to consumer adoption. This constitutes a condition previously observed by Orland (2019) and Probst, Pedersen and Dakkak-Arnoux (2017). In addition, the same variability in the features of hardware that brought about such fragmentation has a direct impact on the suitability or certain types of systems to particular uses and purposes.

10.1.2 The sensory-motor affordances of immersive virtual reality technology.

Based on the analysis of several types of hardware and iVR experiences (see Sections 5.1 and B.1, respectively), three affordances of immersive virtual reality were identified: (1) the sense of presence, (2) the sense of embodiment, and (3) movement.

The sense of presence is a concept that has been theorized (Slater and Usoh, 1993) and researched extensively in relation to immersive and non-immersive VR (Youngblut, 2003; Hvass et al., 2017; Shu et al., 2019; Ratcliffe and Tokarchuk, 2020). As described by Slater (2009) and Wirth et al. (2007), experiencing presence is indicative of the elicitation of the feeling of being in a virtual environment despite knowledge to the contrary, and the perception that what is happening is plausible, thus eliciting appropriate reactions from agents. This is particularly significant in immersive virtual reality as the capacity to visually and aurally isolate agents from reality and to perceptually situate them in a computer-generated space is a fundamental affordance that these kinds of systems can provide.

The sense of embodiment constitutes another central affordance of immersive technologies, particularly HMDs as these can create the necessary conditions to elicit the feeling that an agent is located inside the virtual body (self-location) (Kilteni, Groten and Slater, 2012), has wilful control over it (agency) (Argelaguet et al., 2016), and it is the source of experience (ownership) (Perez-Marcos, Sanchez-Vives and Slater, 2012). As observed by Slater (2017) agents can experience the virtual body as their own regardless of the way it looks. Furthermore, as empirically proved by the Proteus Effect[32], this can bring about changes in behaviour, attitudes, cognition, and psychological state. However, as argued by Slater and Sanchez-Vives (2014), three conditions need to be met for agents to experience some degree of the sense of embodiment: (1) the virtual environment must be experienced from a first-

[32] It consists in a change in attitudes and behaviour due to the effect of a digital representation of the self.

person perspective, (2) there must be visual-proprioceptive correspondence between the virtual and physical body, and (3) movements must be synchronously replicated.

Lastly, concerning the ability to physically move in order to interface with the virtual environment, engaging in it using the body can involve locomotion (Boletsis, 2017), changes in body posture (Kuno et al., 1999), and interaction through gesture (Malerczyk, 2008; Alkemade, Verbeek and Lukosch, 2017; Jang et al., 2017). Although non-immersive technologies commonly integrate gestural interfaces mediated by cameras or touchscreens, only certain types of immersive technologies support whole-body interaction. In that sense, changing the viewpoint can be done by moving around the space and adjusting the body posture.

Similarly, rather than having to press buttons on controllers, or learn a series of symbolic gestures such as flicking a finger in the air to select an object, the manipulation of objects can be done by direct engagement. This implies that instead of being abstractions that need to be learnt, gestures can be supported through natural movement or behaviour such as picking up objects and rotating them as it is done in the real world. This exempts behaviour that is only possible in the virtual domain such as zooming in on objects or changing their size, which still need to rely on symbolic gestures.

10.1.3 Mapping gestural movements to conceptual and procedural content.

Just as symbolic movements can be mapped to certain behaviour in order to interface with the virtual environment and physically engage with manipulatives (Alkemade, Verbeek and Lukosch, 2017), so can natural gestural movements such as grabbing, pinching, squeezing, or releasing. By mapping gestural movements to behaviour in the virtual environment and to the content to be learnt, as shown in Section 5.3, it is possible to assess the congruency of gesture.

The implications of ensuring congruency across physical gestures, the virtual representations of those gestures, and the content to be learnt is twofold. Physical gesture can act as a grounding for new conceptual and procedural understandings as these can be stored in the brain as spatio-motor image schemata (Hurtienne and Israel, 2007). Moreover, such congruency supports the notion that abstract concepts or ideas can be instantiated in bodily experience (Koch, Glawe and Holt, 2011; Johnson-Glenberg and Megowan-Romanowicz, 2017). Findings concerning this are discussed in Section 10.2.6.

10.2 Main empirical study.

The following sections discuss the implications of the findings presented in chapters 6 – 9. These sections correspond to each of the three research questions guiding the main empirical study which aimed to examine how students' measured learning differed between study conditions and to appraise how free movement and direct gestural interaction could shape students' perceptual states (i.e., presence, agency, and body ownership) and the construction of new conceptual and procedural understandings.

10.2.1 Learning gains between study conditions.

This section discusses findings from interview and observational data, as well as the statistical analysis of pre-, post-, and delayed test scores. These tests provided insights into students' learning about science and how these differed between low- and high-end immersive virtual reality systems (see Chapter 6).

Increases in mean test scores from pre-test to post-test, and from post-test to delayed test in both study conditions across experimental groups indicate that both interventions were able to promote learning gains regardless of the mode of delivery (see **Error! Reference source not found.**). This section discusses the implications of the most significant findings concerning such data.

Firstly, participants in the low-end iVR condition who followed a between-groups design in the intervention saw decreased delayed test mean scores. Through a Spearman's test, it was observed that this decrease was correlated to the elapsed time between the last intervention and the delayed test point. Whilst this might suggest that the newly acquired knowledge diminished in the course of the 43-day average delay, the mean scores of participants who took part in the same intervention, but following a within-subject design, did not decrease. This suggests that the decrease could be explained by the small sample size, as there were only 13 data points stemming from the between-groups design, as opposed to 28 from the within-subject design. Resultingly a larger and more balanced sample between experimental groups would have allowed for a clearer pattern to emerge.

Secondly, results from two repeated measures ANOVAs show a strong statistically significant difference in mean test scores between the low- and high-end iVR conditions across experimental groups. This is indicative of two things:

(a) Despite seeing smaller increments after each testing point in both study groups, participants in the high-end iVR condition outperformed those in the low-end iVR condition. This suggests that HoloLAB Champions was more successful in promoting new understandings about chemistry and laboratory procedures than Labster. Although the difficulty of the content could be considered an explanatory factor, it was observed that the way these iVR environments supported embodied forms of interaction also had a significant effect (see Sections 10.2.2, 10.2.4, and 10.2.6).

(b) Participants in the within-subject groups performed better than those following the between-groups design. This could be explained by the differences in sample size or the potential unexpected influence that the first intervention exerted on how participants engaged with the virtual environment during the second.

Thirdly, results from post hoc paired samples t-tests showed that the mean test score increases observed in the low-end iVR condition were driven by increases from pre-test to post-test and from pre-test to delayed test. Comparatively, results from the high-end iVR condition showed significant mean score increases only from pre-test to delayed test. This indicates that whilst Labster was able to promote learning during the intervention, as well as in the retention of new knowledge at an average of 43 days later, HoloLAB Champions was successful only in promoting knowledge retention at the delayed test point.

The findings above are consistent with previous studies comparing non-immersive and immersive learning environments. In those studies, participants in the immersive condition showed increased knowledge retention at least a week after the intervention (see Chittaro and Buttussi, 2015; K. Babu et al., 2018; Meyer, Omdahl and Makransky, 2019). This research, however, differs in two ways: (1) this study is comparing two immersive systems with distinct sensory-motor affordances (see Section 5.2), which suggests that these may be partly responsible for the differences in mean scores between conditions. And (2) the period of knowledge retention measured in this study ranged from 7 to 89 days ($N = 41$) after the last intervention, averaging 43 days ($SD = 22.5$), as opposed to the one week reported in prior literature. This highlights the need for longitudinal studies looking at knowledge retention as this constitutes one of the areas where high-end immersive systems could show the biggest improvements.

Fourthly, statistical analysis of test results against demographics shows a strong positive correlation between mean scores in the delayed tests and year of schooling. There are two possible explanations for this: (a) participants in higher years might have been more familiar with the content compared to those in earlier years; alternatively, (b) the composition of the sample could have biased the results as the only years represented in the sample were 7, 10, 12, and 13 (year 7 had the least participants) (see Figure 7.1).

Lastly, based on recordings of participant engagement with the two iVR systems, it was observed that support for embodied forms of interaction not only shaped what being corporeal in that space meant, but it also influenced the perception of the VEs as meaning making spaces. In that sense, embodied interaction such as gestural movements that simulate how objects are manipulated in the real world could provide the opportunity for the development of motor control, spatial awareness, and procedural skills, all of which can be instantiated as conversational gestures, as observed during interviews (see Section 10.2.4 and Section 10.2.6). This is congruent with Abrahamson and Lindgren's (2014) assertion that "all ongoing processes of sense making, problem solving, and even manipulating symbolic notation […] activate naturalistic perceptuomotor schemes that come from being corporeal agents operating in spatial-dynamical realities" (p. 359).

Furthermore, based on interview responses, it is suggested that simulating risky behaviour and its consequences could contribute to the way students experienced agency and a sense of responsibility for their actions. In that sense, designing an environment that implements scaffolding techniques and supports embodied exploration, discovery, problem solving, and making mistakes could allow students to get a clearer understanding of the subject matter and its underlying processes. As Roussou and Slater (2020) posit, interaction and free exploration in immersive virtual environments can support skills development and promote problem solving by providing opportunities for incongruencies to appear. It must be noted, however, that findings suggest that the lack of guidance or instructional support can result in those incongruencies not being resolved conceptually.

Resultingly, although Labster did not offer such opportunities for incongruencies to appear as the experience was too restrictive and there was little to no support for exploration, its guidance system allowed for scaffolding to take place. On the other hand, HoloLAB Champions, which encouraged free exploration and interaction, made it possible for students to make mistakes and learn from trial and error. However, whenever incongruencies in their understanding appeared, the guidance provided was not restrictive or robust enough to resolve those incongruencies at the underlying conceptual level which could hinder the transferability of such knowledge beyond that particular instance or context.

10.2.2 Comparing experiences of presence between study conditions.

This section discusses findings concerning how free movement and embodied interaction impacted participants' experience of presence, hand ownership, and agency between study conditions (see Chapter 7).

Based on statistical analysis of responses of the immersive virtual reality presence questionnaire (iVRPQ), it was found that presence scores did not differ across gender or year of schooling. This is an expected outcome considering that the perception of presence would not be thought to be influenced by either of the two variables. Resultingly, it was not necessary to split the sample for further analysis. However, significant differences in measured presence were found between study conditions. Results of a Spearman's rho and eta tests show a negative correlation, $r_s(41) = -.47$, $p = .002$, $\eta^2 = .270$. This indicates that participants who performed experiments in the high-end iVR condition (HoloLAB Champions) experienced an increased perception of being physically present in the virtual environment, compared to those who took part in the low-end iVR condition (Labster).

The spread of response values in the iVRPQ (see Figure 7.1), particularly those from the low-end iVR condition, suggests that whilst some participants experienced relatively high or moderate levels of presence, others experienced very little. Based on interview data and observations during the interventions, it was corroborated that, although participants experienced a decreased perception of presence in the low-end iVR condition, the variability of response values could be explained by issues with the system. This included crashes, low framerate, auditory stimuli external to the virtual environment, and the congruency between the environment and the expectations of realism that every participant had in relation to how the environment should look and behave.

Whilst results of Mann-Whitney U tests showed that differences in presence scores between experimental groups (within-subject design and between-groups design) were not significant, they showed that the order in which interventions were administered could have an effect on participants' experience of presence. The observed effect consists in participants reporting higher than average presence scores in the high-end iVR condition and lower than average presence scores in the low-end iVR condition when each was administered as the second intervention. This was more clearly observed in responses to items 1, 5- 8, 10, and 13 of the iVRPQ.

The fact that the anchoring effect described above was not observed in the group following a between-groups design suggests that participant responses in the group following a within-subject design were biased. Further enquiry into this effect showed that, despite the considerable differences in mean ranks between design groups and across study conditions, such differences are not significant. However, the resulting asymptotic $p = .045$ in the low-end iVR condition suggests that this was caused by the small number of data points in the analysed subsamples. Resultingly, whilst there is not enough data to provide a definitive answer concerning this anchoring effect, the observed results highlight a potential future research avenue exploring the way an initial perceptual experience could impact how a participant judges subsequent ones.

Based on data from interviews, it was found that support for touch could have a stronger effect on eliciting the illusion of presence and hand ownership than visual stimuli. This seems to be particularly effective in highly interactive environments such as the ones used for this empirical study. More interestingly, however, is how touch and gestural interaction evoked a sense of agency even when this was limited, as was the case with Labster. Both of these aspects are further discussed in the following sections.

During interviews, participants consistently pointed to “doing” and “grabbing” as contributors to the illusion of hand and body presence. This signalled that controllers such as the ones used in the high-end iVR condition (see Section 4.2.4) essentially became enablers in what constitutes a simple gestural interface. In that sense, these controllers stopped being objects in and of themselves, as they did not need to be held at all times. Instead, whenever held, the controllers perceptually assumed the role of the virtual object with which participants were interacting, be it a pipette, flask, or any other type of laboratory instrument. As reported by participants, this condition contributed to creating the illusion that they were situated in the virtual environment, that the controllers were their hands, and that they had control over what was happening.

The above is particularly important as it provides insights concerning how these types of environments should be designed involving active exploration and allowing users to engage with manipulatives in a more direct and natural way, as these are not often supported by educational VR experiences using low-end hardware. Moreover, this emphasizes the impact that embodied forms of interaction such as the use of natural hand gestures and support for movement such as body postures could have in students' understanding of the content to be learnt.

The controllers introduced the mode of touch to the virtual environments in the empirical study. In HoloLAB Champions, for instance, they supported gestures and allowed for the direct manipulation of objects. However, despite causing an increased sense of presence, they also became a source of visuo-proprioceptive incongruencies. These incongruencies resulted from the simultaneous perception of conflicting stimuli from reality and the virtual environment such as disparities between the shape, weight, or texture of the controllers being held and the virtual manipulatives. Alternatively, as was the case with Labster, participants in the study had to hold the controller at all times. This seemed to cause a disconnect in perceived tactile stimuli when their virtual hand was not holding anything in the virtual environment.

Concerning the above, it was observed that visuo-proprioceptive incongruencies could break the illusions of presence and hand ownership. Interestingly, these incongruencies did not impact the perception of control. This is consistent with a study by Argelaguet et al. (2016) which showed that the perception of agency can be influenced by the way embodied interactions are integrated around the limitations of a certain technology.

Although, Argelaguet et al. (2016) also concluded that the sense of agency does not directly relate to the degrees of freedom of movement that agents are afforded, this assertion goes against the findings in this study. During interviews, participants reported a stronger sense of agency when they were allowed to freely manipulate objects in the virtual environment (see Chapter 8) and such condition is enabled precisely due to support of 6DoF that high-end iVR systems and their experiences can provide.

Lastly, based on the empirical evidence in this research (see Section 7.2), it was found that breaks in the illusion of presence and hand ownership due to visuo-proprioceptive incongruencies could be restored by two means:

(a) Mending the issue that caused the rupture of the illusion. This aligns with Slater's (2009) assertion that place illusion can be quickly restored by reverting the action that caused a break in presence.

(b) Assimilating the new condition through continuous use. This is consistent with theories of brain plasticity (Kolb and Whishaw, 1998; Gamma, 2021) suggesting that brain structures are shaped by experience, thus allowing for visuo-proprioceptive incongruencies to go unnoticed after they become routine. This was observed in different ways during interventions and included participants not noticing sounds made by other people in the room and not perceiving the cable running from the headset to the computer. More interestingly, participants in the low-end iVR condition who reported having experienced a sense of presence, also reported distancing themselves from the experience by mentally attributing interactions to an avatar (see Section 8.2.2).

10.2.3 Systematising the notion of presence in immersive virtual reality

The findings discussed in the previous section illustrate the complexity of understanding a qualia such as the sense of presence. It is argued that experiencing presence in immersive virtual reality environments is dependent on the visual, as well as kinetic, tactile-kinaesthetic stimuli that participants receive. Based on the literature and findings stemming from the empirical work of this research (see Chapter 7), it is proposed that experiencing presence is dependent on three dimensions (see Figure 10.1), of which the consistency and plausibility of the VE are taken from the work of Slater and Sanchez-Vives (2014), whilst the process of assimilation constitutes a new proposition based on observations and interview data from this research (see Section 7.2).

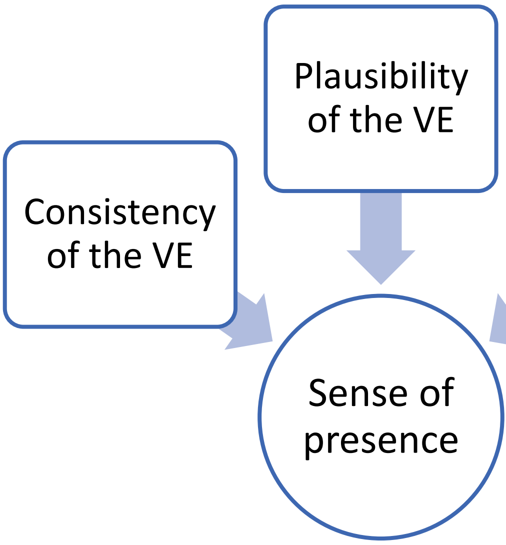


Figure 10.1. Dimensions of the sense of presence in immersive virtual reality environments.

The consistency of the virtual environment is mostly reliant on the visual mode, although other modes of representation can be contributors such as audio. All the components within the virtual space should surround the participant and provide a coherent experience that simulates some aspect of (a) reality.[33] This dimension aligns with the previously discussed notion of place illusion proposed by Slater and Sanchez-Vives (2014) (see Section 3.4.1). The name has been changed, however, to better denote the idea of an environment that is perceptually consistent to convey the sense of being in a "physical" space.

The plausibility of the virtual environment consists in the assumption of the space and what is happening within as plausible. It was observed that this is mostly reliant on the precise replication of behaviour and its effects such as a substance being spilled or glassware breaking when knocked over. This dimension was found to be dependent on the relationship between different modalities such as visual, gesture, and audio. Particularly at the intersection between what is physically performed, and what is observed. Similar to the consistency of the VE or place illusion, this notion is taken from the work of Slater and Sanchez-Vives (2014) who defined it as plausibility illusion (see Section 3.4.1).

There is, however, a third dimension of presence proposed in this research, the process of assimilation of the virtual environment (see Section 7.2). This notion is intimately related to the previous dimension and consists in the adjustment of expectations about the virtual environment, thus leading to the assumption of its plausibility regardless of the degree to which it may resemble reality. In that sense, the flying robot in Labster could be accepted as plausible within the limits of that environment because it is consistent with the space. After constant engagement with it, the robot can become normalised and participants can react to it, thus assimilating its existence. Another example of this was observed with the presence of incongruent visuo-proprioceptive stimuli such as the movement of a hand not being replicated in the VE. The process of assimilation observed in this scenario consisted in the modulation of behaviour as participants tended to stop performing physical movements that were not supported by the system, thus eliminating or minimising breaks in the illusion of presence.

Despite the sense of presence being a subjective perceptual state, it is argued in this research that such perception is driven by the degree to which the affordances of an iVR system can support the aforementioned three dimensions (see Figure 10.1 and Chapter 7).

[33] A virtual environment does not necessarily have to attempt to replicate the real world visually or otherwise. Being computer-generated spaces, virtual environments can also position users within made-up worlds that do not resemble or behave according to notions of our reality such as the laws of physics.

Table 10.1[34] below classifies those dimensions according to the level to which an iVR system could support them. The first degree indicates low presence across the three dimensions, thus denoting a system capable of eliciting only a minimal sense of presence on agents. The second and third degrees indicate moderate and high elicitation of the sense of presence, respectively. These are determined by the low achievement of one or two of the dimensions. Finally, the fourth degree indicates a very high of full elicitation of the three dimensions that comprise the sense of presence.

Table 10.1. Magnitude of the sense of presence in immersive virtual reality environments.

The sense of presence in iVR environments								
Dimensions	**Degrees**							
	1st	**2nd**			**3rd**			**4th**
Consistency	L	L	L	H	L	H	H	H
Plausibility	L	L	H	L	H	L	H	H
Assimilation	L	H	L	L	H	H	L	H

H = High; L = Low

Participants experiencing a very high level of presence would be expected to show congruent reactions to the conditions of the virtual environment. For instance, they would walk around a virtual table or avoid a hole in the ground, they would follow a sound, or step out of the way if an object is about to hit them, and they would attempt to engage with the objects around them by manipulating them, attempting to lean against them or sit on them, thus assuming their materiality.

10.2.4 **Comparing experiences of hand ownership, and agency between study conditions.**

This section discusses findings concerning how free movement and embodied interaction (i.e., hand gestures, body postures, and locomotion) impacted participants' experience of hand ownership and agency between study conditions (see Chapter 8).

[34] Table 10.1, Table 10.2, and Table 10.3 have been adapted for the purpose of this research from a table developed by Johnson-Glenberg (2018, p. 5) illustrating a construct of magnitude in the Embodied Education Taxonomy.

Based on observations and data from interviews, it was found that the perceptions of agency and hand ownership seem to be bound by sensory and motor stimuli (see Section 8.2.1 and Section 8.2.2). Although it was initially hypothesised that the visual mode would be largely responsible for eliciting both illusions, it was found that motor control contributed to a greater degree in this study. This is consistent with the work of Longo et al. (2008, p. 995) who found that, despite being dissociable components, ownership, location, and agency "form a coherent cluster of experience." These comprise a perceptual state defined in this thesis as the sense of embodiment (see Chapter 8).

Regarding the sense of agency, the low-end iVR condition (Labster) was characterised by integrating a visual representation of the participants' hands. However, these hands had limited mobility when it concerned the replication of the participants' translational hand movements such as when reaching for an object or rising and lowering the hands. This condition was described by participants as a limitation, "I […] wanted to move to the other side of the lab to see how it was like, […] and I couldn't do anything, I was stuck in that position" (P07-LiVR). Furthermore, it was recognised that "you could still do what you wanted" (P05-LiVR), which highlights the notion that despite the active engagement and decision making that was required of participants, the perception of agency had constrains dictated by the system's support for free movement.

In contrast, in the high-end iVR condition (HoloLAB Champions), the sense of agency was attributed to the ability to execute the experiments in any order and at the participants' pace, "I could do the steps in whatever order I wanted, so I felt completely in control, and they highlight repercussions like breaking stuff if you dropped it, it was very realistic," (P05-HiVR). Moreover, the simulation of consequences when making mistakes such as spilling substances and breaking glassware reinforced the notion that the participants' actions had a meaningful impact on the environment and the tasks being performed.

Whilst the above was observed to contribute to the perception of realism and plausibility that participants experienced in the virtual environment, it also highlights the potential that mistake-making could offer in these types of environments as a way to encourage reflection and as an approach to scaffold participants' learning. As described by Roussou and Slater (2020), these forms of interaction and free exploration do not only support skills development, but they also promote problem solving. By allowing for incongruencies to emerge, these could be used as the basis to boost learning by guiding students through their zone of proximal development (Vygotskii, 1978).

The findings discussed above provide evidence that the sense of agency was not solely elicited by the amount of active engagement that participants were afforded in the virtual environments. As demonstrated by findings from the high-end iVR condition, agency could be more profoundly influenced and reinforced through motor production (see Section 8.1). This aligns with the observations made by Sato and Yasuda (2005) who looked at discrepancies between predicted and actual outcomes of a given action. This particularly concerns two conditions observed in this research:

(a) The ability to move freely and carry out interactions through natural movements or gestures, rather than point-and-click behaviour, or the memorisation of metaphoric gestures (see Section 8.2). The latter of which could induce cognitive load according to Segal (2011).

(b) The simulation of motor actions and their consequences, namely the replication of body movements and how these affected the virtual environment (see section 8.2.2).

The perception of hand presence and ownership, on the other hand, were found to be elicited through three sensory-motor conditions in this research (see Section 8.2.1): (a) the visual representation of hands, (b) the replication of the participants' hand and body movements, and (c) the congruency between visual and touch modes.

Similar to the sense of agency, it was observed that motor control played a bigger role in evoking a sense of hand ownership and self-location (see Section 8.2.1). In that regard, the virtual controllers in HoloLAB Champions were reported by participants as assuming the role of their physical hands, compared to the virtual hands in Labster. This was attributed to the participants' sense of proprioception and the degree to which their movements were faithfully replicated in the virtual environment. Although this effect has been documented in the literature (Sato and Yasuda, 2005; Slater, Perez-Marcos, et al., 2009; Slater et al., 2010; Kilteni et al., 2015), it was found in this study that such illusory state can be evoked even when the virtual hands are replaced with inanimate objects such as controllers. This further highlights the significance of the replication of hand movements to support a congruent sense of proprioception and maintain the illusions of self-location and ownership that is first evoked through visual means.

10.2.5 Systematising the notions of hand ownership and agency

The sense of embodiment is understood throughout this research as the perceptual experience of inhabiting a body or a part of it (i.e., the hands) as it is often the case in immersive virtual environments. According to Kilteni, Groten, and Slater (2012), the sense of embodiment is supported by three perceptual states, which are proposed in this research as its dimensions (see Figure 10.2).

The sense of self-location refers to the perception of being inside a virtual body. This is closely related to the notion of proprioception in relation to how humans experience movement and the spatial location of their bodies. This is particularly important in virtual reality environments where the agent is placed in a virtual body / avatar or where the arms or hands are brought into the experience through virtual representations or cameras.

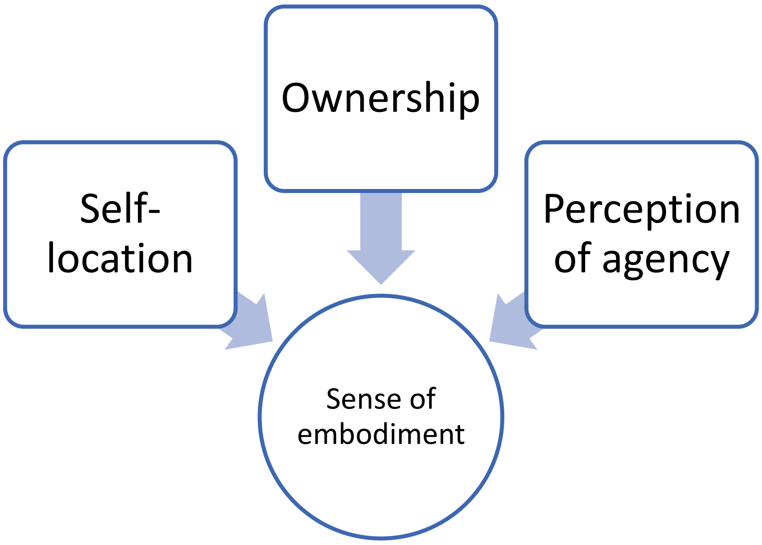


Figure 10.2. Dimensions of the sense of embodiment in immersive virtual reality environments.

The sense of body ownership consists in the self-attribution of the perceptuomotor contingencies being experienced. That is, the behaviour in which the avatar engages is not attributed to the avatar as a separate entity, but to the self as, perceptually, it is the participant who is inside the virtual environment.

Lastly, the sense of agency refers to the experience of action and the wilful motor control over the virtual body. As discussed in Chapter 8, it is possible to experience a low sense of agency even when given a high level of control over what happens in the experience as illustrated by Labster in the low-end iVR condition.

As a result of the above, it can be argued that experiencing a sense of embodiment in immersive virtual reality environments entails that an agent is perceiving his or herself as being inside, owning, and controlling a virtual body. However, this being a subjective perceptual state, the sense of embodiment can be broken when one or more of these dimensions is not fully achieved.

Having observed and analysed these three notions defined by Kilteni, Groten, and Slater (2012) around the sense of embodiment in the empirical work in this research (see Section 3.5 and Chapter 8), a classification offering four potential orders of magnitude in which agents can experience the sense of embodiment across its three dimensions is proposed in Table 10.2. The first degree indicates low presence across the three dimensions, thus denoting that an agent has experienced a minimal sense of embodiment. The second and third degrees indicate moderate and high elicitation of the sense of embodiment, respectively. These are determined by the low elicitation of one or two of the dimensions. Finally, the fourth degree indicates a very high of full elicitation of the three dimensions that comprise the sense of embodiment.

Table 10.2. Magnitude of the sense of embodiment in immersive virtual reality environments.

The sense of embodiment in iVR environments								
Dimensions	Degrees							
	1st	2nd			3rd			4th
Sense of self-location	L	L	L	H	L	H	H	H
Sense of body ownership	L	L	H	L	H	L	H	H
Sense of agency	L	H	L	L	H	H	L	H

H = High; L = Low

Participants experiencing a very high degree of the sense of embodiment would be expected to refer to behaviour experienced in the virtual environment as self-initiated. They would consider having done activities in the VE, rather than having seen them. And they would assume themselves being physically located in the experience, thus eliminating the notion of the avatar as a separate entity that needs to be controlled.

10.2.6 Looking at embodied interaction and its role in shaping conceptual and procedural understandings in science.

This section discusses findings concerning how the embodied engagement that participants had with the virtual environments shaped their understanding of those spaces and of the concepts and procedures these introduced.

Based on the analysis of recordings of interviews with participants (see Chapter 9), it was found that the spatio-dynamic relationships between participants and both virtual environments were instantiated in their gestures. These were observed to depict distance from manipulatives, point of view, and spatial arrangement, all of which were possible due to the first-person-perspective enabled by the iVR systems. This is consistent with the notion that body states play a role in the interpretation of experiences. As argued by Bailey, Bailenson, and Casasanto (2016, p. 223), “body position can contribute to thinking.”

Lhommet and Marsella (2014) posit that gestures can also reflect engagement and interaction, as these can be grounded on behaviour or concrete physical properties. Due to the different affordances of the iVR systems used, gestures from participants who took part in the high-end iVR condition (HoloLAB Champions) were observed to reflect visual, proprioceptive, and touch input, whereas those from participants who took part in the low-end iVR condition (Labster) were grounded on visual properties such as size, and spatial location. This demonstrates that bodily forms of engagement such as natural gestures and body posture could act as tools to support reasoning, thus shaping how concepts and procedures are understood. This is consistent with findings by Bailey, Bailenson, and Casasanto (2016) suggesting that sensory-motor feedback and not just visual input may be important to influence cognition.

It was also found that movement and direct gestural interaction supporting touch brought about behavioural change and the re-evaluation of assumptions about embodied interaction in the virtual environments (see Section 9.2). The former was reflected in actions participants performed. These were aimed at avoiding or correcting mistakes, engaging with the environment in a more natural way, and testing interaction and the simulation of consequences. The latter concerned the congruency of visual, tactile, and kinetic stimuli. The synchronous replication of physical actions and the tactile perception of the controller made participants become more aware of the discordant visual and tactile perceptions of size, shape, and texture of the virtual objects.

Lastly, it was observed that in addition to being co-expressive with speech, gestures were also co-expressive with other gestures within a single communicative act by instantiating the kinetic tactile-kinaesthetic properties of the interfaces or mechanisms for interaction of the VEs (see Section 9.3). Drawing from the work of Segal (2011), it was also observed that the gestures participants performed during interviews were grounded or mapped to (a) concepts, by attributing physical properties that could be depicted, (b) direct touch, by instantiating tactile input and proprioception, and (c) behaviour, by enacting procedures or tasks (see Section 9.3).

Conceptual mapping of gestures did not appear to differ according to the study conditions. Moreover, mapping to direct touch was only observed amongst participants who engaged with HoloLAB Champions, as only this condition afforded gestural interaction, touch, and the direct manipulation of virtual objects (see Section 9.3).

Comparatively, although observed amongst all participants, behavioural mapping of gestures was instantiated differently depending on the study condition (see Section 9.3). Participants in the high-end iVR condition (HoloLAB Champions) performed more pronounced and detailed gestures and postures. These enacted kinetic and visual properties such as moving the head to denote a change in perspective or dragging an object denoting trajectory, speed, and spatial location. In contrast, participants in the low-end iVR condition (Labster) performed more subtle gestural movements that relied solely on visual properties such as the spatial location, size, and shape of virtual objects, thus demonstrating how these affordances influenced reasoning. This is consistent with the assertion that gestures constitute "instantiations of embodied schematic understanding" (Becvar, Hollan and Hutchins, 2007, p. 126) that can play an essential role in representing and conceptualizing ideas.

The relevance of the findings discussed above is two-fold. On the one hand, this work contributes to the body of knowledge on embodied cognition, particularly in immersive virtual environments which, being mediated by technology, bring about special challenges around gestural interaction and other forms of bodily engagement. On the other hand, from a design standpoint, these findings provide insights into how users can engage with virtual environments and how active, physical, and direct involvement with the virtual environments could be central for learning in these types of spaces. iVR experiences designed around movement and interaction mapped to behaviour, conceptual knowledge, and direct touch can foster free engagement, problem solving, experimentation, and trial and error, thus grounding and scaffolding knowledge.

10.2.7 Systematising the notion of embodiment

Embodiment is understood in this research as the degree to which an immersive virtual reality system affords agents opportunities for sensory-motor engagement (i.e., locomotion, free movement, and gestural interaction). Of particular interest is their orientation towards meaning making within a virtual environment. This should not be confused with the term "sense of embodiment" which denotes the perceptual state of inhabiting a virtual body or avatar (see Section 5.2.2, Chapter 8, and Section 10.2.5). Whilst the sense of embodiment describes a perceptual experience that, although afforded by the technology, is subjective to every agent, the notion of embodiment refers to an objective descriptor of the technology itself and the degree to which it enables sensory-motor forms of interaction.

Figure 10.3 illustrates the three dimensions proposed in this research to determine the degree to which an iVR system is capable of supporting motor forms of interaction such as locomotion, free movement, and natural gestures. Two of these dimensions, the notion of sensory-motor engagement and the congruency of gesture, are borrowed from the Taxonomy of Embodiment in Education developed by Johnson-Glenberg and Megowan-Romanowicz (2017).

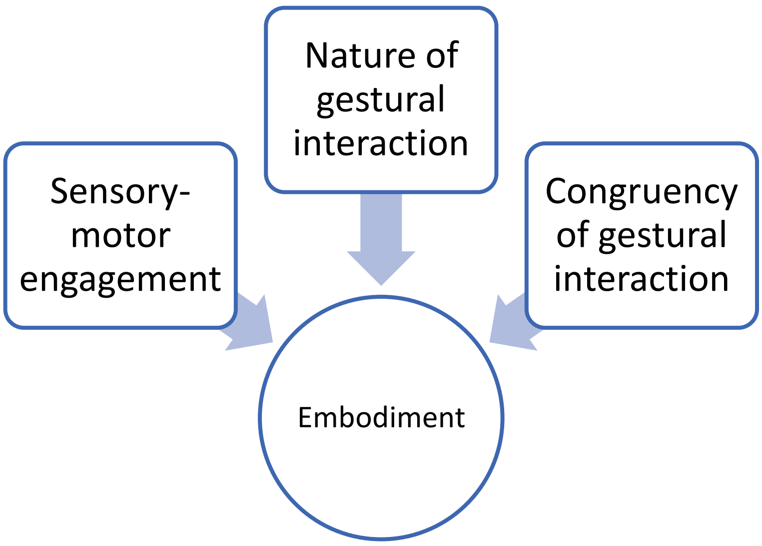


Figure 10.3. Dimensions of the sense of embodiment in immersive virtual reality environments.

The notion of sensory-motor engagement concerns "the magnitude of the motor signal" (Johnson-Glenberg, 2018, p. 4). In that sense, it was observed during interventions that the subtle rotational movements of the wrist and head to interact with manipulatives in Labster do not support the elicitation of body ownership and agency in equal measure to the larger, free-form movements required in HoloLAB Champions. Resultingly, sensory-motor engagement could act as an indicator of the degree of embodiment that an iVR system supports.

The congruency of gestural interaction refers to how movements and conceptual and procedural content in the iVR experience are mapped to each other. In that way, “the gesture should support the gist of the content and give meaningful practice to the learning goal” (Johnson-Glenberg, 2018, p. 4). For instance, when exploring content about gravity, the agent would be expected to manipulate objects vertically on the z or heave axis to illustrate the concept. Comparatively, when discussing something related to rotation and acceleration gestural movements would be expected to increase or decrease in speed and to follow a circular motion.

Lastly, the nature of gestural interaction concerns two aspects describing the relationship between the agent and manipulatives as it was observed in the empirical work for this research (see Chapter 9). The first of these refers to the possibility to interact with virtual manipulatives directly or indirectly. That is, by approaching them and engaging with them as if they were real physical objects, or by engaging with them either through an avatar that is controlled by the agent but not perceptually embodied as it happens in traditional third-person videogames, or by the use of a pointer to perform tasks distally like in low-end iVR systems.

The second aspect refers to the mechanisms used for interaction. These can vary from sight and the use of controllers involving buttons, trackpads, or analogue sticks, to the use of natural or metaphorical gestures. This dimension became an important factor in the empirical work of this research due to the involvement of controllers capable of sensing touch, pressure, and the individual movement of fingers in the high-end iVR condition (see Section 4.2.4). The integration of these capabilities allowed for natural gestures such as grabbing, pinching, twisting, tilting, shaking, throwing, and releasing to be used as mechanisms for interaction, thus eliminating the need of button pressing or having to learn metaphorical gestures that may or may not have any congruency to the tasks and concepts they relate to. An example of this is using a swiping motion with the finger to move or flicking a finger to select an object.

Table 10.3 presents a classification of the dimensions determining the degree to which an iVR system is embodied or supports sensory-motor forms of interaction. The first degree indicates low support across the three dimensions, thus denoting a system with a low capacity for sensory-motor engagement. The second and third degrees indicate moderate and high support for the three dimensions, respectively, and these are defined by the low capacity to enable one or two of the dimensions. Finally, the fourth degree indicates a very high level of support of the three dimensions that define the degree of embodiment of an iVR system.

Table 10.3. Degrees of embodiment of immersive virtual reality systems.

Degrees of embodiment of iVR systems								
Dimensions	**Degrees**							
	1st	**2nd**			**3rd**			**4th**
Sensory-motor engagement	L	L	L	H	L	H	H	H
Nature of gestural interaction	L	L	H	L	H	L	H	H
Congruency of gestural interaction	L	H	L	L	H	H	L	H

H = High; L = Low

Table 10.4 describes the sensory-motor affordances and forms of interaction that could be expected from an immersive virtual reality system at each of the four degrees of embodiment. It must be noted that such properties are hardware dependent and, as a result, variations are possible according to the types of iVR hardware, particularly as more capable systems become available.

Table 10.4. Descriptor of the degrees of embodiment of an immersive virtual reality system.

Descriptor of degrees of embodiment	
Sensory-motor support	**Embodied interaction**
1st Low	
▪ Only experiences designed for seated or standing setups are supported. ▪ Locomotion is not supported. ▪ Only rotational movements of the hands and head are tracked. ▪ Experiences involve surround stereoscopic 3D virtual environments using a screen with a low refresh rate (80 Hz or less) and a narrow field of view (94º or less). ▪ There is support for stereo audio.	▪ There is no support for interaction or the manipulation of virtual objects. ▪ No active engagement from users is required.

2nd Moderate	
▪ Only experiences designed for seated or standing setups are supported. ▪ Locomotion is limited to teleportation. ▪ Only rotational movements of the hands and head are tracked. ▪ Experiences involve surround stereoscopic 3D virtual environments using a screen with mid-range refresh rate (90 Hz) and field of view (95° to 130°). ▪ There is support for stereo audio.	▪ There is limited support for interaction and the manipulation of virtual objects. ▪ Minimal active engagement from users is required. ▪ Interaction is performed distally through gaze, tapping, point-and-click behaviour, or the use of an avatar. ▪ Hand and body rotational and positional movements are not possible but can be simulated in the VE.
3rd High	
▪ Experiences in a room-scale setup are fully supported. ▪ Locomotion can range from small movements such taking a couple of steps to virtual mechanisms such as teleportation, and smooth or continuous traversal. ▪ The user's body can be partially tracked with 6 degrees of freedom of movement. This typically only includes the head and hands. ▪ Gaze, touch, and pressure are not supported. ▪ Experiences involve surround stereoscopic 3D virtual environments using a screen with a refresh rate ranging from 90 Hz to 120 Hz and a field of view ranging from 95° to 150°. ▪ There is support for stereo or 3D spatial audio.	▪ There is moderate support for interaction and the manipulation of virtual objects. ▪ Moderate active engagement from users is required. ▪ Interaction is performed directly by pressing buttons on controllers. It does not support gestures. ▪ Hand and body rotational and positional movements can be tracked and partially replicated. ▪ Supported virtual and physical movements can be replicated and congruently mapped to content.
4th Very high	
▪ Experiences in a room-scale setup are fully supported. ▪ Physically walking is fully supported within the limits of the play area and virtual forms of locomotion such as teleportation are possible as well. ▪ The user's body is tracked with 6 degrees of freedom. This includes rotational and positional movements of head, torso, limbs, and fingers. ▪ Tracking of gaze and support for touch and pressure are supported. ▪ Experiences involve surround stereoscopic 3D virtual environmen9795ts using a screen with high refresh rate (120 Hz) and wide field of view (150° or more). ▪ There is support for 3D spatial audio.	▪ High level of interaction and active involvement of users is required. ▪ Natural gestural interaction is supported. ▪ The manipulation of virtual objects can be done directly rather than distally or through an avatar. ▪ Virtual and physical gestures and movements can be replicated and congruently mapped to content.

Chapter 11: Conclusion

Chapter overview

This chapter provides concluding remarks and discusses the contributions that this research is making to scholarship and professional practice, the limitations of the empirical study, and potential avenues of enquiry for future research.

This research set out to explore learning in immersive virtual reality and the ways in which the sensory-motor affordances of these types of systems such as movement and direct gestural interaction can shape students' perceptual states and the construction of new understandings. The research comprised two phases:

- The preliminary work and pilot studies which had the aims of defining the properties of different iVR systems, appraise how these could enable contingencies for sensory-motor engagement in the VEs, and map gestural movements to conceptual and procedural content (see findings in Section 10.1).
- The main empirical study involved school interventions where participants engaged with two iVR systems to perform experiments in virtual chemistry laboratories, Labster and HoloLAB Champions. This had the aims of examining differences in students' measured knowledge before and after the interventions and appraise how free movement and direct gestural interaction shaped students' perceptual states (i.e., presence, agency, and body ownership) and the construction of new conceptual and procedural understandings (see findings in Section 10.2).

11.1 Concluding remarks

Immersive virtual reality environments simulate some aspect of reality into a coherent construct that can be physically acted upon and perceptually explored. However, as argued in this research, the sensory-motor affordances that agents can experience largely depend on the properties of the hardware. In the case of the systems used in this research, two main components were identified as most impactful due to their capacity to enable locomotion, movement, and direct gestural interaction: a 6DoF tracking system and dual controllers capable of sensing hand and finger position, motion, and pressure.

Through the analysis of different iVR systems and experiences, it was also observed that, despite being enabled by hardware, the replication of movements and gestures is also dependent on having been scripted into the experience itself (i.e., the software). In essence, a virtual object can only be interacted with in a certain manner if it was designed around that possibility, which is contingent on the capacity of the hardware to offer mechanisms for interaction and embodied engagement. During the preliminary work, it was observed that many educational experiences available to consumers do not follow this principle, particularly those which have been released across platforms. In those cases, movement and gestural interaction were found to be absent despite the system itself being capable of supporting them, thus defeating the purpose of using high-end hardware (see Appendix B.1).

The above is the result of the fragmentation of the iVR consumer market (Hruska, 2015; Probst, Pedersen and Dakkak-Arnoux, 2017), which can be detrimental to wide adoption, innovation, industry support, and the development of a cohesive platform specifically tailored to educational iVR experiences.

Although the findings of this research cannot be generalised outside of the small sample that was collected, these provide insights into what could be expected of a larger study. Furthermore, they act as a snapshot of the current state of the technology, thus allowing for the appraisal of their merits for instructional use.

Despite results showing increases in scores with each testing point across the two study conditions, results from the high-end iVR condition (HoloLAB Champions) outperformed those from the low-end iVR condition (Labster). Although drawing a definitive causal relationship between increases in test-scores and the sensory-motor affordances of both iVR systems falls outside of the scope of this research, some of the findings in this study suggest the existence of a potential correlation worth exploring in further research:

(a) Perceptual states. Results from statistical analysis indicate that participants experienced a stronger sense of presence, agency, and hand ownership in the high-end iVR condition. Findings from interviews suggest that, in addition to visuals, these perceptual states were underpinned by the modes of touch and movement. Most significantly, they enabled posture, direct gestural interaction, and wilful control in the high-end iVR condition.

(b) Gestures. The analysis of gestures which participants performed during interviews demonstrate how these instantiated their spatio-dynamic relationships with the VEs, as well as the kinetic tactile-kinaesthetic properties of their interactions with these spaces. Findings indicate that gestures provide a window into how participants grounded new conceptual and procedural understandings. These were underpinned by behaviour, direct touch, and/or physical attributes depending on the sensory-motor affordances of the system used. Participants in the high-end iVR condition performed more pronounced and detailed gestures depicting these forms of grounding.

Consequently, it can be argued that, although no single affordance of the iVR systems can be deemed responsible for the increases in test scores, they all appear to act as partial contributors. This attends to the statistically significant results in the high-end iVR condition and the fact that perceptual states (i.e., presence, agency, and hand ownership) and grounded gestures (conceptual, behavioural, and touch) were more prominently or exclusively observed in this condition.

Gustavsson et al. (2009) argues that virtual and remote laboratories can complement or substitute traditional ones with the added bonus that they do not have operation hours, they do not require a physical space which can limit the number of users, and they are not subject to a budget to keep them operational. Whilst this research concurs with these assertions, it was observed that virtual laboratories also present other challenges such as the need for a dedicated large physical space, the cost of acquisition, specialised support to set up and troubleshoot, the need for individual systems for every student, considerations of time, training, and the lack of educational experiences tailored to specific aims or needs, to name a few.

Although immersive virtual environments and, by extension, virtual laboratories can never fully simulate all aspects of reality and of the experience of a physical laboratory, they can act as viable complements to instruction. As argued by De Jong and Zacharia (2013, pp. 305–306), virtual environments can “simplify learning by highlighting salient information and removing confusing details, […] [and] students can conduct experiments about unobservable phenomena.” (pp.305–306) Furthermore, as observed in this research, students can link abstract notions to concrete, observable processes and construct mental representations based on direct observations, behaviour, experimentation, and trial and error.

Immersive virtual reality experiences, particularly those offered by high-end systems have great potential for use in instructional settings due to their capacity to replicate behaviour, elicit perceptual states, and enable direct touch and gestural interaction for active engagement, exploration, and scaffolding from trial and error. Despite the significant improvements being made, over the past 7 years, there still are important challenges to be overcome for their seamless orchestration into classrooms, and their integration with the school curricula. Ultimately, despite their strengths and promises, the use of iVR systems for education must attend to their fit for purpose and any school implementation must consider whether the benefits of the chosen technology outweigh its drawbacks.

11.2 Contribution and impact

This research builds upon previous studies looking at immersive virtual reality technologies and how these can influence perceptual states and learning outcomes (see Papachristos, Vrellis and Mikropoulos, 2017; Schwartz and Steptoe, 2018; Calvert and Abadia, 2020). The empirical findings in this research will be of interest to schools and practitioners looking to implement iVR technology for instructional use; developers of educational iVR experiences who want to inform their designs around active engagement and embodied interaction; and researchers interested in advancing our understanding of how embodied interaction can be central to supporting conceptual and procedural knowledge construction in educational immersive virtual environments.

This work contributes to existing knowledge in several respects: (a) it describes the interrelationship between the sensory-motor affordances of an iVR system and the kinds of experiences that these can enable; (b) it elucidates the ways in which hardware and sensory-motor affordances contribute to support perceptual states, namely the sense of presence, agency, and hand ownership; (c) it reconceptualises the notion of embodiment in the context of low- and high-end iVR systems; (d) it demonstrates how gestures made during speech provide a window into the ways embodied interaction shaped participants understandings of concepts and procedures; (e) it also demonstrates how such gestures instantiate the kinetic, tactile-kinaesthetic properties of the mechanisms used for interaction in the iVR experiences; and (f) it lays out some of the ground work towards the development of a taxonomy of embodied cognition in immersive virtual reality which includes the degree of embodiment, the sense of presence, and the sense of embodiment.

For practitioners and schools, this research provides insights into how the selection of immersive virtual reality systems should be driven by instructional aims, whilst considering the challenges associated with using these types of technologies, including time, cost, expertise, and access to experiences, to name a few.

For developers of educational iVR experiences, this work provides valuable insights concerning the design of spaces involving active engagement, direct manipulation, and touch. It also highlights the importance of fostering exploration, trial and error, and the simulation of mistakes and their effects, as well as the need to embed scaffolding techniques as part of the experiences' guidance or support system.

Lastly, for researchers, this study advances current understandings around sensory-motor engagement and embodied interaction in immersive virtual reality and highlights potential avenues for exploration going forward in the field of iVR-assisted education.

11.3 Limitations of the study.

A series of limitations were identified in the course of this research, these concern the apparatus, access, methods, and the research design. One of the most palpable challenges with the use of iVR technology in schools is cost, availability of equipment, time constrains, and the need for training, technical support, and a large physical space. The funding for this research was limited and only one researcher was involved in carrying out data collection and analysis. This limited the time that could be dedicated to each of the phases of the study, the number of participants that could be involved, and the amount of equipment that could be acquired, carried to schools on a daily basis, and used simultaneously with the supervision of the researcher. Moreover, the recruitment of schools interested in taking part in the study was similarly challenging due to its intrusiveness as schools had to be in charge of the logistics involved, such as contacting and recruiting students and finding a dedicated space after school hours that could still be supervised by a member of staff.

The limitations on access and recruitment described above also had implications for the statistical analysis of data. The empirical study involved only 27 participants, 13 of whom took part in a single intervention (pathways 3 and 4 following a between groups design), whilst the remaining 14 participants received two interventions (pathways 1 and 2 following a within-subject design). This resulted in 41 data points which was not sufficient for clear patters to emerge, particularly when the data had to be split by school year, intervention group, or study condition. It is also important to note that greater control over the recruitment process would have ensured a more balanced number of participants across the age groups and levels of education being represented. As discussed in Chapter 10, older participants generally showed higher average scores in tests. However, these results could be confounded by the skewed number of data points as higher levels of education had higher representation in the sample.

A longitudinal study with a larger sample of participants, although exponentially more challenging, time-consuming, and expensive, could provide a more comprehensive view of the impact of the use of iVR technology in the classroom. Moreover, this could offer insights into the integration of iVR systems with the curricula, how they can be orchestrated in a lesson, and allow for the assessment of different aspects of the instructional process in a more ecological manner, whilst also providing sufficient data for more nuanced quantitative analysis. Also concerning participants, further control over recruitment could ensure the ages .

Regarding methods of data collection and analysis. The tests that were developed for each VR experience could have involved a larger number of items as the current battery of questions was reduced significantly when it was split to create pre- and post-tests due to the counter-balanced approach that was followed. Furthermore, some of these questions could have enquired about spatial reasoning and touch. Although this was explored during interviews, tests could have captured a different aspect to these given their prominence. Additionally, it was identified that the pre-test could have acted as a confounder when measuring learning gains, particularly among participants who received both interventions as these not only influenced their perceptions of presence and agency, but also their ability to navigate the virtual environment during the second intervention and the content that it presented. This raises concerns regarding the use of the pre-test as a basis from which to measure learning gains in those instances. Although this cannot be fully addressed, controlling for the pre-test as a covariate in the statistical analysis was done as a way to minimise the potential effects.

One final constraint in this research concerned the use of separate commercial virtual experiences for each intervention. Limited time and resources made the design of a custom experience not feasible, particularly as it would have to be compatible with both types of hardware whilst capitalising on the sensory-motor affordances of each. Although the selected experiences were evaluated to ensure thematic parity, level of active engagement required from participants, and full support of the sensory-motor affordances of each system, the differences in content meant that correlations between measured perceptual states, test scores, and level of embodied engagement could not be attributed to each other. A custom-made environment would ensure parity across all variables of study and allow for causal relationships to be identified with more certainty.

11.4 Future avenues of enquiry.

The findings of this study and limitations discussed above suggest several directions for continuing research. One of such areas is the exploration of tactile and free hand input mechanisms for direct interaction. Particularly, the effects that the presence, absence, and gradation of vibrotactile feedback from physical input devices like controllers and gloves can have on the elicitation of the sense of hand ownership and agency.

Another potential avenue of future enquiry concerns collaboration. This can take different shapes, from bringing iVR users together into a single virtual environment to perform activities, to hybrid setups where some students can interact with the virtual environment through a headset, whilst others join through a mobile device like a tablet, smartphone, or laptop computer. Further research in this area may provide insights into how virtual reality technologies can be brought into classrooms without the need for large spaces and multiple headsets, whilst also addressing the need for virtual environments that do not isolate students from each other.

Lastly, iVR as an educational platform offers ample opportunity for exploration. At present, educational virtual environments can be accessed through gaming platforms and closed, all-in-one services. The former provides the liberty of accessing educational iVR experiences individually through videogame platforms like Steam, VivePort, and the Oculus Store. However, these experiences are not curated, and the platforms themselves do not offer any type of features catered to the educational sector such as assessment, classification by discipline, administration of students, etc. Whilst the latter provides some of the aforementioned features, these platforms are tied to in-house experiences and typically non-immersive VR or low-end immersive VR hardware. The development of a platform similar to Moodle that could bring together XR experiences from different companies, whilst maintaining and expanding functionality for the management of student progression and content hosting would require significant investment and resources for research and development. However, this has the potential to truly revolutionise VR-mediated instruction by offering a stable platform and infrastructure on which to build, share, and consume educational VR experiences that cater different needs and disciplines.

References

Abrahamson, D. and Lindgren, R. (2014) ‘Embodiment and embodied design’, in Sawyer, R. K. (ed.) The Cambridge handbook of the learning sciences. 2nd edn. Cambridge, UK: Cambridge University Press, pp. 358–376.

Alexander, A. L. et al. (2005) ‘From gaming to training: a review of studies on fidelity, immersion, presence, and buy-in and their effects on transfer in PC-based simulations and games’, DARWARS Training Impact Group, (November), pp. 1–14.

Alhalabi, W. (2016) ‘Virtual reality systems enhance students’ achievements in engineering education’, Behaviour & Information Technology. Taylor & Francis, 35(11), pp. 919–925. doi: 10.1080/0144929X.2016.1212931.

Alibali, M. W., Boncoddo, R. and Hostetter, A. B. (2014) ‘Gesture in reasoning: an embodied perspective’, in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. London, UK: Routledge, pp. 150–159. doi: 10.4324/9781315775845.ch15.

Alkemade, R., Verbeek, F. J. and Lukosch, S. G. (2017) ‘On the efficiency of a VR hand gesture-based interface for 3D object manipulations in conceptual design’, International Journal of Human–Computer Interaction. Taylor & Francis, 33(11), pp. 882–901. doi: 10.1080/10447318.2017.1296074.

Allen, J. A., Hays, R. T. and Buffardi, L. C. (1986) ‘Maintenance training simulator fidelity and individual differences in transfer of training’, Human Factors: The Journal of the Human Factors and Ergonomics Society, 28(5), pp. 497–509. doi: 10.1177/001872088602800501.

Andaluz, V. H. et al. (2018) ‘Multi-user industrial training and education environment’, in De Paolis, L. T. and Bourdot, P. (eds) Augmented Reality, Virtual Reality, and Computer Graphics. AVR 2018. Lecture Notes in Computer Science, vol 10851. Cham: Springer, pp. 533–546.

Anderson, M. L. (2003) ‘Embodied cognition: a field guide’, Artificial Intelligence, 149(1), pp. 91–130. doi: 10.1016/S0004-3702(03)00054-7.

Argelaguet, F. et al. (2016) ‘The role of interaction in virtual embodiment: effects of the virtual hand representation’, in IEEE Virtual Reality (VR). IEEE Computer Society, pp. 3–10. doi: 10.1109/VR.2016.7504682.

Atkin, A. (2010) *Peirce’s theory of signs*, The Stanford encyclopedia of philosophy (Summer 2013 Edition). Available at: https://plato.stanford.edu/archives/sum2013/entries/peirce-semiotics/.

Avantis Education (2020) ClassVR: virtual reality for schools. Available at: https://www.avantiseducation.com/devices/school-virtual-reality-vr-headset/ (Accessed: 31 May 2020).

Bailey, J. et al. (2012) ‘Presence and memory: immersive virtual reality effects on cued recall’, in Proceedings of the International Society for Presence Research Annual Conference. October 24-26. Philadelphia, PA. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Presence+and+Mem

ory+:+Immersive+Virtual+Reality+Effects+on+Cued+Recall#0.

Bailey, J. O., Bailenson, J. N. and Casasanto, D. (2016) ‘When does virtual embodiment change our minds?’, Presence: Teleoperators and Virtual Environments, 25(3), pp. 222–233. doi: 10.1162/PRES_a_00263.

Bakker, S., Antle, A. N. and van den Hoven, E. (2012) ‘Embodied metaphors in tangible interaction design’, Personal and Ubiquitous Computing, 16(4), pp. 433–449. doi: 10.1007/s00779-011-0410-4.

Banakou, D. and Slater, M. (2014) ‘Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking’, Proceedings of the National Academy of Sciences, 111(49), pp. 17678–17683. doi: 10.1073/pnas.1414936111.

Barnard, D. (2019) Degrees of freedom (DoF): 3-DoF vs 6-DoF for VR headset selection, Virtual Speech. Available at: https://virtualspeech.com/blog/degrees-of-freedom-vr (Accessed: 20 November 2020).

Barsalou, L. W. (1999) ‘Perceptual symbol systems’, Behavioral and Brain Sciences, 22(4), pp. 577–660. doi: 10.1017/S0140525X99002149.

Barsalou, L. W. et al. (2003) ‘Grounding conceptual knowledge in modality-specific systems’, Trends in Cognitive Sciences, 7(2), pp. 84–91. doi: 10.1016/S1364-6613(02)00029-3.

Barsalou, L. W. (2008) ‘Grounded cognition’, Annual Review of Psychology, 59(1), pp. 617–645. doi: 10.1146/annurev.psych.59.103006.093639.

Baum, D. R. et al. (1982) Training effectiveness as a function of training device fidelity. Alexandria, VA. Available at: https://apps.dtic.mil/sti/citations/ADA140997.

Becvar, A., Hollan, J. and Hutchins, E. (2007) ‘Representational gestures as cognitive artifacts for developing theories in a scientific laboratory’, in Resources, Co-Evolution and Artifacts. London, UK: Springer, pp. 117–143. doi: 10.1007/978-1-84628-901-9_5.

Black, J. B. et al. (2012) ‘Embodied cognition and learning environment design’, in Jonassen, D. and Lamb, S. (eds) Theoretical foundations of student-centered learning environments. New York, NY: Routledge.

Blanke, O. and Metzinger, T. (2009) ‘Full-body illusions and minimal phenomenal selfhood’, Trends in Cognitive Sciences, 13(1), pp. 7–13. doi: 10.1016/j.tics.2008.10.003.

Blenkinsopp, R. (2019) What is haptics? Definition of haptic feedback and technology, Ultraleap. Available at: https://www.ultraleap.com/company/news/blog/what-is-haptics/ (Accessed: 12 February 2022).

Bliss, J. P. and Tidwell, P. D. (1995) ‘The effectiveness of virtual reality for administering spatial navigation training to police officers’, in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pp. 936–936. doi: 10.1177/154193129503901412.

Bolas, M. et al. (2016) How will virtual reality change our lives?, BBC News. Available at: https://www.bbc.com/news/technology-36279855 (Accessed: 19 August 2018).

Boletsis, C. (2017) ‘The new era of virtual reality locomotion: a systematic literature review of techniques and a proposed typology’, Multimodal Technologies and Interaction, 1(4), p. 24. doi: 10.3390/mti1040024.

Bonde, M. T. et al. (2014) ‘Improving biotech education through gamified laboratory simulations’, Nature Biotechnology, 32(7), pp. 694–697. doi: 10.1038/nbt.2955.

Borghi, A. M. and Caruana, F. (2015) ‘Embodiment theory’, in International Encyclopedia of the Social & Behavioral Sciences. 2ndi edn. Elsevier, pp. 420–426. doi: 10.1016/B978-0-08-097086-8.56025-5.

Bouchard, S. et al. (2017) ‘Virtual reality compared with in vivo exposure in the treatment of social anxiety disorder: a three-arm randomised controlled trial’, British Journal of Psychiatry, 210(4), pp. 276–283. doi: 10.1192/bjp.bp.116.184234.

Braun, V. and Clarke, V. (2013) Successful qualitative research: a practical guide for beginners. Los Angeles, CA: SAGE.

Brooke, J. (1996) ‘SUS: a “quick and dirty” usability scale’, in Usability Evaluation In Industry. London, UK: CRC Press, pp. 207–212. doi: 10.1201/9781498710411-35.

Bryman, A. (2016) Social research methods. 5th edn. Oxford, UK: Oxford University Press.

Butt, A. L., Kardong-Edgren, S. and Ellertson, A. (2018) ‘Using game-based virtual reality with haptics for skill acquisition’, Clinical Simulation in Nursing. Elsevier, 16, pp. 25–32. doi: 10.1016/j.ecns.2017.09.010.

Buttussi, F. and Chittaro, L. (2018) ‘Effects of different types of virtual reality display on presence and learning in a safety training scenario’, IEEE Transactions on Visualization and Computer Graphics. IEEE Computer Society, 24(2), pp. 1063–1076. doi: 10.1109/TVCG.2017.2653117.

Calvert, J. and Abadia, R. (2020) ‘Impact of immersing university and high school students in educational linear narratives using virtual reality technology’, Computers & Education. Elsevier Ltd, 159(August), p. 104005. doi: 10.1016/j.compedu.2020.104005.

Cambridge English Dictionary (2021a) Immersive. Available at: https://dictionary.cambridge.org/dictionary/english/immersive (Accessed: 12 January 2021).

Cambridge English Dictionary (2021b) Virtual reality. Available at: https://dictionary.cambridge.org/dictionary/english/virtual-reality (Accessed: 12 January 2021).

Cambridge English Dictionary (2022) Movement. Available at: https://dictionary.cambridge.org/dictionary/english/movement (Accessed: 23 March 2022).

Carlin, A. S., Hoffman, H. G. and Weghorst, S. (1997) ‘Virtual reality and tactile augmentation in the treatment of spider phobia: a case report’, Behaviour Research and Therapy, 35(2), pp. 153–158. doi: https://doi.org/10.1016/S0005-7967(96)00085-X.

Casasanto, D. (2009) ‘Embodiment of abstract concepts: good and bad in right- and left-handers’, Journal of Experimental Psychology: General, 138(3), pp. 351–367. doi: 10.1037/a0015854.

Casasanto, D. (2014) ‘Bodily relativity’, in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. London, UK: Routledge, pp. 108–117. doi: 10.4324/9781315775845.ch11.

Chittaro, L. and Buttussi, F. (2015) ‘Assessing knowledge retention of an immersive serious game vs. a traditional education method in aviation safety’, IEEE Transactions on Visualization and Computer Graphics. IEEE, 21(4), pp. 529–538. doi: 10.1109/TVCG.2015.2391853.

Cho, J. et al. (2017) ‘Screen door effect mitigation and its quantitative evaluation in VR display’, SID Symposium Digest of Technical Papers, 48(1), pp. 1154–1156. doi: 10.1002/sdtp.11847.

Choroś, K. and Nippe, P. (2019) 'Software techniques to reduce cybersickness among users of immersive virtual reality environments', in Nguyen, N. T. et al. (eds) Intelligent Information and Database Systems. Yogyakarta, ID: Springer, pp. 638–648.

Clark, A. (2008) Supersizing the mind: embodiment, action, and cognitive extension. Oxford, UK: Oxford University Press.

Clatworthy, K. (2016) 60 years of wiew-master history from Sawyers to Mattel. Available at: http://www.viewmaster.co.uk/htm/history.asp (Accessed: 19 August 2018).

Coburn, J. Q., Freeman, I. and Salmon, J. L. (2017) 'A review of the capabilities of current low-cost virtual reality technology and its potential to enhance the design process', Journal of Computing and Information Science in Engineering, 17(3), pp. 1–15. doi: 10.1115/1.4036921.

Crecente, B. (2016) *VR's long, weird history*, Polygon. Available at: https://www.polygon.com/2016/10/26/13401128/25-vr-greatest-innovators (Accessed: 20 August 2018).

Cruz-Neira, C. et al. (1992) 'The CAVE: audio visual experience automatic virtual environment', Communications of the ACM, 35(6), pp. 64–72. doi: 10.1145/129888.129892.

Cummings, J. J. and Bailenson, J. N. (2016) 'How immersive is enough? A meta-analysis of the effect of immersive technology on user presence', Media Psychology, 19(2), pp. 272–309. doi: 10.1080/15213269.2015.1015740.

Dalgarno, B. et al. (2009) 'Effectiveness of a virtual laboratory as a preparatory resource for distance education chemistry students', Computers & Education. Elsevier, 53(3), pp. 853–865. doi: 10.1016/j.compedu.2009.05.005.

Dawson, M. (2014) 'Embedded and situated cognition', in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. London, UK: Routledge, pp. 59–67. doi: 10.4324/9781315775845.ch6.

Deaky, B. A. and Parv, A. L. (2018) 'Virtual reality for real estate: a case study', IOP Conference Series: Materials Science and Engineering, 399(012013). doi: 10.1088/1757-899X/399/1/012013.

Dede, C. (2009) 'Immersive interfaces for engagement and learning', Science, 323(5910), pp. 66–69. doi: 10.1126/science.1167311.

Digi Capital (2018) Record over $3B AR/VR investment in 2017 ($1.5B+ in Q4). Available at: https://www.digi-capital.com/news/2018/01/record-over-3b-ar-vr-investment-in-2017-1-5b-in-q4/ (Accessed: 19 August 2018).

Dodoo, E. R. et al. (2018) 'Evaluating commodity hardware and software for virtual reality assembly training', Electronic Imaging: The Engineering Reality of Virtual Reality, 6(6), pp. 468-1-468–6. doi: 10.2352/ISSN.2470-1173.2018.03.ERVR-468.

Dourish, P. (2004) Where the action is: the foundations of embodied interaction. Cambridge, MA: MIT Press.

Duncan, I., Miller, A. and Jiang, S. (2012) 'A taxonomy of virtual worlds usage in education', British Journal of Educational Technology, 43(6), pp. 949–964. doi: 10.1111/j.1467-8535.2011.01263.x.

Dunnagan, C. L. et al. (2020) 'Production and evaluation of a realistic immersive virtual reality organic chemistry laboratory experience: infrared spectroscopy', Journal of Chemical Education, 97(1), pp. 258–262. doi: 10.1021/acs.jchemed.9b00705.

Dużmańska, N., Strojny, P. and Strojny, A. (2018) 'Can simulator sickness be avoided? A review on temporal aspects of simulator sickness', Frontiers in Psychology, 9(Nov). doi: 10.3389/fpsyg.2018.02132.

Ekstrom, R. B., French, J. W. and Harmon, H. H. (1976) 'Cognitive factors: their identification and replication', Multivariate Behavioral Research Monographs, 79(2), pp. 3–84.

Ellis, S. R. (2016) Some head-mounted displays and viewers over time, NASA Ames Research Center. Available at: https://humansystems.arc.nasa.gov/groups/acd/projects/hmd_dev.php (Accessed: 20 August 2018).

EON Reality (2021) Augmented and virtual reality solutions. Available at: https://eonreality.com/ (Accessed: 5 February 2020).

Ermi, L. and Mäyrä, F. (2005) 'Fundamental components of the gameplay experience: analysing immersion', in de Castell, S. D. and Jenson, J. (eds) Worlds in play: international perspectives on digital games research. New York, NY: Peter Lang Publishing, pp. 15–27.

Facebook Technologies (2020) 3D audio spatialization, Oculus For Developers. Available at: https://developer.oculus.com/learn/audio-intro-spatialization/?locale=en_GB (Accessed: 1 June 2021).

Falconer, C. J. et al. (2016) 'Embodying self-compassion within virtual reality and its effects on patients with depression', BJPsych Open, 2(1), pp. 74–80. doi: 10.1192/bjpo.bp.115.002147.

Ferrero, A. and Piuri, V. (1999) 'A simulation tool for virtual laboratory experiments in a WWW environment', IEEE Transactions on Instrumentation and Measurement, 48(3), pp. 741–746. doi: 10.1109/19.772214.

Ford-Lanza, A. (2020) What is vestibular input and what therapy helps?, Ceril. Available at: http://ceril.net/index.php/articulos?id=660 (Accessed: 16 October 2020).

Fowler, C. (2015) 'Virtual reality and learning: where is the pedagogy?', British Journal of Educational Technology, 46(2), pp. 412–422. doi: 10.1111/bjet.12135.

Freeman, D. et al. (2017) 'Virtual reality in the assessment, understanding, and treatment of mental health disorders', Psychological Medicine, 47(14), pp. 2393–2400. doi: 10.1017/S003329171700040X.

Gallagher, S. (2015) 'Phenomenology and embodied cognition', in The Routledge Handbook of Embodied Cognition. Routledge. doi: 10.4324/9781315775845.ch1.

Gallagher, S. and Lindgren, R. (2015) 'Enactive metaphors: learning through full-Body engagement', Educational Psychology Review, 27(3), pp. 391–404. doi: 10.1007/s10648-015-9327-1.

Gallese, V. (2008) 'Mirror neurons and the social nature of language: the neural exploitation hypothesis', Social Neuroscience, 3(3–4), pp. 317–333. doi: 10.1080/17470910701563608.

Galvan Debarba, H. et al. (2017) 'Characterizing first and third person viewpoints and their alternation for embodied interaction in virtual reality', PLoS ONE. Edited by M. Botbol, 12(12), p. e0190109. doi: 10.1371/journal.pone.0190109.

Gamberini, L. (2004) ‘Virtual reality as a new research tool for the study of human memory’, CyberPsychology & Behavior, 3(3), pp. 337–342. doi: 10.1089/10949310050078779.

Gamma, E. (2021) Brain plasticity (neuroplasticity), Simply Psychology. Available at: https://www.simplypsychology.org/brain-plasticity.html (Accessed: 16 June 2021).

Gibbs, R. W. J. (2005) Embodiment and cognitive science. Cambridge, UK: Cambridge University Press. doi: 10.1017/CBO9780511805844.

Gibson, J. J. (1977) ‘The theory of affordances’, in Shawand, R. and Bransford, J. (eds) Perceiving, acting, and knowing: toward an ecological psychology. Hillsdale, NJ: Lawrence Erlbaum, pp. 67–82.

Gibson, J. J. (2014) The ecological approach to visual perception. New York, NY: Psychology Press. doi: 10.4324/9781315740218.

Gilbert, N. (2021) 74 virtual reality statistics you must know in 2021/2022: adoption, usage & market share, Finances Online. Available at: https://financesonline.com/virtual-reality-statistics/ (Accessed: 21 September 2021).

GlobalData Technology (2020) History of virtual reality: timeline. Available at: https://www.verdict.co.uk/history-virtual-reality-timeline/ (Accessed: 17 January 2021).

Goldin-Meadow, S. (1999) ‘The role of gesture in communication and thinking’, Trends in Cognitive Sciences, 3(11), pp. 419–429. doi: 10.1016/S1364-6613(99)01397-2.

Goldin-Meadow, S. (2009) ‘How gesture promotes learning throughout childhood’, Child Development Perspectives, 3(2), pp. 106–111. doi: 10.1111/j.1750-8606.2009.00088.x.

Goldstone, R., Landy, D. and Son, J. Y. (2008) ‘A well grounded education: the role of perception in science and mathematics’, in de Vega, M., Glenberg, A., and Graesser, A. (eds) Symbols and embodiment: debates on meaning and cognition. Oxford, UK: Oxford University Press. doi: 10.1093/acprof:oso/9780199217274.001.0001.

Goodale, M. A. and Milner, A. D. (1992) ‘Separate visual pathways for perception and action’, Trends in Neurosciences, 15(1), pp. 20–25. doi: 10.1016/0166-2236(92)90344-8.

Google LLC (2014) Google Cardboard, Google. Available at: https://arvr.google.com/intl/en_uk/cardboard/ (Accessed: 31 May 2020).

Google LLC (2017) ‘Google Daydream View (second generation)’. [Online image]. Available at: https://arvr.google.com/daydream/ (Accessed: 6 June 2020).

Google LLC (2018a) Google Expeditions. Available at: https://edu.google.com.mx/expeditions/#about (Accessed: 19 August 2018).

Google LLC (2018b) Google VR: degrees of freedom, Google Developers. Available at: https://developers.google.com/vr/discover/degrees-of-freedom (Accessed: 7 July 2020).

Greenwald, A. G., McGhee, D. E. and Schwartz, J. L. K. (1998) ‘Measuring individual differences in implicit cognition: the implicit association test.’, Journal of Personality and Social Psychology, 74(6), pp. 1464–1480. doi: 10.1037/0022-3514.74.6.1464.

Greivenkamp, J. E. (2004) Field guide to geometrical optics. Bellingham, WA: SPIE Press. Available at: https://search-proquest-com.libproxy.ucl.ac.uk/docview/200102660?accountid=14511.

Gustavsson, I. et al. (2009) ‘On objectives of instructional laboratories, individual assessment, and use of collaborative remote laboratories’, IEEE Transactions on Learning Technologies, 2(4), pp. 263–274. doi: 10.1109/TLT.2009.42.

Guterstam, A., Abdulkarim, Z. and Ehrsson, H. H. (2015) ‘Illusory ownership of an invisible body reduces autonomic and subjective social anxiety responses’, Scientific Reports, 5(9831). doi: 10.1038/srep09831.

Haddrill, M. and Heiting, G. (2020) Peripheral vision loss (tunnel vision): Causes and treatments, All About Vision. Available at: https://www.allaboutvision.com/en-gb/conditions/peripheral-vision/ (Accessed: 21 October 2020).

Hamilton, D. et al. (2020) ‘Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design’, Journal of Computers in Education. Springer. doi: 10.1007/s40692-020-00169-2.

Hamilton, I. (2021) FinchRing as a new gesture controller shown with Nreal, UploadVR. Available at: https://uploadvr.com/finchring-nreal/ (Accessed: 28 March 2021).

Hampe, B. (ed.) (2005) From perception to meaning: image schemas in cognitive linguistics. Berlin, DE: Mouton de Gruyter. doi: 10.1515/9783110197532.

HaptX (2021) HaptX gloves: the only VR gloves with true-contact haptics. Available at: https://haptx.com/virtual-reality/ (Accessed: 6 April 2021).

Harnad, S. (1990) ‘The symbol grounding problem’, Physica D: Nonlinear Phenomena, 42(1–3), pp. 335–346. doi: 10.1016/0167-2789(90)90087-6.

Hart, S. G. and Staveland, L. E. (1988) ‘Development of NASA-TLX (Task Load Index): results of empirical and theoretical research’, in Advances in Psychology, pp. 139–183. doi: 10.1016/S0166-4115(08)62386-9.

Hasler, B. S., Spanlang, B. and Slater, M. (2017) ‘Virtual race transformation reverses racial in-group bias’, PLoS ONE. Edited by A. Avenanti, 12(4), p. e0174965. doi: 10.1371/journal.pone.0174965.

Hatfield, G. (2014) ‘Cognition’, in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. Abingdon, UK: Routledge, pp. 361–373. doi: 10.4324/9781315775845.ch34.

Hayden, S. (2020) Samsung is terminating its VR video apps on all devices, Road to VR. Available at: https://www.roadtovr.com/samsung-terminating-vr-video-apps-devices/ (Accessed: 6 February 2021).

Hays, R. T. and Singer, M. J. (1989) ‘Definitions and problems in training system design’, in Hays, R. T. and Singer, M. J. (eds) Simulation fidelity in training system design: bridging the gap between reality and training. New York, NY: Springer, pp. 4–22. doi: 10.1007/978-1-4612-3564-4_1.

Heilig, M. L. (1962) ‘Sensorama simulator’. United States Patent Office. Available at: http://www.mortonheilig.com/SensoramaPatent.pdf (Accessed: 19 August 2018).

Hejtmanek, L. et al. (2020) ‘How much of what we learn in virtual reality transfers to real-world navigation?’, Multisensory Research, 33(4–5), pp. 479–503. doi: 10.1163/22134808-20201445.

Hendrix, C. M. (1994) Exploratory studies on the sense of presence in virtual environments as a function of visual and auditory display parameters. University of Washington. Available at:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.6.2562&rep=rep1&type=pdf.

Herold, B. (2014) Oculus Rift fueling new vision for virtual reality in K-12, Education Week. Available at: https://www.edweek.org/teaching-learning/oculus-rift-fueling-new-vision-for-virtual-reality-in-k-12/2014/08 (Accessed: 5 February 2021).

Hillis, K. (1999) A critical history of virtual reality, Digital Sensations. University of Minnesota Press. doi: 10.5749/j.cttts6mg.6.

Hoffman, C. (2018) *What is a monitor's r*efresh rate and how do I change it?, How-To-Geek. Available at: https://www.howtogeek.com/359691/what-is-a-monitors-refresh-rate-and-how-do-i-change-it/ (Accessed: 21 October 2020).

Hoffman, H. G. et al. (2014) 'Feasibility of articulated arm mounted Oculus Rift virtual reality goggles for adjunctive pain control during occupational therapy in pediatric burn patients', Cyberpsychology, Behavior, and Social Networking, 17(6), pp. 397–401. doi: 10.1089/cyber.2014.0058.

Hruska, J. (2015) Oculus founder confirms VR is shaping up into an unavoidably fragmented mess, ExtremeTech. Available at: https://www.extremetech.com/gaming/209989-oculus-founder-confirms-vr-is-shaping-up-into-an-unavoidably-fragmented-mess (Accessed: 20 January 2021).

Hruska, J. (2020) Oculus *Go headset discontinued, Quest games won't require Oculus store*, ExtremeTech. Available at: https://www.extremetech.com/gaming/312001-oculus-go-headset-discontinued-quest-games-wont-require-oculus-store (Accessed: 6 February 2021).

HTC Corporation (2016) 'HTC VIVE 3D virtual reality system'. [Online image]. Available at: https://www.vive.com/us/product/vive-virtual-reality-system/ (Accessed: 9 June 2020).

HTC Corporation (2020) VIVE Pro HMD user guide. Available at: https://dl4.htc.com/Web_materials/Manual/Vive_HMD/User_Guide/VIVE_Pro_HMD_User_Guide.pdf (Accessed: 9 February 2021).

Hurtienne, J. and Israel, J. H. (2007) 'Image schemas and their metaphorical extensions', in Proceedings of the 1st international conference on Tangible and embedded interaction - *TEI '07*. New York, NY: ACM Press, pp. 127–134. doi: 10.1145/1226969.1226996.

Hutson, M. (2018) 'Here's what the future of haptic technology looks (or rather, feels) like.', Knowable Magazine. Smithsonianmag.com, 28 December. doi: 10.1146/annurev-control-060117-105043.

Hvass, J. et al. (2017) 'Visual realism and presence in a virtual reality game', in 2017 3DTV Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON). Copenhagen, DK: IEEE Computer Society, pp. 1–4. doi: 10.1109/3DTV.2017.8280421.

IGI Global (2021) What is visual artifacts?, Dictionary search. Available at: https://www.igi-global.com/dictionary/visual-artifacts/65812 (Accessed: 17 February 2021).

Immersive VR Education (2018) Immersive VR education: learn through experience. Available at: http://immersivevreducation.com/about-us/ (Accessed: 19 August 2018).

Intel (2020) What is the difference between integrated graphics and discrete graphics? Available at: https://www.intel.com/content/www/us/en/support/articles/000057824/graphics.html

(Accessed: 1 June 2021).

Ioannou, M. and Ioannou, A. (2020) 'Technology-enhanced embodied learning: designing and evaluating a new classroom experience', Educational Technology & Society, 23(3), pp. 81–94.

Jang, S. et al. (2017) 'Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment', Computers & Education. Elsevier, 106, pp. 150–165. doi: 10.1016/j.compedu.2016.12.009.

Jenkins, A. (2019) The fall and rise of VR: the struggle to make virtual reality get real, Fortune. Available at: https://fortune.com/longform/virtual-reality-struggle-hope-vr/ (Accessed: 4 February 2021).

Jensen, L. and Konradsen, F. (2018) 'A review of the use of virtual reality head-mounted displays in education and training', Education and Information Technologies. Education and Information Technologies, 23(4), pp. 1515–1529. doi: 10.1007/s10639-017-9676-0.

Jewitt, C. (2014) 'An introduction to multimodality', in Jewitt, C. (ed.) The Routledge handbook of multimodal analysis. 2nd edn. London, UK: Routledge.

Jewitt, C. and Price, S. (2012) 'Multimodal approaches to video analysis of digital learning environments', in The 26th BCS Conference on Human Computer Interaction (HCI). Birmingham, UK, pp. 1–4. doi: 10.14236/ewic/HCI2012.105.

Johnson-Glenberg, M. C. et al. (2011) 'Semi-virtual embodied learning-real world STEM assessment', in Annetta, L. and Bronack, S. (eds) Serious educational game assessment. Rotterdam, NL: Sense Publishers, pp. 241–257. doi: 10.1007/978-94-6091-329-7_15.

Johnson-Glenberg, M. C. et al. (2014) 'Collaborative embodied learning in mixed reality motion-capture environments: two science studies.', Journal of Educational Psychology, 106(1), pp. 86–104. doi: 10.1037/a0034008.

Johnson-Glenberg, M. C. et al. (2016) 'Effects of embodied learning and digital platform on the retention of physics content: centripetal force', Frontiers in Psychology, 7(Nov), pp. 1–22. doi: 10.3389/fpsyg.2016.01819.

Johnson-Glenberg, M. C. (2017) 'Embodied education in mixed and mediated realties', in Liu, D. et al. (eds) Virtual, augmented, and mixed realities in education. Singapore, SG: Springer, pp. 193–217.

Johnson-Glenberg, M. C. (2018) 'Immersive VR and education: embodied design principles that include gesture and hand controls', Frontiers in Robotics and AI, 5, pp. 1–19. doi: 10.3389/frobt.2018.00081.

Johnson-Glenberg, M. C. (2019) 'The necessary nine: design principles for embodied VR and active STEM education', in Díaz, P. et al. (eds) Learning in a digital world: perspective on interactive technologies for formal and informal education. Singapore, SG: Springer, pp. 83–112.

Johnson-Glenberg, M. C. et al. (2020) 'Embodied agentic STEM education: effects of 3D VR compared to 2D PC', in 2020 6th International Conference of the Immersive Learning Research Network (iLRN). IEEE, pp. 24–30. doi: 10.23919/iLRN47897.2020.9155155.

Johnson-Glenberg, M. C. and Megowan-Romanowicz, C. (2017) 'Embodied science and mixed reality: how gesture and motion capture affect physics education', Cognitive

Research: Principles and Implications, 2(1), p. 24. doi: 10.1186/s41235-017-0060-9.

Johnson, M. (1987) The body in the mind: the bodily basis of meaning, imagination, and reason. Chicago, IL: University of Chicago Press.

Johnston, A. P. R. et al. (2018) 'Journey to the centre of the cell: virtual reality immersion into scientific data', Traffic, 19(2), pp. 105–110. doi: 10.1111/tra.12538.

de Jong, T., Linn, M. C. and Zacharia, Z. C. (2013) 'Physical and virtual laboratories in science and engineering education', Science, 340(6130), pp. 305–308. doi: 10.1126/science.1230579.

K. Babu, S. et al. (2018) 'Virtual reality learning environments for vocational education: a comparison study with conventional instructional media on knowledge retention', in 18th International Conference on Advanced Learning Technologies (ICALT). IEEE, pp. 385–389. doi: 10.1109/ICALT.2018.00094.

Kaspar, K. et al. (2014) 'The experience of new sensorimotor contingencies by sensory augmentation', Consciousness and Cognition. Elsevier, 28(1), pp. 47–63. doi: 10.1016/j.concog.2014.06.006.

Ke, F., Lee, S. and Xu, X. (2016) 'Teaching training in a mixed-reality integrated learning environment', Computers in Human Behavior, 62, pp. 212–220. doi: 10.1016/j.chb.2016.03.094.

Kendon, A. (2004) Gesture: visible action as utterance. Cambridge, UK: Cambridge University Press.

Kilteni, K. et al. (2015) 'Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception', Frontiers in Human Neuroscience, 9(MAR). doi: 10.3389/fnhum.2015.00141.

Kilteni, K., Groten, R. and Slater, M. (2012) 'The sense of embodiment in virtual reality', Presence: Teleoperators and Virtual Environments, 21(4), pp. 373–387. doi: 10.1162/PRES_a_00124.

Klein, A. (2015) The world of 3D-imaging!, Stereoscopy. Available at: https://www.stereoscopy.com/ (Accessed: 18 July 2020).

Koch, S. C., Glawe, S. and Holt, D. V. (2011) 'Up and down, front and back: movement and meaning in the vertical and sagittal axes', Social Psychology, 42(3), pp. 214–224. doi: 10.1027/1864-9335/a000065.

Kolb, B. and Whishaw, I. Q. (1998) 'Brain plasticity and behavior', Annual Review of Psychology, 49(1), pp. 43–64. doi: 10.1146/annurev.psych.49.1.43.

Kosslyn, S. M. (2005) 'Mental images and the brain', Cognitive Neuropsychology. Psychology Press, 22(3–4), pp. 333–347. doi: 10.1080/02643290442000130.

Krauss, R. M., Chen, Y. and Chawla, P. (1996) 'Non-verbal behavior and non-verbal communication: what do conversational hand gestures tell us?', in Advances in Experimental Social Psychology, pp. 389–450. doi: 10.1016/S0065-2601(08)60241-5.

Kress, G. R. (2010) Multimodality: a social semiotic approach to contemporary communication. London: Routledge.

Kress, G. R. (2014) 'What is mode?', in Jewitt, C. (ed.) The Routledge handbook of multimodal analysis. 2nd Ed. London: Routledge (Routledge handbooks), pp. 54–67.

Krokos, E., Plaisant, C. and Varshney, A. (2018) 'Virtual memory palaces: immersion aids recall', Virtual Reality. Springer, pp. 1–15. doi: 10.1007/s10055-018-0346-3.

Kuno, S. et al. (1999) 'Postural adjustment response to depth direction moving patterns produced by virtual reality graphics.', The Japanese Journal of Physiology, 49(5), pp. 417–424. doi: 10.2170/jjphysiol.49.417.

Kwon, C. (2019) 'Verification of the possibility and effectiveness of experiential learning using HMD-based immersive VR technologies', Virtual Reality. Springer, 23(1), pp. 101–118. doi: 10.1007/s10055-018-0364-1.

Labster (2018) 'Pipetting simulation'. [Digital] Android OS. Copenhagen: Labster. Available at: https://www.labster.com/simulations/pipetting-master-the-technique/.

Labster (2021) 150+ virtual labs for universities and high schools. Available at: https://www.labster.com/ (Accessed: 5 February 2021).

Lakoff, G. and Johnson, M. (1999) Philosophy in the flesh: the embodied mind and its challenge to western thought. New York, NY: Basic Books.

Lang, B. (2018) *How VR's next generation shows key signs of a maturing market*, Road to VR. Available at: https://www.roadtovr.com/how-vr-next-generation-shows-key-signs-of-a-maturing-market/ (Accessed: 19 August 2018).

Lang, B. (2021a) Analysis: monthly active VR headsets on Steam pass 2 million milestone, Road to VR. Available at: https://www.roadtovr.com/steam-survey-vr-monthly-active-user-2-million-milestone/ (Accessed: 21 March 2021).

Lang, B. (2021b) Facebook reveals latest wrist-worn prototypes for XR input & haptics, RoadtoVR. Available at: https://www.roadtovr.com/facebook-reveals-latest-wrist-worn-controller-prototype-for-xr-input-haptics/ (Accessed: 28 March 2021).

Lenggenhager, B., Mouthon, M. and Blanke, O. (2009) 'Spatial aspects of bodily self-consciousness', Consciousness and Cognition. Elsevier, 18(1), pp. 110–117. doi: 10.1016/j.concog.2008.11.003.

Lhommet, M. and Marsella, S. (2014) 'Metaphoric gestures: towards grounded mental spaces', in Bickmore, T., Marsella, S., and Sidner, C. (eds) Intelligent Virtual Agents. Cham, CH: Springer, pp. 264–274.

Lin, J. J.-W. et al. (2002) 'Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment', in Proceedings IEEE Virtual Reality 2002. IEEE Computer Society, pp. 164–171. doi: 10.1109/VR.2002.996519.

Lindgren, R. et al. (2016) 'Enhancing learning and engagement through embodied interaction within a mixed reality simulation', Computers & Education. Elsevier, 95, pp. 174–187. doi: 10.1016/j.compedu.2016.01.001.

Liu, R. et al. (2020) 'Effects of an immersive virtual reality-based classroom on students' learning performance in science lessons', British Journal of Educational Technology, 51(6), pp. 2034–2049. doi: 10.1111/bjet.13028.

Longo, M. R. et al. (2008) 'What is embodiment? A psychometric approach', Cognition, 107(3), pp. 978–998. doi: 10.1016/j.cognition.2007.12.004.

Loreto-Quijada, D. et al. (2014) 'Differential effects of two virtual reality interventions: distraction versus pain control', Cyberpsychology, Behavior, and Social Networking, 17(6), pp. 353–358. doi: 10.1089/cyber.2014.0057.

Lou, X. et al. (2020) 'Hand-adaptive user interface: improved gestural interaction in virtual reality', Virtual Reality. Springer London, (0123456789). doi: 10.1007/s10055-020-00461-7.

Louis, T. et al. (2019) 'Is it real? Measuring the effect of resolution, latency, frame rate and jitter on the presence of virtual entities', in Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces. New York, NY: ACM Press, pp. 5–16. doi: 10.1145/3343055.3359710.

Di Luca, M. et al. (2021) 'Locomotion vault: the extra mile in analyzing VR locomotion techniques', in Conference on Human Factors in Computing Systems. New York, NY: AMC. doi: 10.1145/3411764.3445319.

Maister, L. et al. (2015) 'Changing bodies changes minds: owning another body affects social cognition', Trends in Cognitive Sciences, 19(1), pp. 6–12. doi: 10.1016/j.tics.2014.11.001.

Makransky, G. et al. (2016) 'Simulation based virtual learning environment in medical genetics counseling: an example of bridging the gap between theory and practice in medical education', BMC Medical Education, 16(1), p. 98. doi: 10.1186/s12909-016-0620-6.

Makransky, G., Terkildsen, T. S. and Mayer, R. E. (2019) 'Adding immersive virtual reality to a science lab simulation causes more presence but less learning', Learning and Instruction. Pergamon, 60, pp. 225–236. doi: 10.1016/j.learninstruc.2017.12.007.

Malerczyk, C. (2008) 'Dynamic gestural interaction with immersive environments', in 16th International Conference in Central Europe on Computer Graphics, Visualization and *Computer Vision, WSCG'2008*, pp. 161–166.

Malizia, A. and Bellucci, A. (2012) 'The artificiality of natural user interfaces', Communications of the ACM, 55(3), pp. 36–38. doi: 10.1145/2093548.2093563.

MANUS (2021) Prime II motion capture gloves. Available at: https://www.manus-vr.com/vr-gloves (Accessed: 6 April 2021).

Mariscal, G. et al. (2020) 'Virtual reality simulation-based learning', Education in the Knowledge Society (EKS), 21(11), pp. 1–15. doi: 10.14201/eks.23004.

Martin, A. (2007) 'The representation of object concepts in the brain', Annual Review of Psychology, 58(1), pp. 25–45. doi: 10.1146/annurev.psych.57.102904.190143.

Martinez-Lincoln, A., Tran, L. M. and Powell, S. R. (2018) 'What the hands tell us about mathematical learning: a synthesis of gesture use in mathematics instruction', Gesture, 17(3), pp. 375–416. doi: 10.1075/gest.17014.mar.

Matheson, H. E. and Barsalou, L. W. (2018) 'Embodiment and grounding in cognitive neuroscience', in Thompson-Schill, S. L. (ed.) *Stevens' Handbook of Experimental* Psychology and Cognitive Neuroscience (Vol. 3 Language and Thought). Hoboken, NJ: John Wiley & Sons, pp. 1–27. doi: 10.1002/9781119170174.epcn310.

McMahan, A. (2014) 'Immersion, engagement, and presence: a method for analyzing 3-D video games', in Wolf, M. J. P. and Perron, B. (eds) The video game theory reader. New York, NY: Routledge, pp. 67–86. doi: 10.4324/9780203700457.

McNeill, D. (1992) Hand and mind: what gestures reveal about thought. Chicago, IL: University of Chicago Press.

MEL Science (2020) MEL chemistry VR. Available at: https://melscience.com/GB-en/vr/ (Accessed: 31 May 2020).

Merchant, Z. et al. (2014) ‘Effectiveness of virtual reality-based instruction on students’ learning outcomes in K-12 and higher education: a meta-analysis’, Computers & Education. Elsevier, 70, pp. 29–40. doi: 10.1016/j.compedu.2013.07.033.

Merleau-Ponty, M. (2012) Phenomenology of perception. London, UK: Routledge.

Merriam-Webster (no date) Peripheral, Merriam-Webster.com dictionary. Available at: https://www.merriam-webster.com/dictionary/peripheral (Accessed: 27 October 2020).

Meyer, O. A., Omdahl, M. K. and Makransky, G. (2019) ‘Investigating the effect of pre-training when learning through immersive virtual reality and video: A media and methods experiment’, Computers & Education, 140, p. 103603. doi: 10.1016/j.compedu.2019.103603.

Microsoft (2019) Azure Kinect body tracking joints, Azure Kinect DK Documentation. Available at: https://docs.microsoft.com/en-us/azure/kinect-dk/body-joints (Accessed: 22 November 2020).

Microsoft (2020a) HoloLens 2 gestures for authoring and navigating, Microsoft Docs: Dynamics 365 Guides. Available at: https://docs.microsoft.com/en-us/dynamics365/mixed-reality/guides/authoring-gestures-hl2 (Accessed: 26 May 2021).

Microsoft (2020b) Inside-out tracking, Windows Mixed Reality Enthusiast Documentation. Available at: https://docs.microsoft.com/en-us/windows/mixed-reality/enthusiast-guide/tracking-system (Accessed: 22 November 2020).

Milgram, P. and Kishino, F. (1994) ‘A taxonomy of mixed reality visual-displays’, IEICE Transactions on Information and Systems, 77(12), pp. 1321–1329.

Moreau-Mathis, J. (2014) *God rays? What’s that?*, Community Play 3D. Available at: https://medium.com/community-play-3d/god-rays-whats-that-5a67f26aeac2#.l7of1sdun (Accessed: 17 February 2021).

Moreno, R. and Mayer, R. E. (2002) ‘Learning science in virtual reality multimedia environments: role of methods and media.’, Journal of Educational Psychology, 94(3), pp. 598–610. doi: 10.1037/0022-0663.94.3.598.

Mosso-Vázquez, J. L. et al. (2014) ‘Virtual reality for pain management in cardiac surgery’, Cyberpsychology, Behavior, and Social Networking, 17(6), pp. 371–378. doi: 10.1089/cyber.2014.0198.

Mountford, V. A., Tchanturia, K. and Valmaggia, L. (2016) ‘“What are you thinking when you look at me?” A pilot study of the use of virtual reality in body image’, Cyberpsychology, Behavior, and Social Networking, 19(2), pp. 93–99. doi: 10.1089/cyber.2015.0169.

Munfarid (2020) VRXOne: VR STEM lab. Available at: https://munfarid.org/immersive-learning-programs/k-12-educcation/vr-stem-lab (Accessed: 5 February 2021).

Nathan, M. J. (2008) ‘An embodied cognition perspective on symbols, gesture, and grounding instruction’, in Symbols and Embodiment Debates on meaning and cognition. Oxford, UK: Oxford University Press, pp. 375–396. doi: 10.1093/acprof:oso/9780199217274.003.0018.

Nelson, B. (2013) Inertial measurement sensors improve efficiency, safety in farm equipment. Available at: https://www.oemoffhighway.com/electronics/sensors/article/10979955/inertial-measurement-sensors-improve-safety-in-ag-equipment (Accessed: 1 July 2018).

Nemec, M. et al. (2017) ‘Using virtual reality in education’, in 15th International Conference on

Emerging eLearning Technologies and Applications (ICETA). Stary Smokovec, SK: IEEE Computer Society, pp. 1–6. doi: 10.1109/ICETA.2017.8102514.

Nilsson, N. C., Nordahl, R. and Serafin, S. (2016) ‘Immersion Revisited: A review of existing definitions of immersion and their relation to different theories of presence’, Human Technology, 12(2), pp. 108–134. doi: 10.17011/ht/urn.201611174652.

Noë, A. (2004) Action in perception. London, UK: MIT Press.

O’Regan, J. K. and Noë, A. (2001) ‘A sensorimotor account of vision and visual consciousness’, Behavioral and Brain Sciences, 24(05), pp. 939–973. doi: 10.1017/S0140525X01000115.

Orland, K. (2019) How Open*XR could glue virtual reality’s fragmenting market together*, Ars Technica. Available at: https://arstechnica.com/gaming/2019/03/how-openxr-could-glue-together-virtual-realitys-fragmenting-market/ (Accessed: 6 June 2021).

Osso VR (2021) Virtual Reality Surgical Training Platform. Available at: https://ossovr.com/ (Accessed: 12 March 2021).

Ozacar, K. et al. (2017) ‘A low-cost and lightweight 3D interactive real estate-purposed indoor virtual reality application’, ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, IV-4/W4(4W4), pp. 307–310. doi: 10.5194/isprs-annals-IV-4-W4-307-2017.

Pande, P. et al. (2021) ‘Long-term effectiveness of immersive VR simulations in undergraduate science learning: lessons from a media-comparison study’, Research in Learning Technology, 29(1063519), pp. 1–24. doi: 10.25304/rlt.v29.2482.

Di Paolo, E. A., Rohde, M. and De Jaegher, H. (2010) ‘Enaction: toward a new paradigm for cognitive science’, in Stewart, J., Gapenne, O., and Paolo, E. A. Di (eds) Enaction toward a new paradigm for cognitive science. Cambridge, MA: MIT Press, pp. 33–87.

Di Paolo, E. and Thompson, E. (2015) ‘The enactive approach’, in The Routledge Handbook of Embodied Cognition. Routledge. doi: 10.4324/9781315775845.ch7.

Papachristos, N. M., Vrellis, I. and Mikropoulos, T. A. (2017) ‘A comparison between Oculus Rift and a low-cost smartphone VR headset: immersive user experience and learning’, in 2017 IEEE 17th International Conference on Advanced Learning Technologies (ICALT). IEEE Computer Society, pp. 477–481. doi: 10.1109/ICALT.2017.145.

Pellas, N., Mystakidis, S. and Kazanidis, I. (2021) ‘Immersive virtual reality in K-12 and higher education: a systematic review of the last decade scientific literature’, Virtual Reality. Springer. doi: 10.1007/s10055-020-00489-9.

Perez-Marcos, D., Sanchez-Vives, M. V. and Slater, M. (2012) ‘Is my hand connected to my body? The impact of body continuity and arm alignment on the virtual hand illusion’, Cognitive Neurodynamics, 6(4), pp. 295–305. doi: 10.1007/s11571-011-9178-5.

Philip, L. J. (1998) ‘Combining quantitative and qualitative approaches to social research in human geography - an impossible mixture?’, Environment and Planning A: Economy and Space, 30(2), pp. 261–276. doi: 10.1068/a300261.

Piaget, J. (1963) The origins of intelligence in children. Translated by M. Cook. New York, NY: W. W. Norton & Co.

Planey, J. and Lindgren, R. (2020) ‘Examining modalities of embodied interactions and the effects on learning from a collaborative science simulation’, in Gresalfi, M. and Horn, I. S. (eds) The Interdisciplinarity of the Learning Sciences, 14th International Conference of the Learning Sciences (ICLS) 2020. Nashville, TN: International Society of the Learning Sciences, pp. 605–608. doi: 10.22318/icls2020.605.

Poetker, B. (2019) The very real history of virtual reality (+A look ahead). Available at: https://learn.g2.com/history-of-virtual-reality (Accessed: 16 January 2021).

Price, S. et al. (2009) ‘Technology and embodiment: relationships and implications for knowledge, creativity and communication’, Beyond Current Horizons, (May), pp. 1–22. Available at: http://www.beyondcurrenthorizons.org.uk/technology-and-embodiment-relationships-and-implications-for-knowledge-creativity-and-communication/.

Prieur, J. et al. (2020) ‘The origins of gestures and language: history, current advances and proposed theories’, Biological Reviews, 95(3), pp. 531–554. doi: 10.1111/brv.12576.

Prince, S. (1996) ‘True lies: perceptual realism, digital images, and film theory’, Film Quarterly, 49(3), pp. 27–37. doi: 10.1525/fq.1996.49.3.04a00040.

Probst, L., Pedersen, B. and Dakkak-Arnoux, L. (2017) Digital transformations monitor: augmented and virtual reality. Available at: https://ati.ec.europa.eu/sites/default/files/2020-05/Augmented and Virtual Reality vf.pdf (Accessed: 20 January 2021).

Punch, K. F. (1998) Introduction to social research: quantitative and qualitative approaches. Thousand Oaks, CA: Sage.

Pylyshyn, Z. (1999) ‘Is vision continuous with cognition?: the case for cognitive impenetrability of visual perception’, Behavioral and Brain Sciences, 22(3), pp. 341–365. doi: 10.1017/S0140525X99002022.

Qi, E. (2020) Oculus to bring lifelike immersion to mass market, Counterpoint Research. Available at: https://www.counterpointresearch.com/oculus-to-bring-lifelike-immersion-to-mass-market/ (Accessed: 19 March 2021).

Radianti, J. et al. (2020) ‘A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda’, Computers & Education. Elsevier, 147(December 2019), p. 103778. doi: 10.1016/j.compedu.2019.103778.

Raees, M. and Ullah, S. (2019) ‘GIFT: gesture-based interaction by fingers tracking, an interaction technique for virtual vnvironment’, International Journal of Interactive Multimedia and Artificial Intelligence, 5(5), p. 115. doi: 10.9781/ijimai.2019.01.002.

Rakkolainen, I. et al. (2017) ‘Extreme field-of-view for head-mounted displays’, in 3DTV Conference: The True Vision - Capture, Transmission and Display of 3D Video. IEEE, pp. 1–4. doi: 10.1109/3DTV.2017.8280417.

Ratcliffe, J. and Tokarchuk, L. (2020) ‘Presence, embodied interaction and motivation: distinct learning phenomena in an immersive virtual environment’, in Proceedings of the 28th ACM International Conference on Multimedia. New York, NY, USA: ACM, pp. 3661–3668. doi: 10.1145/3394171.3413520.

RedboxVR (2020) RedboxVR: immersive technologies. Available at: https://redboxvr.co.uk/ (Accessed: 5 February 2021).

Richards, D. and Taylor, M. (2015) ‘A comparison of learning gains when using a 2D simulation tool versus a 3D virtual world: an experiment to find the right representation involving the Marginal Value Theorem’, Computers & Education. Elsevier, 86, pp. 157–171. doi: 10.1016/j.compedu.2015.03.009.

Ridenour, C. S. and Newman, I. (2008) Mixed methods research: exploring the interactive continuum. Carbondale, IL: Southern Illinois University Press. Available at: Project MUSE muse.jhu.edu/book/22619.

Riener, C. and Stefanucci, J. (2014) ‘Perception and/for/with/as action’, in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. London, UK: Routledge, pp. 99–107. doi: 10.4324/9781315775845.ch10.

Riva, G. (2005) ‘Virtual reality in the treatment of eating disorders and obesity: state of the art and future challenges’, Annual Review of Cybertherapy and Telemedicine. Edited by B. K. Wiederhold, A. H. Bullinger, and G. Riva, 3, pp. 39–46.

Rizzo, A. A. et al. (2009) ‘VR PTSD exposure therapy results with active duty OIF/OEF combatants’, Studies in health technology and informatics, 142, pp. 277–82. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19377167.

Rizzolatti, G. and Sinigaglia, C. (2010) ‘The functional role of the parieto-frontal mirror circuit: interpretations and misinterpretations’, Nature Reviews Neuroscience, 11(4), pp. 264–274. doi: 10.1038/nrn2805.

Robertson, A. (2016) *The ultimate VR headset buyer’s guide*, The Verge. Available at: https://www.theverge.com/a/best-vr-headset-oculus-rift-samsung-gear-htc-vive-virtual-reality (Accessed: 21 March 2021).

Robertson, A. (2019) Phone-based VR is officially over, The Verge. Available at: https://www.theverge.com/2019/10/16/20915791/google-daydream-samsung-oculus-gear-vr-mobile-vr-platforms-dead (Accessed: 6 February 2021).

Roussou, M. and Slater, M. (2020) ‘Comparison of the effect of interactive versus passive virtual reality learning activities in evoking and sustaining conceptual change’, IEEE Transactions on Emerging Topics in Computing, 8(1), pp. 233–244. doi: 10.1109/TETC.2017.2737983.

Saffer, D. (2009) Designing gestural interfaces. Sebastopol, CA: O’Reilly.

Sato, A. and Yasuda, A. (2005) ‘Illusion of sense of self-agency: discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership’, Cognition, 94(3), pp. 241–255. doi: 10.1016/j.cognition.2004.04.003.

Schell Games (2018) ‘HoloLAB Champions: chemiluminescence’. [Digital] PC. Pittsburgh: Schell Games. Available at: https://www.schellgames.com/games/hololab-champions/ (Accessed: 15 February 2019).

Schroeder, B. L. et al. (2017) ‘Presence and usability do not directly predict procedural recall in virtual reality training’, in Communications in Computer and Information Science, pp. 54–61. doi: 10.1007/978-3-319-58753-0_9.

Schubert, T., Friedmann, F. and Regenbrecht, H. (2001) ‘The experience of presence: factor analytic insights’, Presence: Teleoperators and Virtual Environments, 10(3), pp. 266–281. doi: 10.1162/105474601300343603.

Schwartz, R. and Steptoe, W. (2018) ‘The immersive VR self: performance, embodiment and presence in immersive virtual reality environments’, in Papacharissi, Z. (ed.) A Networked Self and Human Augmentics, Artificial Intelligence, Sentience. New York, NY: Routledge, pp. 108–116.

Schwind, V. et al. (2019) ‘Using presence questionnaires in virtual reality’, in Proceedings of *the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. New York, NY: ACM Press, pp. 1–12. doi: 10.1145/3290605.3300590.

Scorolli, C. (2014) 'Embodiment and Language', in Shapiro, L. (ed.) The Routledge handbook of embodied cognition. London, UK: Routledge, pp. 127–138. doi: 10.4324/9781315775845.ch13.

Seale, C. (2012) Researching society and culture. 3rd edn. London, UK: Sage.

Segal, A. (2011) Do gestural interfaces promote thinking? Embodied interaction: congruent gestures and direct-touch promote performance in math. Columbia University. doi: 10.7916/D8DR32GK.

Serpa, F. and Eloy, S. (2020) 'How non-designers understand the architecture design project: a comparative study using immersive virtual reality.', Interaction Design and Architecture(s), 45, pp. 287–301. Available at: http://www.mifav.uniroma2.it/inevent/events/idea2010/doc/45_13.pdf.

Shapiro, L. A. (2012) 'Embodied cognition', in Margolis, E., Samuels, R., and Stich, S. P. (eds) The Oxford handbook of philosophy of cognitive science. Oxford, UK: Oxford University Press. doi: 10.1093/oxfordhb/9780195309799.013.0006.

Sheets-Johnstone, M. (2000) 'Kinetic tactile-kinesthetic bodies: ontogenetical foundations of apprenticeship learning', Human Studies, 23(4), pp. 343–370. Available at: https://www.jstor.org/stable/20011289.

Sherman, W. R. and Craig, A. B. (2003) Understanding virtual reality: interface, application, and design. San Francisco, CA: Elsevier.

Shin, D.-H. (2017) 'The role of affordance in the experience of virtual reality learning: Technological and affective affordances in virtual reality', Telematics and Informatics. Elsevier, 34(8), pp. 1826–1836. doi: 10.1016/j.tele.2017.05.013.

Shu, Y. et al. (2019) 'Do virtual reality head-mounted displays make a difference? A comparison of presence and self-efficacy between head-mounted displays and desktop computer-facilitated virtual environments', Virtual Reality. Springer, 23(4), pp. 437–446. doi: 10.1007/s10055-018-0376-x.

Slater, M. et al. (1998) 'The influence of body movement on subjective presence in virtual environments', Human Factors: The Journal of the Human Factors and Ergonomics Society, 40(3), pp. 469–477. doi: 10.1518/001872098779591368.

Slater, M. (1999) 'Measuring presence: a response to the Witmer and Singer presence questionnaire', Presence: Teleoperators and Virtual Environments, 8(5), pp. 560–565. doi: 10.1162/105474699566477.

Slater, M. (2004) 'How colorful was your day? Why questionnaires cannot assess presence in virtual environments', Presence: Teleoperators and Virtual Environments, 13(4), pp. 484–493. doi: 10.1162/1054746041944849.

Slater, M., Lotto, B., et al. (2009) 'How we experience immersive virtual environments: the concept of presence and its measurement', Anuario de Psicología, 40(2), pp. 193–210.

Slater, M., Perez-Marcos, D., et al. (2009) 'Inducing illusory ownership of a virtual body', Frontiers in Neuroscience, 3(2), pp. 214–220. doi: 10.3389/neuro.01.029.2009.

Slater, M. (2009) 'Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments', Philosophical Transactions of the Royal Society, 364(1535), pp. 3549–3557. doi: 10.1098/rstb.2009.0138.

Slater, M. et al. (2010) ‘First person experience of body transfer in virtual reality’, PLoS ONE, 5(5). doi: 10.1371/journal.pone.0010564.

Slater, M. (2017) ‘Implicit learning through embodiment in immersive virtual reality’, in Liu, D. et al. (eds) Virtual, augmented, and mixed realities in education. Singapore, SG (Springer), pp. 19–33.

Slater, M. (2018) ‘Immersion and the illusion of presence in virtual reality’, British Journal of Psychology, 109(3), pp. 431–433. doi: 10.1111/bjop.12305.

Slater, M. and Sanchez-Vives, M. V. (2014) ‘Transcending the self in immersive virtual reality’, Computer, 47(7), pp. 24–30. doi: 10.1109/MC.2014.198.

Slater, M. and Sanchez-Vives, M. V. (2016) ‘Enhancing our lives with immersive virtual reality’, Frontiers in Robotics and AI, 3(December), pp. 1–47. doi: 10.3389/frobt.2016.00074.

Slater, M. and Steed, A. (2000) ‘A virtual presence counter’, Presence: Teleoperators and Virtual Environments, 9(5), pp. 413–434. doi: 10.1162/105474600566925.

Slater, M. and Usoh, M. (1993) ‘Presence in immersive virtual environments’, in Proceedings of IEEE Virtual Reality Annual International Symposium. IEEE Computer Society, pp. 90–96. doi: 10.1109/VRAIS.1993.380793.

Slater, M. and Wilbur, S. (1997) ‘A framework for immersive virtual environments (FIVE): speculations on the role of presence in virtual environments’, Presence: Teleoperators and Virtual Environments, 6(6), pp. 603–616. doi: 10.1162/pres.1997.6.6.603.

Snyder, C. (2016) Introduction to virtual reality concepts. Available at: http://www.leadingones.com/articles/intro-to-vr-4.html (Accessed: 1 July 2018).

Stauffert, J.-P., Niebling, F. and Latoschik, M. E. (2020) ‘Latency and cybersickness: impact, causes, and measures. A review’, Frontiers in Virtual Reality, 1(November), pp. 1–10. doi: 10.3389/frvir.2020.582204.

Stavroulia, K.-E. et al. (2019) ‘Virtual reality environments (VREs) for training and learning’, in Díaz, P. et al. (eds) Learning in a digital world: perspective on interactive technologies for formal and informal education. Singapore, SG: Springer, pp. 195–211.

Stolz, S. A. (2015) ‘Embodied learning’, Educational Philosophy and Theory. Routledge, 47(5), pp. 474–487. doi: 10.1080/00131857.2013.879694.

Streeck, J. (2008) ‘Depicting by gesture’, Gesture, 8(3), pp. 285–301. doi: 10.1075/gest.8.3.02str.

Suh, A. and Prophet, J. (2018) ‘The state of immersive technology research: A literature analysis’, Computers in Human Behavior. Elsevier, 86, pp. 77–90. doi: 10.1016/j.chb.2018.04.019.

Sutherland, I. E. (1968) ‘A head-mounted three dimensional display’, in Proceedings of the December 9-*11, 1968, fall joint computer conference, part I (AFIPS ’68 (Fall, part I))*. New York, NY: ACM Press, p. 757. doi: 10.1145/1476589.1476686.

Sweller, J., Ayres, P. and Kalyuga, S. (2011) Cognitive load theory. New York, NY: Springer. doi: 10.1007/978-1-4419-8126-4.

Tajadura-Jiménez, A. et al. (2017) ‘Embodiment in a child-like talking virtual body influences object size perception, self-identification, and subsequent real speaking’, Scientific Reports, 7(1), pp. 1–13. doi: 10.1038/s41598-017-09497-3.

Tashakkori, A. and Teddlie, C. (eds) (2010) Handbook of mixed methods in social and behavioral research. 2nd edn. Thousand Oaks, CA: Sage.

Taylor, J. L. (2009) ‘Proprioception’, in Encyclopedia of Neuroscience. Elsevier, pp. 1143–1149. doi: 10.1016/B978-008045046-9.01907-0.

Teddlie, C. and Tashakkori, A. (2009) Foundations of mixed methods research: integrating quantitative and qualitative approaches in the social and behavioral sciences. Thousand Oaks, CA: Sage.

Thisgaard, M. and Makransky, G. (2017) ‘Virtual learning simulations in high school: effects on cognitive and non-cognitive outcomes and implications on the development of STEM academic and career choice’, Frontiers in Psychology, 8(May). doi: 10.3389/fpsyg.2017.00805.

Thomas Jha, R., Price, S. and Motion, A. (2020) ‘Designing “embodied” science learning experiences for young children’, in Zaphiris, P. and Ioannou, A. (eds) Learning and Collaboration Technologies. Designing, Developing and Deploying Learning Experiences. Cham: Springer, pp. 207–225.

Tsakiris, M., Prabhu, G. and Haggard, P. (2006) ‘Having a body versus moving your body: How agency structures body-ownership’, Consciousness and Cognition, 15(2), pp. 423–432. doi: 10.1016/j.concog.2005.09.004.

Tsakiris, M., Schütz-Bosbach, S. and Gallagher, S. (2007) ‘On agency and body-ownership: phenomenological and neurocognitive reflections’, Consciousness and Cognition, 16(3), pp. 645–660. doi: 10.1016/j.concog.2007.05.012.

Tsyktor, V. (2019) What is non-immersive virtual reality?, CyberPulse. Available at: https://cyberpulse.info/what-is-non-immersive-virtual-reality-definition-examples/ (Accessed: 4 February 2021).

Tversky, B., Morrison, J. B. and Betrancourt, M. (2002) ‘Animation: can it facilitate?’, International Journal of Human-Computer Studies, 57(4), pp. 247–262. doi: 10.1006/ijhc.2002.1017.

Usoh, M. et al. (2000) ‘Using presence questionnaires in reality’, Presence: Teleoperators and Virtual Environments, 9(5), pp. 497–503. doi: 10.1162/105474600566989.

Valve Corporation (2016) SteamVR tracking, Steamworks. Available at: https://partner.steamgames.com/vrlicensing (Accessed: 7 May 2021).

Valve Corporation (2018) Introducing SteamVR skeletal input, SteamVR News. Available at: https://store.steampowered.com/news/app/250820/view/2898585530113862726 (Accessed: 6 April 2021).

Valve Corporation (2019) ‘Valve Index controllers’. [Online image]. Available at: https://store.steampowered.com/sub/354234/ (Accessed: 9 June 2020).

Vandenberg, S. G. and Kuse, A. R. (1978) ‘Mental rotations, a group test of three-dimensional spatial visualization’, Perceptual and Motor Skills, 47(2), pp. 599–604. doi: 10.2466/pms.1978.47.2.599.

Varela, F. J., Rosch, E. and Thompson, E. (2017) The embodied mind: cognitive science and human experience. 2nd ed. Cumberland, MD: MIT Press.

Vazquez, C. et al. (2018) ‘Words in motion: Kinesthetic language learning in virtual reality’, in 18th International Conference on Advanced Learning Technologies, ICALT 2018. IEEE, pp. 272–276. doi: 10.1109/ICALT.2018.00069.

Vilà-Giménez, I. and Prieto, P. (2021) 'The value of non-referential gestures: a systematic review of their cognitive and linguistic effects in children's language development', Children, 8(2), p. 148. doi: 10.3390/children8020148.

Virtual reality society (2017) History Of virtual reality. Available at: https://www.vrs.org.uk/virtual-reality/history.html (Accessed: 19 August 2018).

Virtual Reality Society (2017) Virtual reality tracking systems. Available at: https://www.vrs.org.uk/virtual-reality-gear/tracking.html (Accessed: 9 February 2021).

Vuletic, T. et al. (2019) 'Systematic literature review of hand gestures used in human computer interaction interfaces', International Journal of Human-Computer Studies, 129, pp. 74–94. doi: 10.1016/j.ijhcs.2019.03.011.

Vygotskii, L. S. (1978) Mind in society: the development of higher psychological processes. Edited by M. Cole and A. R. Luriia. Cambridge, MA: Harvard University Press.

Wamsley, E. J. and Stickgold, R. (2010) 'Dreaming and offline memory processing', Current Biology, 20(23), pp. R1010–R1013. doi: 10.1016/j.cub.2010.10.045.

Webster, R. (2016) 'Declarative knowledge acquisition in immersive virtual learning environments', Interactive Learning Environments. Taylor & Francis, 24(6), pp. 1319–1333. doi: 10.1080/10494820.2014.994533.

Weis, S. (2018) An overview of roomscale tracking technologies, Packet39. Available at: https://packet39.com/blog/2018/10/07/roomscale-tracking-technologies/ (Accessed: 22 November 2020).

Williams, A. S. and Ortega, F. R. (2020) 'Understanding gesture and speech multimodal interactions for manipulation tasks in augmented reality using unconstrained elicitation', arXiv, 26(12), pp. 3479–3489. Available at: http://arxiv.org/abs/2009.06591.

Wilson, A. D. and Golonka, S. (2013) 'Embodied cognition is not what you think it is', Frontiers in Psychology, 4. doi: 10.3389/fpsyg.2013.00058.

Wilson, M. (2002) 'Six views of embodied cognition', Psychonomic Bulletin & Review, 9(4), pp. 625–636. doi: 10.3758/BF03196322.

Wirth, W. et al. (2007) 'A process model of the formation of spatial presence experiences', Media Psychology, 9(3), pp. 493–525. doi: 10.1080/15213260701283079.

Within (2020) Within: extraordinary stories in virtual reality. Available at: https://www.with.in/ (Accessed: 5 February 2021).

Witmer, B. G. and Singer, M. J. (1998) 'Measuring presence in virtual environments: a presence questionnaire', Presence: Teleoperators and Virtual Environments. New York, NY: ACM Press, 7(3), pp. 225–240. doi: 10.1162/105474698565686.

Wroblewski, L. (2010) Touch gesture reference guide, Lukew: Ideation + design. Available at: https://www.lukew.com/ff/entry.asp?1071 (Accessed: 25 May 2021).

Wu, H. et al. (2019) 'Understanding freehand gestures: a study of freehand gestural interaction for immersive VR shopping applications', Human-centric Computing and Information Sciences. Springer Berlin Heidelberg, 9(1), p. 43. doi: 10.1186/s13673-019-0204-7.

Xambó, A. (2015) 'Embodied music interaction: creative design synergies between music performance and HCI', in Broahurst, S. and Price, S. (eds) Digital bodies: creativity and technology in the arts and humanities. London, UK: Macmillan.

Yasen, M. and Jusoh, S. (2019) 'A systematic review on hand gesture recognition techniques, challenges and applications', PeerJ Computer Science, 5(9), p. e218. doi: 10.7717/peerj-cs.218.

Yee, N. and Bailenson, J. (2007) 'The proteus effect: the effect of transformed self-representation on behavior', Human Communication Research, 33(3), pp. 271–290. doi: 10.1111/j.1468-2958.2007.00299.x.

Youngblut, C. (2003) Experience of presence in virtual environments, Institute for Defense Analyses. Alexandria, VA. doi: 10.21236/ADA427495.

Yun, E. (2020) Central vision vs. peripheral vision, OXSIGHT. Available at: https://www.oxsight.co.uk/news/central-vision-vs-peripheral-vision/ (Accessed: 21 October 2020).

Zhou, Z. et al. (2018) 'Personalized planning and training system for brachytherapy based on virtual reality', Virtual Reality. Springer. doi: 10.1007/s10055-018-0350-7.

zSpace (2018) zSpace AR/VR learning experiences. Available at: https://zspace.com/ (Accessed: 19 August 2018).

Appendix A: Ethics and informed consent

Appendix overview

This section is comprised by the instruments used to obtain ethics approval and informed consent from participants and their parents:

- **A.1 Information brochure and privacy notice:** This is the information brochure and privacy notice given to participants as part of a briefing. It indicates eligibility criteria to take part in the study, it details what participating entails, and provides contact details for further information. A similar brochure was given to students to hand over to their parents as a supplement to the consent form.
- **A.2 Participant and parental consent forms:** These are the forms used to obtain informed consent from participants and their parents or carers.
- **A.3 Approved ethics application**: This is the last page of the ethics form for the research indicating approval from the Research Ethics Committee at UCL: Institute of Education.

A.1 Information brochure and privacy notice.

Institute of Education

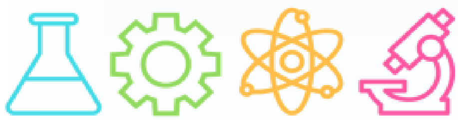
UCL

Information brochure and privacy notice

for participants in research studies

Title of research:

The role of interaction, agency, and presence in supporting conceptual and procedural knowledge about science in immersive virtual reality.



(March for science 2017)

UCL Research Ethics Committee Approval ID Number: Z6364106/2018/02/89

You have been invited to participate in a research study looking at how physical interactions in immersive virtual reality (VR) environments can help you understand science concepts.

Please read this information carefully before agreeing to participate. The researcher is happy to answer any questions you may have.

What is the purpose of this study?

This study investigates how the feeling of being inside a virtual world and physically interacting with it may help you better understand science concepts. The study compares two types of VR technology that support different ways of interacting and performing experiments in two chemistry laboratories.

Why me?

You have been invited to participate in this research study because your school is interested in collaborating with the researcher to explore new and interesting tools for teaching and learning through technology in STEAM subjects.

Do I have to participate?

Your participation is voluntary and anonymous and it is OK if you change your mind later and decide not to do it after all as long as it is before March 2020 when analysis will start. You will not receive marks, money, or anything for participating, but you'll get to try some cool VR tech.

What will I do if I participate?

You will attend one or two 90-minute sessions where you will learn about chemistry and how to use lab equipment.

During the sessions you will perform chemistry experiments using two types of virtual reality technology, answer questionnaires about the technology and your experience in the virtual environment, and have a brief interview with the researcher where you will be asked about the things you did in the virtual environment and how you interpreted the ideas presented.

The sessions will take place in your school at a date and time to be determined. A month later, you will be asked to answer a final text to see how much you remember about the chemistry lessons in VR.

What VR technology will I use?

You will use the VR headsets in the pictures below to perform experiments in two virtual chemistry laboratories: *Labster* and *HoloLAB Champions*.

(Daydream View 2017)

(HTC Vive, 2017)
(Index controllers, 2019)

Will I be recorded?

Yes. Your participation and interviews will be video/audio recorded so that we can analyse the ways in which you interacted with the virtual labs and how you used the technology. But don't worry, the recordings will be kept in a safe place and only the research team will see them.

What are the benefits and risks of participating?

Most people don't feel anything, but some may get dizzy, feel their eyes getting tired, or a light headache. The researcher will adjust the headset, screen, and lenses to your eyes to avoid this, but if you experience any of these symptoms, tell him and he will stop the experience and help you so you don't feel that way.

The benefit of participating is that you may learn things about science that might be useful for your lessons at school such as how to use some lab equipment and you will get to play and have fun with cool VR technology.

Will my participation be anonymous? and What will happen to the information collected?

Yes, measures will be taken so that nobody can know that the information we collect refers to you and everything will be processed and stored securely according to UK law.

Only anonymised information and censored recordings will be used in the publication of the study findings and recordings will be destroyed after the research and the dissemination of its findings has ended.

Data protection privacy notice:

The data controller for this project will be University College London. The UCL Data Protection Office provides oversight of UCL activities involving the processing of personal data, and can be contacted at data-protection@ucl.ac.uk UCL's Data Protection Officer is Lee Shailer.

The data indicated in this brochure will be processed for the purposes outlined in this notice. The legal basis that will be used to process them is that of 'public task.' Your data will be processed so long as it is required for this research project and it will be anonymised or pseudonymised.

If you are concerned about how your personal data is being processed, please contact UCL in the first instance at data-protection@ucl.ac.uk. If you remain unsatisfied, you may wish to contact the Information Commissioner's Office (ICO). Contact details, and details of data subject rights are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

Who is funding the research?

This project is funded by the government of Mexico through the sponsorship of the National Council of Science and Technology.

CONACYT

References and additional information:

ColdFusion. (2017). What are Virtual and Augmented Realities?. [Online Video]. 1 April 2017. Available from: https://www.youtube.com/watch?v=f9MwaH6oGEY. [Accessed: 22 December 2017].

Daydream View 2, 2017, digital photograph. Google, accessed 24 June 2019 https://www.aniwaa.com/product/vr-ar/google-daydream-view-2/

HTC Vive, 2017, digital photograph. Electronic products, accessed 05 December 2017 https://www.electronicproducts.com/uploadedImages/Multimedia/Video/HTC-Vive.JPG

March for science, 2017, digital photograph. Logo, accessed 24 December 2017 http://marchforscience-houston.webflow.io/

Serino, J., 2017, Labster—Virtual laboratories. Digital photograph, accessed 05 December 2017 https://s3.amazonaws.com/poly-screenshots.angel.co/enhanced_screenshots/531014-original.jpg

Researchers' contact details:

Researcher: Omar Ceja (omar.salgado.17@ucl.ac.uk)

Primary Supervisor: Sara Price (sara.price@ucl.ac.uk)

UCL Institute of Education. Department of Culture, Communication and Media. UCL Knowledge Lab

23-29 Emerald St. London WC1N 3QS

A.2 Participant and parental consent forms.

Institute of Education

UCL

CONSENT FORM FOR PARTICIPANTS IN RESEARCH STUDIES

Title of study:
The role of interaction, agency, and presence in supporting conceptual and procedural knowledge about science in immersive virtual reality.
This study has been approved by the UCL Research Ethics Committee with project ID number: Z6364106/2018/02/89

Thank you for deciding to participate in this research study. Please read the information brochure and feel free to contact the researcher if you have any questions or concerns before you fill out this form. **Please tick the boxes bellow to indicate that you agree to those points and sign and date the sheet in the spaces provided at the bottom.**

I confirm that I have read and understood the information in the brochure, and if I had any questions, they were answered by the researcher.	☐
I confirm that I have voluntarily decided to participate in the research study described in the brochure.	☐
I consent to the following data to be collected: • Notes made from observations of my participation and interviews. • Questionnaires or tests about the content of the VR experiences. • Video/audio recording, screen captures (pictures), and transcripts of the interviews and my use of the VR technology. • Measurements of my interpupillary distance to adjust the headsets to my eyes. • My age, gender, and year of schooling.	 ☐ ☐ ☐ ☐ ☐
I consent for the data listed above to be used for the purpose of research, including the dissemination of findings in publications.	☐
I understand that the data listed above will be anonymised before it is used for publication in order to protect my identity.	☐
I understand that my confidentiality will be protected, but it is limited or conditional to any evidence of wrongdoing, danger, or harm in which case, the researcher will inform me, my parent or guardian, and school of the reasons for having to break it.	☐
I understand that the video/audio recordings of my participation will be kept safely in UCL's servers for the duration of the research and the dissemination of its findings and only the research team will have access to them.	☐
I understand that all data will be collected, processed, and kept securely according to data protection regulations in the UK.	☐
I understand the risks and benefits of participating in this research study as indicated in the information brochure.	☐
I understand that there are no incentives, monetary or otherwise for participating.	☐
I understand that I can stop participating at any time without having to give a reason up to March 2020 when data analysis is expected to take place, and that all data collected from my participation up to that point will be deleted from the database unless otherwise agreed.	☐
I understand that I can approach or contact the researcher regarding any matter related to the research and/or my child's participation in it.	☐

______________________________ ____/____/____
Full name Date

UCL Institute of Education
UCL Knowledge Lab
23-29 Emerald St, Holborn, London WC1N 3QS, UK
Tel: +44 (0)77 1541 1026
omar.salgado.17@ucl.ac.uk
www.ucl.ac.uk/ioe

Institute of Education

UCL

CONSENT FORM FOR PARENTS OR CARERS OF STUDENT PARTICIPANTS IN RESEARCH STUDIES

Title of study:
The role of interaction, agency, and presence in supporting conceptual and procedural knowledge about science in immersive virtual reality.

This study has been approved by the UCL Research Ethics Committee with project ID number: Z6364106/2018/02/89

Thank you for considering letting your child participate in this research study. Please read the information brochure and feel free to contact the researcher if you have any questions or concerns before you fill out this form. **Please tick the boxes on the right-hand side to indicate that you agree to each of the points. Sign and date the sheet in the spaces provided at the bottom.**

I confirm that I have read and understood the information in the brochure, and if I had any questions, they were addressed by the researcher.	☐
I confirm that my child has voluntarily decided to participate in the research study described in the brochure.	☐
I consent to the following data to be collected about my child:	
• Notes made from observations of his/her participation and interviews.	☐
• Questionnaires or tests about the content of the VR experiences.	☐
• Video/audio recordings, screen captures (pictures), and transcripts of his/her interviews and use of the VR technology.	☐
• Measurements of his/her interpupillary distance to adjust the headsets to his/her eyes.	☐
• His/her age, gender, and year of schooling.	☐
I consent for the data listed above to be used for the purpose of research, including the dissemination of findings in publications.	☐
I understand that the data listed above will be anonymised before it is used for publication in order to protect my child's identity.	☐
I understand that my child's confidentiality will be protected, but it is limited or conditional to any evidence of wrongdoing, danger, or harm in which case, the researcher will inform you, your child, and the school of the reasons for having to break it.	☐
I understand that the video/audio recordings of my child's participation will be kept safely in UCL's servers for the duration of the research and the dissemination of its findings and only the research team will have access to them.	☐
I understand that all data will be collected, processed, and kept securely according to data protection regulations in the UK.	☐
I understand the risks and benefits of participating in this research study as indicated in the information brochure.	☐
I understand that there are no incentives, monetary or otherwise for participating.	☐
I understand that my child can stop participating at any time without having to give a reason up to March 2020 when data analysis is expected to take place, and that all data collected from his/her participation up to that point will be deleted from the database unless otherwise agreed.	☐
I understand that I can approach or contact the researcher regarding any matter related to the research and/or my child's participation in it.	☐

______________________________ Full name of parent or carer

______________________ Signature

____/____/____ Date

UCL Institute of Education
UCL Knowledge Lab
23-29 Emerald St, Holborn, London WC1N 3QS, UK
Tel: +44 (0)77 1541 1026
omar.salgado.17@ucl.ac.uk
www.ucl.ac.uk/ioe

A.3 Approved ethics application.

Departmental use	
If a project raises particularly challenging ethics issues, or a more detailed review would be appropriate, the supervisor **must** refer the application to the Research Ethics and Governance Coordinator (via ioe.researchethics@ucl.ac.uk so that it can be submitted to the Research Ethics Committee for consideration. A departmental research ethics coordinator or representative can advise you, either to support your review process, or help decide whether an application should be referred to the REC. *Also see 'when to pass a student ethics review up to the Research Ethics Committee':* *http://www.ioe.ac.uk/about/policiesProcedures/42253.html*	
Student name	Omar Ceja Salgado
Student department	CCM
Course	PhD
Project title	The role of interaction, agency, and presence in supporting conceptual and procedural knowledge about science in immersive virtual reality.
Reviewer 1	
Supervisor/first reviewer name	Sara Price
Do you foresee any ethical difficulties with this research?	Recommend researcher verbally goes through the information with student participants, as well as giving a written version
Supervisor/first reviewer signature	[redacted]
Date	13/03/18
Reviewer 2	
Second reviewer name	Mina Vasalou
Do you foresee any ethical difficulties with this research?	No
Supervisor/second reviewer signature	[redacted]
Date	13/03/2018
Decision on behalf of reviews	
Decision	Approved ☑ Approved subject to the following additional measures ☐ Not approved for the reasons given below ☐ Referred to REC for review ☐
Points to be noted by other reviewers and in report to REC	
Comments from reviewers for the applicant	
Once approved by both reviewers students should submit the ethics application form to the Centre for Doctoral Education team IOE.CDE@ucl.ac.uk.	

Appendix B: Evaluation of iVR software

Appendix overview

This section is comprised by the instruments designed for and employed in the analysis of iVR software during the preliminary studies:

- **B.1 Evaluation matrix of immersive virtual reality experiences:** This table shows the evaluation that was done on immersive virtual reality experiences that were initially considered for the empirical study.
- **B.2 Descriptive matrix of Labster (Pipetting: Mastering the Technique):** This table presents the evaluation of the virtual laboratory used for the low-end iVR condition. The matrix details general aspects of the experience and establishes the relationship between learning outcomes and interactions.
- **B.3 Descriptive matrix of HoloLAB Champions (Chemiluminescence):** This table presents the evaluation of the virtual laboratory used for the high-end iVR condition. The matrix details general aspects of the experience and establishes the relationship between learning outcomes and interactions.

B.1 Evaluation matrix of immersive virtual reality experiences.

Evaluation of virtual reality experiences (section 1)							
VR experience	Section	Description	Duration	Platform	Technical features		
					Tutorial / gameplay	Language	Perspective type
3D Organon VR Anatomy	N/A	Anatomy viewer. It includes a comprehensive number of body elements with a brief description of their function. All elements are labelled and can be observed up close. Surrounding elements can be faded for a better view of the element of interest. Bone animations are included as well.	N/A	HTC Vive / Steam VR.	There is a help section that details how to use the controllers to navigate the menus and manipulate body element. Interaction is in a point and click style, but objects can be manipulated as if the controllers were hands.	English text and narration of names of body parts.	Immersive.
Edmersiv	Geography experience	Science museum and lab. Many of the activities involve video and simulation of processes. However, there is not much in-depth information about the concepts.	00:08:06	HTC Vive / Steam VR.	N/A (Most experiences rely on pointing and clicking for selection. When needed, pointers appear on the screen).	English narration and subtitles.	Immersive.

YOU	N/A	This is an anatomy viewer. Although it does not contain information about the organs, they are animated and labelled. The experience is particularly useful for the understanding of diseases and how organs function. It is possible to have a view of the inside of organs and the animations that show how healthy and diseased organs work.	N/A	HTC Vive / Steam VR.	There is a tutorial section at the beginning which explains how to navigate the menus and visualize body elements.	Text in English, no narration, or subtitles.	Immersive.
The Body VR	Journey Inside a Cell	Students are miniaturised and placed inside a pod that takes them on a tour inside a cell. There are 7 sections in the experience which explain elements and functions.	00:11:21	HTC Vive / Steam VR.	N/A (Not necessary during the experiences. Menu navigation is by pointing and clicking on the trigger).	Narration in English and Spanish. No subtitles available. Audio is important as text is minimal.	Immersive.
Lifeliqe VR Museum	Bohr Model of the Atom of Oxygen	This is a space where students can visualize different things and learn about them.	N/A	HTC Vive / Steam VR.	On screen tutorial and legends on controllers permanently.	Narration in English, text in English or Spanish.	Immersive.

Titans of Space 2.0	Long Tour	Students take a tour of the Solar System on a spacecraft. They can read facts about the bodies, see real photos, rotate them, and shrink them to see their surface up close.	00:30:00	HTC Vive / Steam VR.	On screen tutorial and legends on controllers permanently.	Text in English and Spanish. No narration.	Immersive.
The Stanford Ocean Acidification Experience	N/A	Students are taken on a guided tour that explains ocean acidification and its repercussions.	00:08:00	HTC Vive / Steam VR.	Explanations offered throughout the experience. The trigger in the controller is used for selection, but the controller must be in contact with the object.	English narration. No subtitles.	Immersive.
Labster	VR version: • Electron transport chain. • Lab safety virtual lab. • Pigment extraction. Desktop version: • Acids and bases. • Antibodies. • Carbohydrates. • Diabetes. • Evolution.	Science laboratory experiences and simulations with integrated assessment.	VR version: 00:30:00; 00:20:00; 00:30:00 Desktop version: 00:29:00; 00:40:00; 00:25:00; 00:35:00; 00:29:00;	VR version: Lenovo Mirage Solo Daydream platform. Desktop version: Web-based.	Embedded in the experiences.	English narration and subtitles.	VR version: immersive. Desktop version: non-immersive.

	• Introductory lab. • Light and polarization.		00:38:00; 00:25:00				
EON Experience	Various.	Software to visualise components. They can be created and expanded with external links, quizzes, etc.	N/A	Web-based or with dedicated software: EON Creator 9.0 and EON Experience Player 9.0.	N/A	Annotations on the objects presented.	Non-immersive.
HoloLAB Champions	Chemiluminescence.	Gamified virtual chemistry laboratory where students can perform experiments on chemiluminescence, identify unknown chemicals as well as practice lab skills such as pouring liquids, and measuring, scaling, and transferring substances.	01:00:00	HTC Vive / Steam VR.	There is no tutorial, but there is a book that shows how to perform procedures and actions that might be useful for the experiments.	Audio and text in English.	Immersive.

Evaluation of virtual reality experiences (section 2)						
VR experience	Technical features			Sense of presence		Sense of embodiment
	Type of setup	Tracking	Controllers	Place illusion	Plausibility illusion	
3D Organon VR Anatomy	Room-scale recommended although the only use of the feature is to walk around the model.	Tracked controllers and headset. 6DoF.	High-end interactivity. Controllers do not need to get in contact with objects to interact with them. A ray of light comes out of the virtual controllers to select elements on the menus or manipulate body elements on the model.	There are three possible scenarios: a practitioner's office, and a white or black background. The illusion is maintained as movement away from the model is limited and not encouraged.	The only interactive elements are the menus and the models. The illusion is maintained as the rest of the objects in the room cannot be reached so users cannot try interacting with them.	There is no visual embodied representation. The controllers are visually represented as they are needed for interactions.
Edmersiv	Room-scale setting recommended. Students can walk physically within the limits of the play area. Locomotion is limited to teleportation to specific locations in the environment.	Tracked controllers and headset. 6DoF.	High-end interactivity. The trigger can be used to manipulate and attract objects; however, the virtual representation of the controllers does not need to get in contact with objects as there is a ray of light that is used for selection. Capabilities of the controllers are	The main area is a museum with stations spread around the area. Additional spaces include a science laboratory and the Colosseum.	Plausibility illusion is somewhat broken by interaction through a beacon of light emanating from the controllers and the limited options for teleportation. Additionally, some objects are not interactive.	There is no virtual embodied representation. The controllers are visually represented as they are needed for interactions.

			underused. Manipulation of objects is possible, but most of the times meaningless.			
YOU	Room-scale, but its capabilities are limited to walking around organs. Room-scale or standing settings are recommended.	Tracked controllers and headset. 6DoF.	Middle-end interactivity. Tracked controllers are used for interaction. There is no manipulation of objects, interactivity is limited to pointing and clicking.	Void space in main areas and the interior of organs. Place illusion irrelevant in the former and determined by the visuals and the assumption of having been miniaturised in the latter.	Given the assumption that the participant is inside an organ or in an undetermined simulator plausibility is maintained.	There is no virtual embodied representation. The controllers are visually represented as they are needed for interactions.
The Body VR	Room-scale, but its capabilities are not utilized. It is recommended that students take the tour in a seated position.	Tracked controllers and headset. 6DoF.	Low-end interactivity. Tracked controllers are used for interaction, but there is no meaningful use for them. Minimal information is shown in front of participants. They can move displayed elements or throw copies of them to the environment (there is no purpose of either action). Interactivity can be a distractor. It is recommended that participants take the	Afforded by being transported in a pod. The environment is unreal, but due to the narrative and simulations, place illusion is achieved.	Due to lack of interaction, plausibility illusion is maintained.	There is no virtual embodied representation. The controllers can be included, but they can be a distractor.

			tour without the controllers.			
Lifeliqe VR Museum	Room-scale setting recommended.	Tracked controllers and headset. 6DoF.	Middle-end interactivity. Tracked controllers are used for interaction. There is no manipulation of objects, interactivity is limited to pointing and clicking.	The space is a futuristic museum. It is a big dome and experiences or objects to visualize are presented in the centre.	Easily broken when trying to directly interact with objects.	There is no virtual embodied representation. The controllers are visually represented as they are needed for interactions.
Titans of Space 2.0	Seated experience recommended as it can be disorienting and due to the physical space, no walking is necessary.	Tracked controllers and headset. 6DoF.	Middle-end interactivity. Tracked controllers are used for interaction. The buttons on the controllers can be used to perform actions such as rotating and shrinking planets and controlling the interface. The later can also be done by pointing and clicking at screen buttons using the trigger.	The inside of a space probe. It disappears when approaching a celestial body to give an unobstructed view and reappears when on the move.	Broken if students try to interact with buttons in the pod that don't have a function. When interaction is possible, buttons light up.	There is no virtual embodied representation. The controllers are visually represented as they are needed for interactions.
The Stanford Ocean	Room-scale setting recommended. The are no forms	Tracked controllers and	High-end interactivity. Manipulation of objects is minimal, but scripted as part of the narrative;	There are three scenarios: a street, a boat, and the bottom of the ocean. There is a	Plausibility can be broken if the student tries to manipulate elements that have not	Hands are visually represented in the virtual environment and students are

Acidification Experience	of locomotion other than physical walking, but due to the nature of the experience, students do not need to move further than the boundary limits.	headset. 6DoF.	therefore, it is meaningful.	combination of rendered scenes and photogrammetry.	been scripted. The experience does not encourage exploration as it is guided. As long as students follow the instructions, this form of illusion can be maintained.	encouraged to use them to interact with it.
Labster	The immersive VR version is a standing experience with limited locomotion.	Although the technolog y allows for 6DoF the experienc es are designed with 3DoF in mind.	Limited interactivity. Manipulation is not possible; controllers are used as pointers.	Laboratory and scenarios related to the experiences.	Limited locomotion and manipulation of objects can break the illusion. Activities are guided so exploration and trial are not encouraged.	Some scenes present hand representations, but they are not tracked which does not create the illusion of embodiment.
EON Experience	N/A	N/A	Tapping on a touchscreen / use of mouse.	N/A	The visualization of the objects. Although they can be rotated, there is no manipulation beyond that which breaks the illusion.	N/A

HoloLAB Champions	Room-scale / Standing.	Tracked controllers and headset. 6DoF.	High-end interactivity. In order to perform experiments, students must manipulate objects; however, only the trigger is used to engage with virtual objects. The use of the pipette is the only instance where also the track pad is used.	Chemistry laboratory / TV studio with audience.	Direct manipulation with objects reactions and interactions with the environment support the illusion; however, it is broken when objects do not always behave naturally such as flasks not breaking.	There are no visual representations of the body; however, the controllers give a sense of hands manipulation.

B.2 Descriptive matrix of Labster (Pipetting: Mastering the Technique).

Descriptive matrix of the pipetting simulation in Labster (section 1)				
Sections	**Learning objectives**	**Learning outcomes**	**Estimated time**	**Instructions**
Tutorial	To familiarize yourself with the interface on the tablet and how to navigate the virtual environment.	Students will be able to navigate the virtual space and the interface seamlessly.	00:06:30	Follow the AI guidance either through audio or by reading the closed captioning on the tablet.
Visiting the indoor farm	To ground the experience to real life uses.	None.	00:02:00	Listen to the narration and pick up the 3D printed protein, and the cob when instructed.
Preparing a tube with buffer	To create a dilution series of the protein extracted from the cob.	Students will learn how to select the appropriate pipette according to the volume of liquid they need to measure. Students will learn how to use the pipette to draw up and dispense fluids, use the two-step function and the order in which all operations need to be performed for avoid errors and cross contamination.	00:26:00	Follow the AI guidance either through audio or by reading the closed captioning on the tablet to learn how to select and use the pipettes, dispose tips, measure volumes, and mix fluids using the stop on the pipette.
Diluting the protein solution	To create a dilution series of the protein extracted from the cob.	Students will learn how a dilution series is performed.	00:10:00	Follow the AI guidance either through audio or by reading the closed captioning on the tablet to learn how perform the dilution. Additional theory is needed which can be found in the tablet.

Performing a Bradford assay	To perform a Bradford assay to determine the concentration of the BHL protein.	Students will have a better understanding of how the Bradford assay can help them quantify the protein content in a sample more precisely using a dilution series.	00:13:00	Follow the AI guidance either through audio or by reading the closed captioning on the tablet to learn how to perform the Bradford assay and read the results. Additional theory is needed which can be found in the tablet.

Descriptive matrix of the pipetting simulation in Labster (section 2)

Sections	Laboratory equipment	Skills	Control scheme	Guidance system
Tutorial	Tablet (LabPad).	Navigating the virtual environment.	Point and click on trackpad for interactions. Use volume buttons to change the audio, the home button to summon the main menu, or the App button to bring up or down the LabPad.	Step by step instructions on the tablet and orally from the AI assistant. There is not much room for exploration as students are instructed what to do.
Visiting the indoor farm	None.	None.	Point and click on trackpad for interactions. Use volume buttons to change the audio, the home button to summon the main menu, or the App button to bring up or down the LabPad.	Step by step instructions on the tablet and orally from the AI assistant. There is not much room for exploration as students are instructed what to do.
Preparing a tube with buffer	Pipette, pipette tips, buffer, microcentrifuge tube.	Selecting the appropriate pipette to the volume of fluid. Changing and disposing pipette tips. Measuring the correct volumes in the pipette.	Point and click on trackpad for interactions. Use volume buttons to change the audio, the home button to summon the main menu, or the App button to bring up or down the LabPad.	Step by step instructions on the tablet and orally from the AI assistant. There is not much room for exploration as students are instructed what to do.

		Using the correct positioning of the pipette when drawing up or dispensing fluids. Using the two stops of the pipette. Mixing fluids in the microcentrifuge tubes using the first stop of the pipette.		
Diluting the protein solution	Pipettes, pipette tips, BHL protein, microcentrifuge tube.	Selecting the appropriate pipette to the volume of fluid. Changing and disposing pipette tips. Measuring the correct volumes in the pipette. Performing a dilution series.	Point and click on trackpad for interactions. Use volume buttons to change the audio, the home button to summon the main menu, or the App button to bring up or down the LabPad.	Step by step instructions on the tablet and orally from the AI assistant. There is not much room for exploration as students are instructed what to do.
Performing a Bradford assay	Pipettes, pipette tips, microcentrifuge tubes, microplate, microplate shaker, microplate reader.	Performing a Bradford assay to determine the concentration of a protein in a sample.	Point and click on trackpad for interactions. Use volume buttons to change the audio, the home button to summon the main menu, or the App button to bring up or down the LabPad.	Step by step instructions on the tablet and orally from the AI assistant. There is not much room for exploration as students are instructed what to do.

B.3 Descriptive matrix of HoloLAB Champions (Chemiluminescence)

Descriptive matrix of the chemiluminescence experience in HoloLAB Champions (section 1)				
Sections	**Learning objectives**	**Learning outcomes**	**Estimated time**	**Instructions**
1. Beaker seeker	Demonstrate identification of lab glassware.	Students will be able to identify and name commonly used glassware in a chemistry lab.	00:01:07	Pour three unidentified coloured liquids into three separate types of glassware.
2. Acceptable Error (1)	Demonstrate pouring estimated volumes.	Students will learn how to roughly measure and transfer liquid substances between glassware.	00:02:20	Measure a given amount of a liquid into three beakers.
3. Precision Panic (2)	Demonstrate reading a meniscus.	Students will discover the relationship between a type of substance and the visual illusion created in glassware which directly determines how a meniscus should be read.	00:03:00	Look at different liquids in graduated cylinders and Erlenmeyer flasks and identify the amount of liquid they contain by reading the meniscus.
4. Chemical Barista* (3)	Demonstrate pouring specific volumes.	Students will learn how to measure liquid substances more precisely by using graduated glassware and applying their knowledge on how to read a meniscus properly.	00:02:43	Measure a given amount of a liquid into two beakers and an Erlenmeyer flask.
5. Tiny Transfer* (4)	Demonstrate using a Mohr Pipette	Students will learn how to measure precise, small volumes by using a Mohr pipette.	00:02:35	Measure a precise amount of liquid to be transferred to a different glassware using a Mohr pipette.
6. Glow, Dye, Glow* (5)	Demonstrate three chemiluminescent reactions.	Students will learn how a chemiluminescent reaction is created by mixing substances.	00:02:40	Measure a precise amount of liquid to be mixed with a dye to create a reaction.
7. Weigh of the World	Demonstrate the use of an analytical balance.	Students will learn how to measure mass using an analytical balance.	00:01:45	Measure the mass of glassware with an analytical balance.

8. Tare Test	Demonstrate use of the tare functionality.	Students will discover the importance of the tare function in the analytical balance to measure only the mass of the substances in glassware.	00:01:00	Measure the mass of the substances inside flasks by subtracting the mass of the glassware.
9. Mass Hysteria* (6)	Demonstrate measurement of mass.	Students will learn how to measure precise amounts of a substance using scoops and an analytical balance.	00:04:40	Measure a precise amount of a substance using an analytical balance.
10. RatiOh-No* (7)	Demonstrate scaling of volume and mass measurements.	Students will learn how to measure and scale up or down given amounts of substances.	00:16:00	Measure precise amounts of liquids and substances using measuring glassware and an analytical balance.
Glowing Flask Challenge* (8)	Create a glowing flask using a chemiluminescent reaction.	Students will discover how to create a glowing flask by applying what they have learned in previous experiments to properly mix the right amounts of different substances to obtain a chemiluminescent reaction.	00:08:50	Measure precise amounts of liquid and solid substances to create a chemiluminescent reaction (a glowing flask).

Descriptive matrix of the chemiluminescence experience in HoloLAB Champions (section 2)

Sections	Laboratory equipment	Behaviour	Skills	Control scheme	Guidance system
1. Beaker seeker	Beakers, Erlenmeyer flask, graduated cylinder.	Manipulation, pouring.	Identifying glassware, pouring / transferring liquids.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, names and uses of glassware.
2. Acceptable Error* (1)	Beakers.	Manipulation, pouring, reading meniscus.	Pouring / transferring liquids, measuring liquid substances, reading meniscus to identify precise volumes in glassware.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, names and uses of glassware, information on how to read a

					meniscus and how to measure mass and volume.
3. Precision Panic* (2)	Erlenmeyer flasks, graduated cylinders.	Manipulation, reading meniscus.	Reading meniscus to identify precise volumes in glassware.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, names and uses of glassware, information on how to read a meniscus and how to measure mass and volume.
4. Chemical Barista* (3)	Beakers, Erlenmeyer flasks, graduated cylinders.	Manipulation, pouring, reading meniscus.	Pouring / transferring liquids, measuring liquid substances, reading meniscus to identify precise volumes in glassware.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, information on how to read a meniscus and how to measure mass and volume.
5. Tiny Transfer* (4)	Beaker, Erlenmeyer flasks, Mohr pipette.	Manipulation, reading pipette.	Transferring and measuring precise amounts of liquids with a pipette.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects. Tap or press and hold the trackpads while holding the pipette to draw or release liquids.	Procedure for the experiment, information on how to use the controller whilst holding the pipette and how to measure mass and volume, pipetting tips for precise measuring of liquids.
6. Glow, Dye, Glow* (5)	Erlenmeyer flasks, stoppers, pipettes, Mohr pipette, scoop.	Reading pipette, shaking.	Measuring solid substances, transferring, and measuring precise amounts of liquids with a pipette, identifying dyes by the colour they emit in a reaction.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects. Tap or press and hold the trackpads	Procedure for the experiment, information about chemiluminescent reactions and dyes, how to use the controller whilst holding the pipette, and how to measure mass and

				while holding the pipette to draw or release liquids.	volume, pipetting tips for precise measuring of liquids,
7. Weigh of the World	Erlenmeyer flask, graduated cylinder, analytical balance.	Manipulation, operating an analytical balance.	Using an analytical balance and the tare function.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, information about the analytical balance, how to tare, and how to measure mass and volume.
8. Tare Test	Erlenmeyer flasks, stoppers, analytical balance.	Manipulation, operating an analytical balance.	Using an analytical balance and the tare function, measuring substances by subtracting the mass of the glassware.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, information about the analytical balance, how to tare, and how to measure mass and volume.
9. Mass Hysteria* (6)	Beaker, scoops, weigh boat, analytical balance.	Manipulation, operating an analytical balance, scooping substances.	Using an analytical balance and the tare function, scooping, and measuring precise amounts of a solid substance.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects.	Procedure for the experiment, information about the analytical balance, how to tare, and how to measure mass and volume.
10. RatiOh-No* (7)	Beakers, graduated cylinders, scoops, weigh boats, pipette, analytical balance,	Manipulation, operating an analytical balance, scooping substances, pouring, reading meniscus,	Pouring / transferring / scooping solid and liquid substances, measuring liquid and solid substances, reading meniscus to identify precise volumes in glassware, transferring and measuring precise amounts of liquids with a pipette, using an analytical balance and the tare function, measuring substances by subtracting	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects. Tap or press and hold the trackpads while holding the pipette to draw or release liquids.	Procedure for the experiment, information on how to use the controller whilst holding the pipette, how to measure mass and volume, about the analytical balance, and how to tare, pipetting tips for precise measuring of liquids.

	Erlenmeyer flasks.	reading pipette.	the mass of the glassware, scaling up or down amounts of substances.		
Glowing Flask Challenge* (8)	Analytical balance, pipette, scoops, graduated cylinder, weigh boats, beakers, Erlenmeyer flasks, stopper.	Manipulation, operating an analytical balance, scooping substances, pouring, reading meniscus, reading pipette, shaking.	Pouring / transferring / scooping solid and liquid substances, measuring liquid and solid substances, reading meniscus to identify precise volumes in glassware, transferring and measuring precise amounts of liquids with a pipette, using an analytical balance and the tare function, measuring substances by subtracting the mass of the glassware, scaling up or down amounts of substances.	Approach virtual objects and grab controllers to select them, pick them up, or hold them. Let go of controllers to release objects. Tap or press and hold the trackpads while holding the pipette to draw or release liquids.	Procedure for the experiment, information about how to measure mass and volume, about chemiluminescent reactions, and dyes, how to read a meniscus, about the analytical balance, and how to use the controller whilst holding the pipette, names and uses of glassware, pipetting tips for precise measuring of liquids.
(x) = order of the sections in fast mode. * = essential tasks in fast mode.					

Appendix C: Methods of data collection and analysis

Appendix overview

This section is comprised by the different quantitative and qualitative data collection instruments used for the main study:

- **C.1 Semi-structured interview schedule:** This guide was used to conduct the 41 interviews that took place at the end of every intervention.
    - **C.1.1 Low-end iVR condition.**
    - **C.1.2 High-end iVR condition.**
- **C.2 Coding framework:** This is the final coding framework used for the thematic analysis of interviews.
- **C.3 Tests for low-end iVR condition:** These tests were administered to participants who performed experiments in the Pipetting Simulation of the Labster virtual chemistry laboratory.
    - **C.3.1 Form A pre-test / Form B post-test.**
    - **C.3.2 Form A post-test / Form B pre-test.**
    - **C.3.3 Delayed test.**
- **C.4 Tests for high-end iVR condition:** These tests were administered to participants who performed experiments using the HoloLAB Champions: Chemiluminescence virtual chemistry laboratory.
    - **C.4.1 Form A pre-test / Form B post-test.**
    - **C.4.2 Form A post-test / Form B pre-test.**
    - **C.4.3 Delayed test.**
- **C.5 Immersive virtual reality presence questionnaire (iVRPQ):** This questionnaire was administered to all participants after every intervention regardless of the study condition they had been allocated to.

- C.5.1 Inter-item correlation matrix of presence questionnaire.
  - **C.5.2 Measures of central tendency of items responses.**
- **C.6 Comparison of descriptive statistics of test scores:** This table shows descriptive statistics of Pre-, Post-, and Delayed test scores in the low- and high-end iVR conditions, across experimental groups and lists mean score differences.
- **C.7 Q-Q plots showing the distribution of mean test scores across experimental groups:** These graphs stem from the Shapiro-Wilk tests performed to verify the assumption of normality of data in Section 6.1.
  - **C.7.1 Q-Q plot showing the distribution of pre-test scores in the within-subject group for the low-end iVR condition.**
  - **C.7.2 Q-Q plot showing the distribution pre-test scores in the between-groups group for the low-end iVR condition.**
  - **C.7.3 Q-Q plot showing the distribution of post-test scores in the within-subject group for the low-end iVR condition.**
  - **C.7.4 Q-Q plot showing the distribution post-test scores in the between-groups group for the low-end iVR condition.**
  - **C.7.5 Q-Q plot showing the distribution of delayed test scores in the within-subject group for the low-end iVR condition.**
  - **C.7.6 Q-Q plot showing the distribution delayed test scores in the between-groups group for the low-end iVR condition.**
  - **C.7.7 Q-Q plot showing the distribution of pre-test scores in the within-subject group for the high-end iVR condition.**
  - **C.7.8 Q-Q plot showing the distribution pre-test scores in the between-groups group for the high-end iVR condition.**
  - **C.7.9 Q-Q plot showing the distribution of post-test scores in the within-subject group for the high-end iVR condition.**
  - **C.7.10 Q-Q plot showing the distribution post-test scores in the between-groups group for the high-end iVR condition.**
  - **C.7.11 Q-Q plot showing the distribution of delayed test scores in the within-subject group for the high-end iVR condition.**

- **C.7.12 Q-Q plot showing the distribution delayed test scores in the between-groups group for the high-end iVR condition.**

C.1 Semi-structured interview schedule.

C.1.1 **Low-end iVR condition.**

Perceived learning:

- Things learnt from the VR experience.

Procedural knowledge:

- How do you use a micro-pipette? (Tips, two stops).
- How do you know which pipette to use if you need to transfer a certain amount of a substance?

Conceptual knowledge:

- What is a serial dilution?
- What would be the benefit for society to create modified food like the corn in the VR experience?

Bodily interactions:

- Forms of interaction with the manipulatives in the virtual chemistry lab.
- How would you compare interactions in the virtual environment to what you do in school practicals?
- How would you compare interactions in this experience to those in the other VR lab? (Only for participants who have participated in the other condition previously).

Agency and locomotion:

- Discuss the level of control over what was happening in the virtual environment.
- How much freedom did you experience in terms of being able to move in the virtual space such as to reach and grab things, move to a different part of the lab, or place objects wherever you wanted?

Body/hand ownership and proprioception:

- Did you feel at any point that the virtual hands were yours? What made you feel that way?
- Did you at any point feel that your virtual and real hands were not in the same physical position?
- Unnatural behaviour.

C.1.2 **High-end iVR condition.**

Perceived learning:

- Things learnt from the VR experience.

Procedural knowledge:

- How do you measure solids and liquids?
- Use of the Mohr pipette.

Conceptual knowledge:

- What is the purpose of the tare function in the analytical balance?
- What would you say a chemiluminescent reaction is?

Bodily interactions:

- Forms of interaction with the manipulatives in the virtual chemistry lab.
- How would you compare interactions in the virtual environment to what you do in school practicals?
- How would you compare interactions in this experience to those in the other VR lab? (Only for participants who have participated in the other condition previously).

Agency and locomotion:

- Discuss the level of control over what was happening in the virtual environment.
- How much freedom did you experience in terms of being able to move in the virtual space such as to reach and grab things, move to a different part of the lab, or place objects wherever you wanted?

Body/hand ownership and proprioception:

- Did you notice you did not have virtual hands in the VR lab? Did the controllers feel like your hands? What made you feel that way?
- Did you at any point feel that your virtual and real hands were not in the same physical position?
- Unnatural behaviour.

C.2 Coding framework for interviews.

Hierarchical coding		Descriptors	Exemplars
Behaviour and interactivity	Afforded actions and motion	Description of actions or behaviour that is possible due to the capabilities of the VR system.	“In this one, I had more freedom to like control things because I was actually pouring it and like it was more realistic because if you accidentally touched another beaker, it would fall down... so yeah.” [12]
	Congruency of interactions	Examples of how well actions that needed to be performed were mapped to a concept or the appropriate gesture used in a real scenario (i.e., tilting a scoop to slowly release its contents).	“So, you use your hands, and it outlines it in blue so you can pick it up and if you want to put something down, then you put it down, you release your grip.” [16]
	Difficulties or issues	Instances where participants describe problems with the hardware, the controllers, interactions, or visuals.	“No, apart from when it started flashing, that was difficult because I had to stop and carry on... if I was in the middle of doing something, that was kind of difficult trying not to drop it or spill it.” [10]
	Embodied actions	Discussion of behaviour grounded in physical engagement with the virtual environments.	“I think it's just the feeling of not directly touching something or moving it around and just waiting for someone else to do it for you.” [9]
	Intuitiveness of interactions	Discussions about the difficulty of the mechanisms required for interaction.	“Yeah, it's a bit of a habit to scroll my finger because... it just felt weird, but then towards the end I wouldn't do that, but I'd just like get close to it because I just felt like... it's just how I would read if I'm doing a practical.” [6]
	Mechanisms of interaction	Use of controllers and how they shaped how participants engaged with the virtual environments.	“I used the remote to click on things and move them. I also moved my head so I could turn direction.” [16]

	Unnatural behaviour		Actions that deviate from expectation and what could be physically done.	“Because it's not really natural for you to shove a spoon through a flask to get it out, but I noticed that you could do that.” [8]
Knowledge construction	Repetition and muscle memory		Discussions about the imprinting of procedures through repetition.	“Hmmm, I learnt about the whole... with the pipette filler... with the pipette you have to remove the contents before like a lot of the time before adding a new like substance, I can't remember what it was called. Yeah, you'd have to empty it, I felt that I had to repeat that step a lot, that's how it feel [sic]... just to prevent contamination with the other...” [7]
	Scaffolding		Progression of the actions performed for the experiments, the application of what was learnt previously, and the increased difficulty with every step.	“[…] they would give you a little bit of equipment and they will tell you like 3 steps, as you press the submit lever, they'll cheer for you, have a few jokes and then they'll put more equipment and the more equipment and then more steps.” [14]
	Science understanding	Conceptual or declarative knowledge	Discussions about participants' understanding or interpretations of concepts, notions, interrelations, or phenomena presented in the virtual environments.	“If it ranges from 200 to 1000, you choose the 100, the P100 one, it if ranges from 20 to 200, you use the P20... 200, and 2 to 20 use the P20.” [17]
		Procedural knowledge	Describing the replication of a process or other information through memorization rather than the understanding of underlying meanings.	“OK. So, first of all, you have to get the right pipette, and then you have to get the tip, so you have to check the measurements, like the volume... range and then you have to pick up the correct tip. I think the blue one was different to the yellow one.” [16]
		Self-reported new knowledge	Any notion, concept, or procedure the participant claimed not to have known previously to the interventions and therefore, is self-attributed as having	“Yeah, I... I did learn about the meniscus right now and I did learn about the... I didn't know that you could... like dye would change the colour of the liquid. I thought if you had a natural substance like sodium, it would just keep the same colour.” [24]

			been learnt through their involvement in them.	
	Shift of focus		Instances when participants shift their attention from something when they understand there is no risk such as breaking things or mixing the wrong chemicals.	“That's one's obviously more realistic, you can still spill stuff and break stuff, you have to be aware of where you're placing stuff, to be aware of your safety, whereas this one, you can actually stop being aware of your safety because it did stuff for you […]” [22]
Perceptual states	Extrapolation of the self		Instances when participants discussed picturing themselves performing an activity that they only observed someone else do or identifying the virtual hands as belonging to someone they controlled or embodied.	“[…] usually when you have like a written down practical, I still try to imagine my own self doing it. Let's say we're doing about how prepare a slide for onion cell also like I remember myself like peeling the epidermal tissue, I still try to remember either way, like imagining if I were doing it because in my opinion, I feel like that's easier for me to learn.” [14]
	Sense of agency and control		Descriptions of how participants experienced locomotion, and the liberty to perform the experiments and interact with the manipulatives at will, as opposed to being constrained or directed.	“Obviously, you couldn't like, walk around, and see in that way, but you could look around to see what was around you, where you are. Yeah, there's obviously, there's always... I felt a sense of restriction because there are only certain actions that you can do, yeah, but besides that, you still feel like you're kind of there because there's a whole view all the way around.” [21]
	Sense of presence	Body ownership and presence	Narrations about awareness of their body being inside the virtual environment.	“If I were to put my hand out right now and I see the table, but during the experience I saw the lab desk that they gave us, I didn't see any of the tables surrounding us in here. It's kind of strange. I thought it's weird.” [6]
		Hand ownership	Descriptions of how participants made sense of the presence or absence of virtual hands and whether they	“Yeah, I lifted my actual hand thinking that the iPad would move, so I was quite absorbed in it, at one point, but then yes, after that, I understood that was the virtual thing.” [19]

			experienced a sense of ownership over them.	
Virtual environments	Adjusting to the alternate reality		Behaviour participants had to engage in to adjust to the affordances of the virtual environments in terms of locomotion and interaction.	“[…] the little blue outline made it a bit easier to kind of assume where your hands would be.” [22]
	Cheating the VE		Behaviour carried out with the purpose of skipping steps during the experiments.	“I did it the first time and said I put it wrong the first time and I was like... I don't know why I got it wrong so then I just kept on redoing the first one and keep putting it on to see if I got it right and once, I got it right I moved on to the next one I kept checking if I was right or wrong.” [1]
	Discussing guidance and support		Comments regarding the guidance system embedded in the virtual laboratories.	“In a way yeah... because even with guidance I would kind of struggle sometimes, I'd have to do it multiple times to find out what she's actually talking about and to like practice and look around and find it... figure it out... yeah I get what you mean, if I didn't have that guidance it would probably take much longer for me to do what I am supposed to do.” [11]
	Drawing comparisons between interventions		Description of similarities and/or differences participants perceived between their use of the VR systems in both interventions.	“Well, yeah, it's a little less realistic in a way. In the first one if you needed to actually grab something, you could move your hand around slightly, like you would in real life, but in this one was just pointing and clicking so it was a little bit strange, different yeah.” [18]
	Drawing comparisons to reality		Description of similarities and differences between the virtual labs and real-life situations and environments.	“It was... it was a lot like in school, like you do miss or knock something over... it happens in the real world like it happens in that, if you drop something you have to pick it up, so it's quite close to the real world in terms of that, but how it looked.” [21]

	Making mistakes and their consequences	Comments regarding the lack of physical consequences in the virtual laboratories opening the possibility to learn from making mistakes.	"it's less dangerous as well because you never know if you can break something in a lab whereas this one, even if you break it, it's not real." [12]
	Meeting expectations	Comments on the expectations that participants had of the virtual environments and whether these were met.	"When I couldn't workout with like... getting the liquid into the micro dish, I kept on just reaching out and clicking towards it or just reaching towards it thinking something was going to happen because I... I was like… I didn't know what to do. Or with the tablet, I kept looking down and reaching it and I would be like, oh no, I have to click it because I could always see the corner of it a bit, then I'd always go to… right go and grab it up." [15]

C.3 Tests for low-end iVR condition.

C.3.1 **Form A pre-test / Form B post-test.**

Labster Test

How old are you? ___________

What is the name of your school?

____

What year of school are you in? ___________

For researcher's use:								
Participant ID:				Date:				
Pathway:	1	2	3	4	Gender:	1	2	
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B							

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

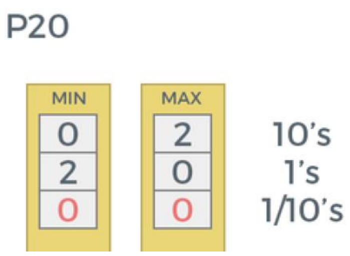
1. **What do you think a Bradford assay is used for?**

☐ a) To measure the level of absorption of a solution.
☐ b) To determine the protein content in a solution.
☐ c) To measure the concentration of dye in a solution.
☐ d) To measure how diluted a solution is.

2. **Why do you think it is important to use a micropipette of the size or volume range that is appropriate to the amount of the substance to be measured?**

☐ a) To avoid the pipette from drawing large amounts of a substance.
☐ b) To avoid having to draw a measurement several times to get the correct amount.
☐ c) To avoid over or underloading the pipette with the solution.
☐ d) To avoid producing an inaccurate measurement.

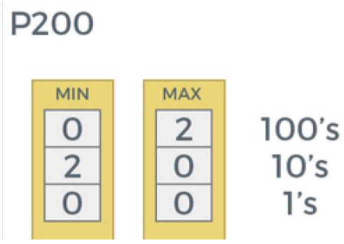
3. **Look at the image. Tick the option that you think indicates the range of the P20 micro pipette.**



☐ a) 2-20 µl
☐ b) 1-200 µl
☐ c) 20-200 µl
☐ d) 10-20 µl

µl = microlitre

4. Look at the image. Tick the option that you think indicates the range of the P200 micro pipette.



☐ a) 200-400 µl
☐ b) 1-200 µl
☐ c) 20-200 µl
☐ d) 200-1000 µl

µl = microlitre

5. What do you think should be done with the pipette before and after every use?

☐ a) Get a fresh tip and discard it after using it.
☐ b) Discard the remaining liquid in the pipette.
☐ c) Re-set the volume measurements to make sure they are accurate.
☐ d) Clean the tip of the pipette with a tissue.

6. Which of the following do you think is the appropriate technique to draw a substance with a micro pipette?

☐ a) Press the plunger to the second stop, hold the pipette vertically, dip it to the bottom of the liquid, and quickly release the plunger.
☐ b) Press the plunger to the first stop, hold the pipette against the side of the tube, dip the tip 5 mm into the liquid, and release the plunger.
☐ c) Hold the pipette against the side of the tube, dip the tip halfway into the liquid, and pump the plunger twice.
☐ d) Press the plunger to the first stop, hold the pipette vertically, dip it 3-4 mm into the liquid, and slowly release the plunger.

mm - millilitres

C.3.2 **Form A post-test / Form B pre-test.**

Labster Test

How old are you? ___________

What is the name of your school?

____

What year of school are you in? ___________

For researcher's use:							
Participant ID:			**Date:**				
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B						

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

1. **The Bradford assay only works at low protein concentrations (0.05 to 0.5 mg/mL). How do you think the concentration of protein in a sample can be reduced?**

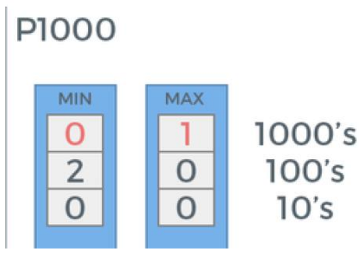
☐ a) By concentrating the sample.
☐ b) By purifying the sample.
☐ c) By diluting the sample.
☐ d) By evaporating the sample.

mg = milligram
mL = millilitre

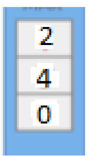
2. **Look at the image. Tick the option that you think indicates the range of the P1000 micro pipette.**

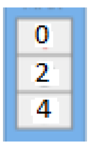
☐ a) 400-1000 µl
☐ b) 1000-1200 µl
☐ c) 1-1000 µl
☐ d) 200-1000 µl

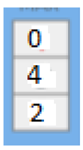
µl = microlitre

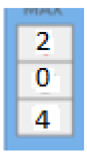


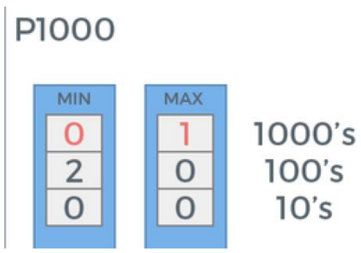
3. **Look at the images. Which of the following readings of the P1000 micro pipette do you think is showing a volume of 240 µl?**

☐ a) 

☐ b) 

☐ c) 

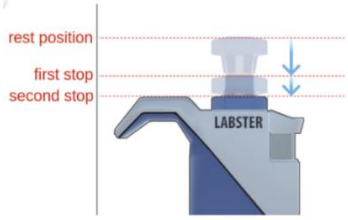
☐ d) 



4. Why do you think only sterile pipette tips are used in the lab and why are they replaced after every use?

☐ a) To prevent the reproduction of proteins.
☐ b) To avoid the contamination of the sample.
☐ c) So that they can be reused.
☐ d) To make pipetting more precise.

5. Micro pipettes have a plunger with two stops. What do you think is the purpose of the second stop?



☐ a) To mix the solution in the tip.
☐ b) To avoid the contamination of the sample.
☐ c) To push out the remaining liquid in the tip.
☐ d) To draw up more liquid.

6. Which of the following do you think is the appropriate technique to dispense a substance with a micro pipette?

☐ a) Press the plunger to the first stop, hold the pipette vertically into the empty tube, or just below the surface, and press the plunger further to the second stop.
☐ b) Press the plunger to the second stop, hold the pipette against the side of the empty tube or just below the surface, and release the plunger.
☐ c) Hold the pipette against the side of the empty tube or just below the surface of the liquid is there is any and press the plunger to the second stop.
☐ d) Hold the pipette vertically in the empty tube or just below the surface of a liquid if there is any and press the plunger to the first stop.

C.3.3 **Delayed test.**

Labster Test

How old are you? ___________

What is the name of your school?

____

What year of school are you in? ___________

For researcher's use:								
Participant ID:				**Date:**				
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**	
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B							

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

1. **What is a Bradford assay used for?**

☐ a) To measure the level of absorption of a solution.
☐ b) To determine the protein content in a solution.
☐ c) To measure the concentration of dye in a solution.
☐ d) To measure how diluted a solution is.

2. **The Bradford assay only works at low protein concentrations (0.05 to 0.5 mg/mL). How can the concentration of protein in a sample be reduced?**

☐ a) By concentrating the sample.
☐ b) By purifying the sample.
☐ c) By diluting the sample.
☐ d) By evaporating the sample.

mg = milligram
mL = millilitre

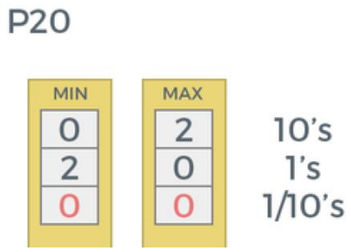
3. **Why is it important to use a micropipette of the size or volume range that is appropriate to the amount of the substance to be measured?**

☐ a) To avoid the pipette from drawing large amounts of a substance.
☐ b) To avoid having to draw a measurement several times to get the correct amount.
☐ c) To avoid over or underloading the pipette with the solution.
☐ d) To avoid producing an inaccurate measurement.

4. Look at the image and indicate what the range of the P20 micro pipette is.

☐ a) 2-20 µl
☐ b) 1-200 µl
☐ c) 20-200 µl
☐ d) 10-20 µl

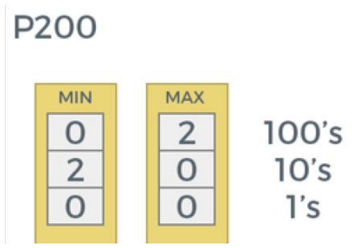
µl = microlitre



5. Look at the image and indicate what the range of the P200 micro pipette is.

☐ a) 200-400 µl
☐ b) 1-200 µl
☐ c) 20-200 µl
☐ d) 200-1000 µl

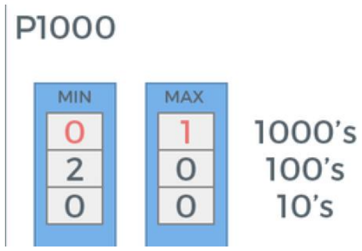
µl = microlitre



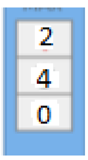
6. Look at the image and indicate what the range of the P1000 micro pipette is.

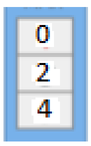
☐ a) 400-1000 µl
☐ b) 1000-1200 µl
☐ c) 1-1000 µl
☐ d) 200-1000 µl

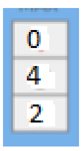
µl = microlitre

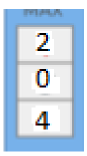


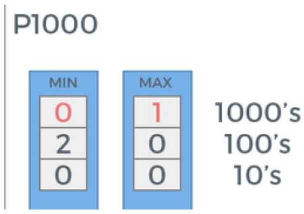
7. Look at the images. Which of the following readings of the P1000 micro pipette shows a volume of 240 µl?

☐ a) 

☐ b) 

☐ c) 

☐ d) 



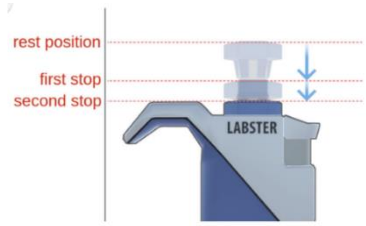
8. What should be done with the pipette before and after every use?

☐ a) Get a fresh tip and discard it after using it.
☐ b) Discard the remaining liquid in the pipette.
☐ c) Re-set the volume measurements to make sure they are accurate.
☐ d) Clean the tip of the pipette with a tissue.

9. Why are only sterile pipette tips used in the lab and why are they replaced after every use?

☐ a) To prevent the reproduction of proteins.
☐ b) To avoid the contamination of the sample.
☐ c) So that they can be reused.
☐ d) To make pipetting more precise.

10. Micro pipettes have a plunger with two stops. What is the purpose of the second stop?



☐ a) To mix the solution in the tip.
☐ b) To avoid the contamination of the sample.
☐ c) To push out the remaining liquid in the tip.
☐ d) To draw up more liquid.

11. Which of the following is the appropriate technique to draw a substance with a micro pipette?

☐ a) Press the plunger to the second stop, hold the pipette vertically, dip it to the bottom of the liquid, and quickly release the plunger.
☐ b) Press the plunger to the first stop, hold the pipette against the side of the tube, dip the tip 5 mm into the liquid, and release the plunger.
☐ c) Hold the pipette against the side of the tube, dip the tip halfway into the liquid, and pump the plunger twice.
☐ d) Press the plunger to the first stop, hold the pipette vertically, dip it 3-4 mm into the liquid, and slowly release the plunger.

mm - millilitres

12. Which of the following is the appropriate technique to dispense a substance with a micro pipette?

☐ a) Press the plunger to the first stop, hold the pipette vertically into the empty tube, or just below the surface, and press the plunger further to the second stop.
☐ b) Press the plunger to the second stop, hold the pipette against the side of the empty tube or just below the surface, and release the plunger.
☐ c) Hold the pipette against the side of the empty tube or just below the surface of the liquid is there is any and press the plunger to the second stop.
☐ d) Hold the pipette vertically in the empty tube or just below the surface of a liquid if there is any and press the plunger to the first stop.

C.4 Tests for high-end iVR condition.

C.4.1 **Form A pre-test / Form B post-test.**

How old are you? __________

What is the name of your school?

____

What year of school are you in? __________

For researcher's use:								
Participant ID:			**Date:**					
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**	
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B							

HoloLAB Champions Test

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

1. **Tick the box to match the names of laboratory equipment to their descriptions:**

	Beaker 	Erlenmeyer flask 	Graduated cylinder 	Mohr pipette 	Weigh boat 	Scoops 	Analytical balance 
a) Graduated glassware used for pouring solutions and storing them. It can be closed with a stopper, and it has a cylindrical neck, flat bottom, and conical body.							
b) Graduated glassware that is used for mixing, heating, or simply holding substances.							
c) Graduated glassware that is used for measuring precise amounts of liquids.							
d) Instrument used to transfer small, more precise amounts of a liquid between different glassware.							

2. Tick the <u>two</u> boxes that describe the appropriate way to read the amount there is of a liquid in a tube.

☐ a) Use the measurement at the bottom of a concave meniscus.
☐ b) Use the measurement at the top of a concave meniscus.
☐ c) Use the measurement at the top of a convex meniscus.
☐ d) Use the measurement at the bottom of a convex meniscus.

3. Tick the box of the column that gives the answers to the questions or statements in every row.

	Represented as "g"	Represented as "ml" or "mL"	In grams	In millilitres	The amount of matter in something	The amount of space something takes up
a) What is mass?						
b) How is volume measured?						
c) Symbol of the units used to measure mass.						

C.4.2 **Form A post-test / Form B pre-test.**

How old are you? ___________

What is the name of your school?

____

What year of school are you in? ___________

For researcher's use:								
Participant ID:			**Date:**					
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**	
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B							

HoloLAB Champions Test

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

1. **Tick the box to match the names of laboratory equipment to their descriptions:**

	Beaker 	Erlenmeyer flask 	Graduated cylinder 	Mohr pipette 	Weigh boat 	Scoops 	Analytical balance 
a) Instrument used to transfer solid substances from one container to another.							
b) Instrument used to hold solid substances when measuring their mass.							
c) Instrument used to measure the mass of substances.							

2. **When you look at a liquid in a tube, its surface looks curved. What is the name of that curvature?**

☐ a) Meniscus
☐ b) Concave

☐ c) Convex

3. Tick the box of the column that gives the answers to the questions or statements in every row.

	Represented as "g"	Represented as "ml" or "mL"	In grams	In millilitres	The amount of matter in something	The amount of space something takes up
a) What is volume?						
b) How is mass measured?						
c) Symbol of the units used to measure volume.						

4. The tare function in the analytical balance is used to...

☐ a) ...measure only the mass of substances and not the added weight of the glassware.
☐ b) ...measure only the volume of substances and not the added weight of the glassware.
☐ c) ...measure the mass of substances and the glassware that contains them.
☐ d) ...measure the volume of substances and the glassware that contains them.

C.4.3 **Delayed test.**

How old are you? ___________

What is the name of your school?

____

What year of school are you in? ___________

For researcher's use:								
Participant ID:			**Date:**					
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**	
Type:	☐ Pre ☐ Post ☐ Delayed ☐ Form A ☐ Form B							

HoloLAB Champions Test

Instructions:

Please tick the box of the answer that best completes all the statements or answers the questions. If in doubt, choose the answer that seems more likely to be correct to you.

1. **Tick the box to match the names of laboratory equipment to their descriptions:**

	Beaker 	Erlenmeyer flask 	Graduated cylinder 	Mohr pipette 	Weigh boat 	Scoops 	Analytical balance 
a) Graduated glassware used for pouring solutions and storing them. It can be closed with a stopper, and it has a cylindrical neck, flat bottom, and conical body.							
b) Graduated glassware that is used for mixing, heating, or simply holding substances.							
c) Graduated glassware that is used for measuring precise amounts of liquids.							
d) Instrument used to transfer small, more precise amounts of a liquid between different glassware.							

	Beaker 	Erlenmeyer flask 	Graduated cylinder 	Mohr pipette 	Weigh boat 	Scoops 	Analytical balance 
e) Instrument used to transfer solid substances from one container to another.							
f) Instrument used to hold solid substances when measuring their mass.							
g) Instrument used to measure the mass of substances.							

2. **When you look at a liquid in a tube, its surface looks curved. What is the name of that curvature?**

☐ a) Meniscus
☐ b) Concave
☐ c) Convex

3. **Tick the <u>two</u> boxes that describe the appropriate way to read the amount there is of a liquid in a tube.**

☐ a) Use the measurement at the bottom of a concave meniscus.
☐ b) Use the measurement at the top of a concave meniscus.
☐ c) Use the measurement at the top of a convex meniscus.
☐ d) Use the measurement at the bottom of a convex meniscus.

4. Tick the box of the column that gives the answers to the questions or statements in every row.

	Represented as "g"	Represented as "ml" or "mL"	In grams	In millilitres	The amount of matter in something	The amount of space something takes up
a) What is mass?						
b) What is volume?						
c) How is mass measured?						
d) How is volume measured?						
e) Symbol of the units used to measure mass.						
f) Symbol of the units used to measure volume.						

5. The tare function in the analytical balance is used to...

☐ a) ...measure only the mass of substances and not the added weight of the glassware.
☐ b) ...measure only the volume of substances and not the added weight of the glassware.
☐ c) ...measure the mass of substances and the glassware that contains them.
☐ d) ...measure the volume of substances and the glassware that contains them.

C.5 Immersive virtual reality presence questionnaire (iVRPQ).

How old are you? __________

What is the name of your school?

____

____

What year of school are you in? __________

For researcher's use:								
Participant ID:				**Date:**				
Pathway:	**1**	**2**	**3**	**4**	**Gender:**	**1**	**2**	
Intervention:								
☐ Labster				☐ HoloLAB Champions				

Instructions:

The following questions and statements are based on the iGroup Presence Questionnaire (Schubert, Friedmann and Regenbrecht, 2001) and they explore how you perceived and experienced being in the virtual chemistry lab.

Please mark with an X the box with the number that better describes your agreement to the statements or answers to the questions below. The are no right or wrong answers as this survey is about your perception of how you experienced being in the virtual laboratory.

1. Whist in the virtual environment, I felt like I was really there.	1	2	3	4	5
	I never felt that way	I rarely felt that way	I sometimes felt that way	I often felt that way	I always felt that way
2. I felt that the virtual environment was all around me.	1	2	3	4	5
	I never felt that way	I rarely felt that way	I sometimes felt that way	I often felt that way	I always felt that way
3. I felt like I was only seeing pictures or a video.	5	4	3	2	1
	I never felt that way	I rarely felt that way	I sometimes felt that way	I often felt that way	I always felt that way
4. It felt like I was <u>not</u> inside the virtual environment.	5	4	3	2	1
	I never felt that way	I rarely felt that way	I sometimes felt that way	I often felt that way	I always felt that way

5. I felt like I was in the virtual environment doing things, rather than manipulating something from outside of it.

1	2	3	4	5
I never felt that way	I rarely felt that way	I sometimes felt that way	I often felt that way	I always felt that way

6. I felt that my hands and/or body were in the virtual environment.

1	2	3	4	5
I did not feel they were there	I rarely felt they were there	I sometimes felt they were there	I often felt they were there	I always felt they were there

7. Without trying, I was aware of things happening outside of the virtual environment like sounds, the temperature of the room, other people, the headset, controller(s), or cables.

5	4	3	2	1
I was not aware at all	I was rarely aware	I was moderately aware	I was often aware	I was extremely aware

8. I completely or mostly forgot about the real world when I was in the virtual environment.

1	2	3	4	5
I never forgot	I rarely forgot	I sometimes forgot	I often forgot	I completely forgot

9. When I was in the virtual environment, I tried to still pay attention to what was happening in the real world.

5	4	3	2	1
I did not pay attention at all	I rarely paid attention	I sometimes paid attention	I often paid attention	I always paid attention

10. I was completely captivated by the virtual world.

1	2	3	4	5
I was not captivated at all	I was rarely captivated	I was moderately captivated	I was often captivated	I was extremely captivated

11. The virtual world looked realistic to me.

1	2	3	4	5
It did not look realistic at all	Realism was very minimal	It looked moderately realistic	It looked quite realistic	It looked extremely realistic

12. Things in the virtual environment looked similarly to real life.

1	2	3	4	5
They were completely different	Similarities were minimal	They were moderately similar	They were mostly similar	They were extremely similar

13. Things in the virtual environment behaved like I would expect if they were real.

1	2	3	4	5
They did not behave at all like in real life	They behaved very little like in real life	They behaved moderately like in real life	They behaved almost like in real life	They behaved extremely like in real life

14. When thinking about the experience, the virtual environment feels more like a place I visited, rather than a place I saw on a video.

1	2	3	4	5
It completely feels like something I saw, like watching a video	It feels a bit like watching a video	It feels like a combination between a place I was in and	It somewhat feels like a place I visited	It completely feels like a place I visited

C.5.1 **Inter-item correlation matrix of presence questionnaire.**

	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
Item 1	1.000	0.663	0.244	0.272	0.343	0.632	0.558	0.461	0.544	0.727	0.665	0.298	0.654	0.400
Item 2	0.663	1.000	0.080	0.167	0.445	0.552	0.388	0.503	0.287	0.727	0.449	0.028	0.487	0.413
Item 3	0.244	0.080	1.000	0.383	0.011	0.179	0.335	0.295	0.263	0.165	0.190	0.345	0.184	0.201
Item 4	0.272	0.167	0.383	1.000	0.138	0.394	0.237	0.201	0.228	0.336	0.190	0.097	0.110	0.011
Item 5	0.343	0.445	0.011	0.138	1.000	0.493	0.166	0.457	0.203	0.283	0.087	0.006	0.262	0.553
Item 6	0.632	0.552	0.179	0.394	0.493	1.000	0.327	0.522	0.447	0.758	0.387	0.064	0.479	0.401
Item 7	0.558	0.388	0.335	0.237	0.166	0.327	1.000	0.485	0.558	0.518	0.327	0.185	0.360	0.396
Item 8	0.461	0.503	0.295	0.201	0.457	0.522	0.485	1.000	0.366	0.548	0.424	0.244	0.545	0.421
Item 9	0.544	0.287	0.263	0.228	0.203	0.447	0.558	0.366	1.000	0.515	0.350	0.158	0.296	0.210
Item 10	0.727	0.727	0.165	0.336	0.283	0.758	0.518	0.548	0.515	1.000	0.484	0.154	0.574	0.393
Item 11	0.665	0.449	0.190	0.190	0.087	0.387	0.327	0.424	0.350	0.484	1.000	0.102	0.709	0.073
Item 12	0.298	0.028	0.345	0.097	0.006	0.064	0.185	0.244	0.158	0.154	0.102	1.000	0.330	0.043
Item 13	0.654	0.487	0.184	0.110	0.262	0.479	0.360	0.545	0.296	0.574	0.709	0.330	1.000	0.314
Item 14	0.400	0.413	0.201	0.011	0.553	0.401	0.396	0.421	0.210	0.393	0.073	0.043	0.314	1.000

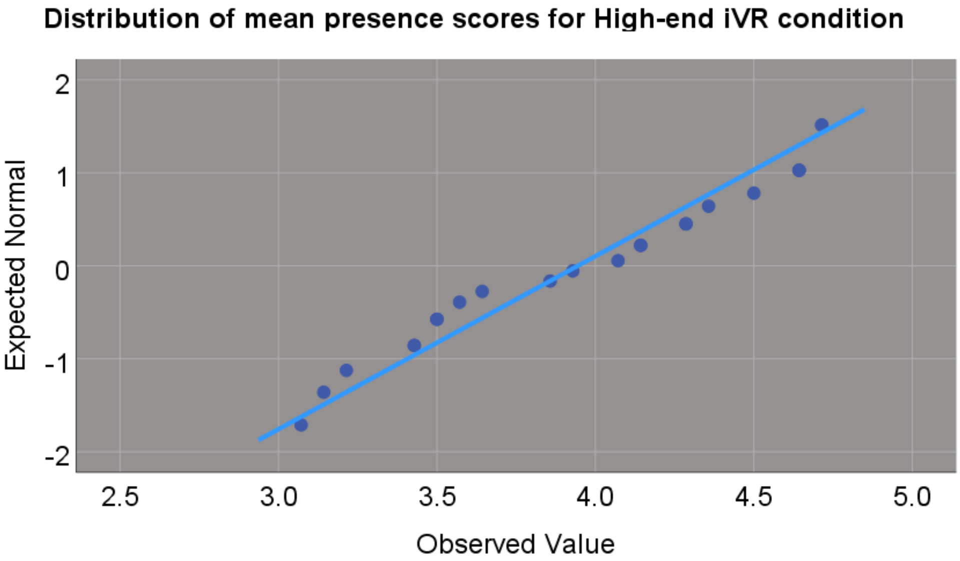
C.5.2 **Measures of central tendency of items responses.**

Presence questionnaire items		Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
High-end iVR	Mean	4.23	4.55	3.91	3.91	4.00	4.05	3.95	4.05	4.27	4.55	3.18	3.27	3.86	3.45
	N	22	22	22	22	22	22	22	22	22	22	22	22	22	22
	Std. Deviation	0.922	0.739	1.231	1.377	1.345	1.133	0.999	1.046	0.935	0.671	1.181	1.202	0.889	1.335
Low-end iVR	Mean	3.37	3.63	2.89	3.16	3.79	2.79	3.00	2.95	3.58	3.63	2.74	2.89	3.47	2.68
	N	19	19	19	19	19	19	19	19	19	19	19	19	19	19
	Std. Deviation	1.212	1.422	1.100	1.068	1.273	1.398	1.155	1.177	1.216	1.212	0.933	1.100	0.964	1.157

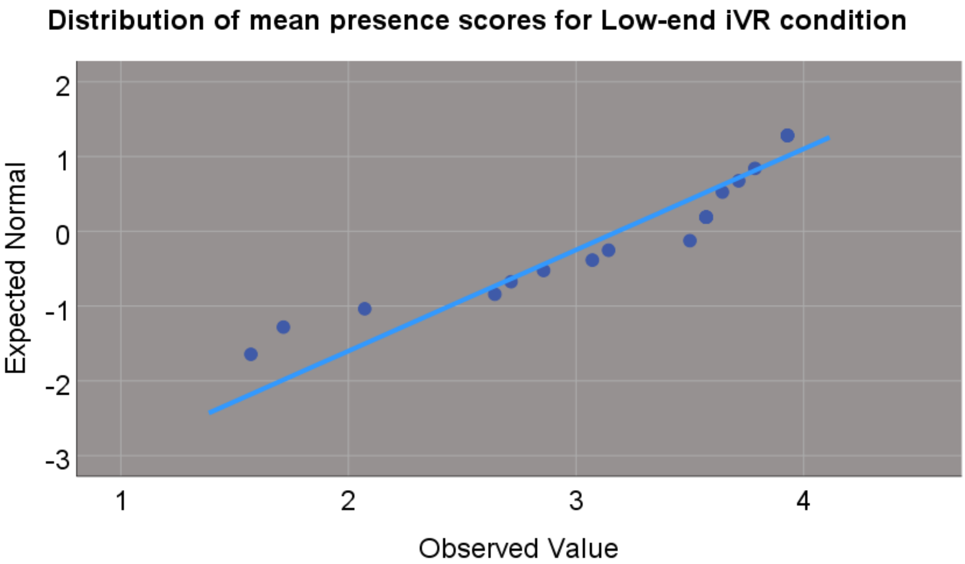
C.5.3 **Tests verifying assumptions for Mann-Whitney U test to compare mean presence scores between conditions and across experimental groups.**

Two tests were performed to verify that assumptions were met:

- Results of a Shapiro-Wilk test showed that mean scores were only close to normal distribution in the high-end iVR condition with W(22) = .936, p = .163.



Results for the low-end iVR condition W(19) = .853, p = .008 show there is no normal distribution of mean scores.



- Results of a Levene's test using medians to make it more appropriate for non-parametric tests showed homogeneity or equality of error variances in the full dataset, $F(1, 39) = 0.520$, $p = .475$. This is a result that is also reflected when splitting the sample between the low-end iVR condition, $F(1, 17) = 0.579$, $p = .457$, and the hight-end iVR condition, $F(1, 20) = 0.491$, $p = .492$.

Consequently, due to sample sizes and the lack of normal distribution of responses, it was decided to use non-parametric tests to compare presence mean scores, namely Mann-Whitney U tests.

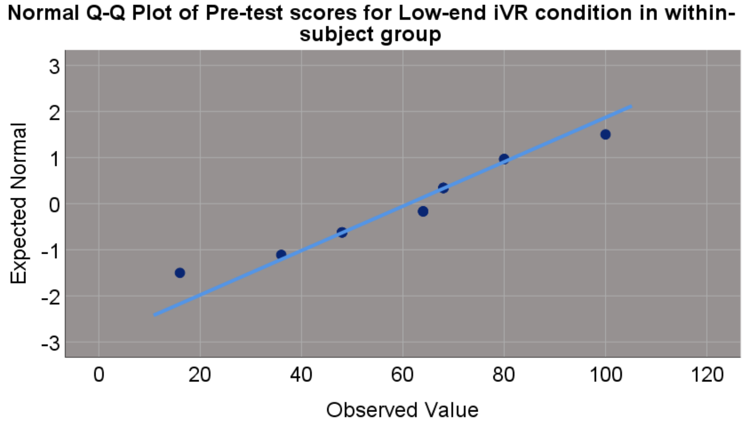
C.6 Q-Q plots showing the distribution of mean test scores across experimental groups.

In order to compare mean test scores for each study condition (low- and high-end iVR) across experimental groups, preliminary tests were carried out to verify assumptions for the necessary repeated measures analysis of variance (ANOVA). Firstly, Mauchly's tests were performed on mean scores stemming from the low-end iVR condition, $X^2(2) = .948$, $p = .653$, and the high-end iVR condition, $X^2(2) = .903$, $p = .380$. Results indicate that the assumption of sphericity has not been violated.

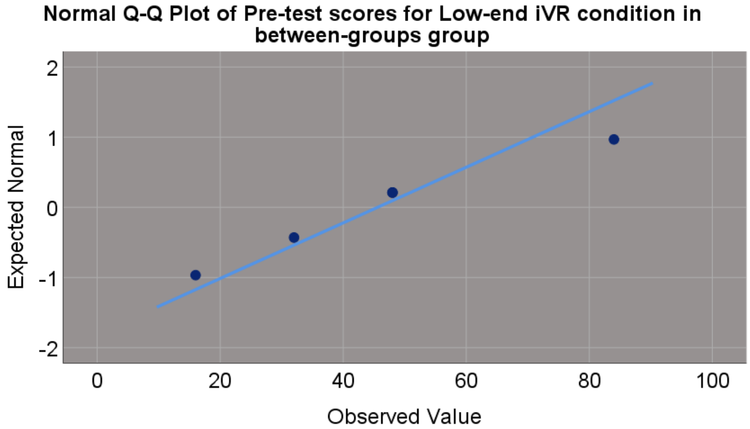
Secondly, Shapiro-Wilk tests were performed on each of the dependent variables to look at the normality of data across the levels of the independent variable. Results from the low-end iVR condition indicate that data follows a normal distribution in the pre-test in the group following a within-subject design, $W(14) = .950$, $p = .568$ (see Appendix C.6.1), as well as the one following the between-groups design, $W(5) = .945$, $p = .700$ (see Appendix C.6.2). Results from the post-test in the within-subject group indicate data do not follow a normal distribution, $W(14) = .869$, $p = .041$ (see Appendix C.6.3), as opposed to data in the group following a between-groups design which do, $W(5) = .966$, $p = .847$ (see Appendix C.6.4). Finally, results from the delayed test show that data follows a normal distribution in both, the within-subject group, $W(14) = .940$, $p = .422$ (see Appendix C.6.5), and the group following a between-groups design, $W(5) = .970$, $p = .876$ (see Appendix C.6.6).

Comparatively, results from the high-end iVR condition indicate that data from the pre-test in the within-subject group, $W(14) = .909$, $p = .150$ (see Appendix C.6.7), and the group following a between-groups design, $W(8) = .924$, $p = .469$ (see Appendix C.6.8) follow a normal distribution. Results from the post-test in the within-subject group, $W(14) = .828$, $p = .011$ (see Appendix C.6.9), indicate data are not normally distributed, in contrast to that in the group following a between-groups design where data follow a normal distribution, $W(8) = .878$, $p = .181$(see Appendix C.6.10). Finally, results from the delayed-test indicate that data follow a normal distribution in both, the within-subject group, $W(14) = .915$, $p = .183$ (see Appendix C.6.11), and the group following a between-groups design, $W(8) = .859$, $p = .118$ (see Appendix C.6.12).

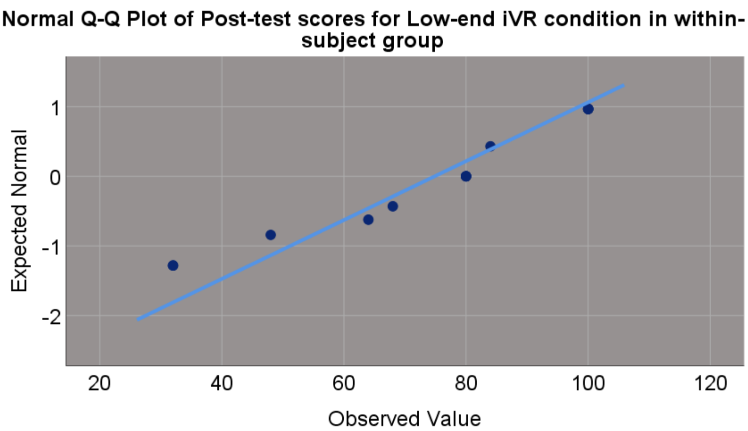
C.6.1 **Q-Q plot showing the distribution of pre-test scores in the within-subject group for the low-end iVR condition.**



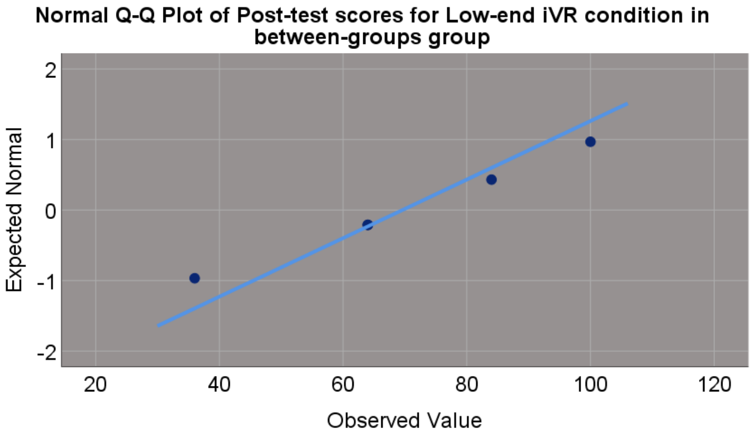
C.6.2 **Q-Q plot showing the distribution pre-test scores in the between-groups group for the low-end iVR condition.**



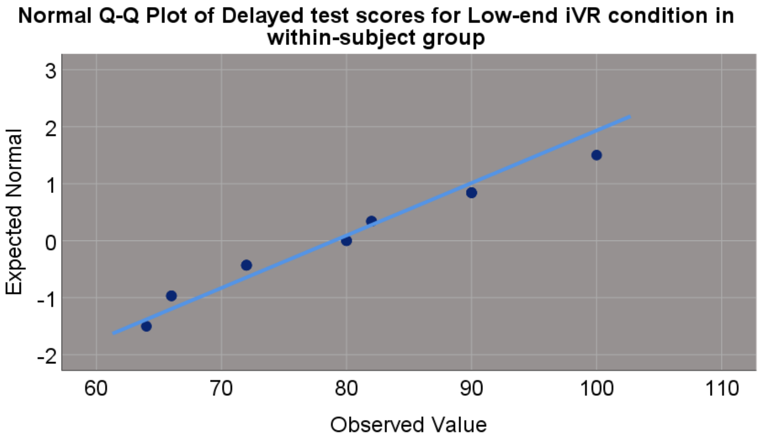
C.6.3 **Q-Q plot showing the distribution of post-test scores in the within-subject group for the low-end iVR condition.**



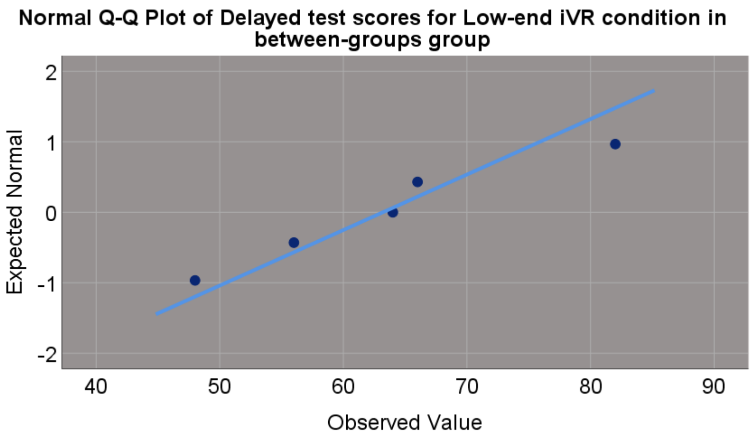
C.6.4 **Q-Q plot showing the distribution post-test scores in the between-groups group for the low-end iVR condition.**



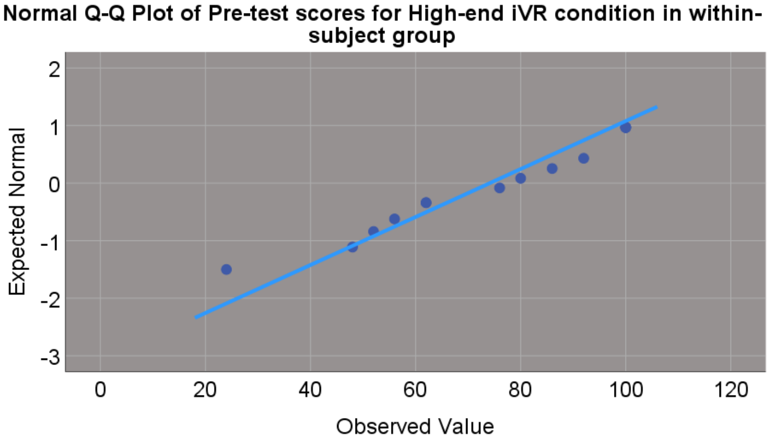
C.6.5 **Q-Q plot showing the distribution of delayed test scores in the within-subject group for the low-end iVR condition.**



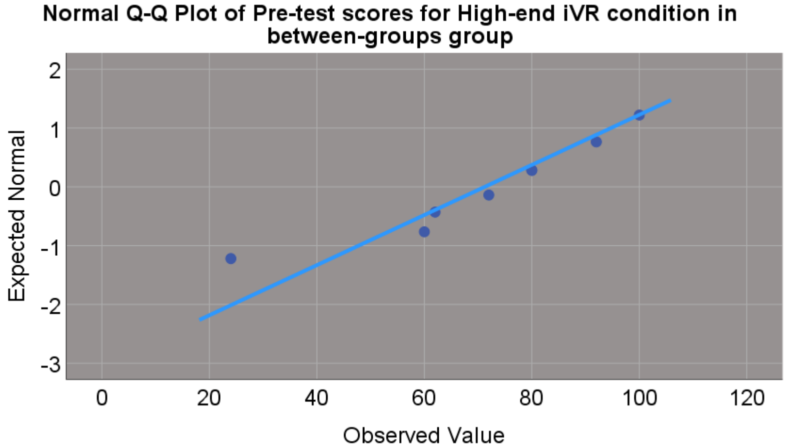
C.6.6 **Q-Q plot showing the distribution delayed test scores in the between-groups group for the low-end iVR condition.**



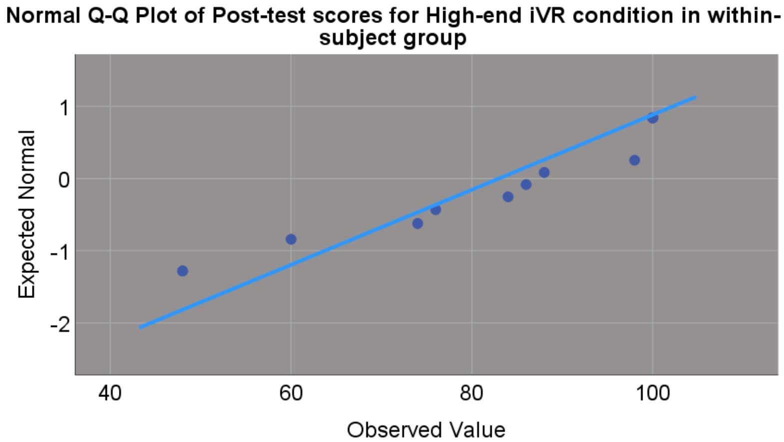
C.6.7 **Q-Q plot showing the distribution of pre-test scores in the within-subject group for the high-end iVR condition.**



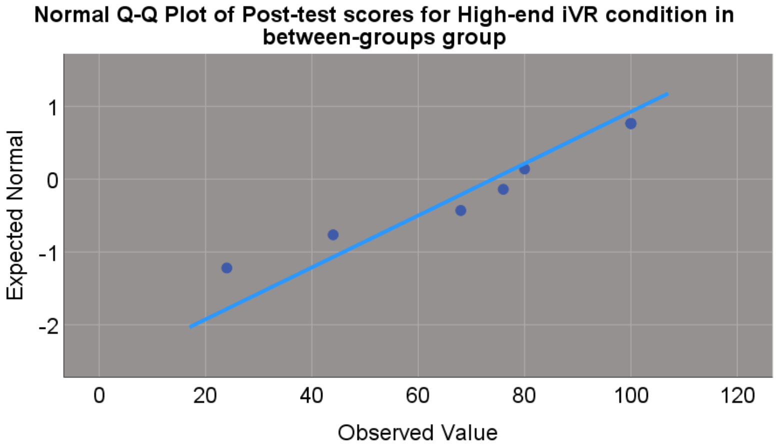
C.6.8 **Q-Q plot showing the distribution pre-test scores in the between-groups group for the high-end iVR condition.**



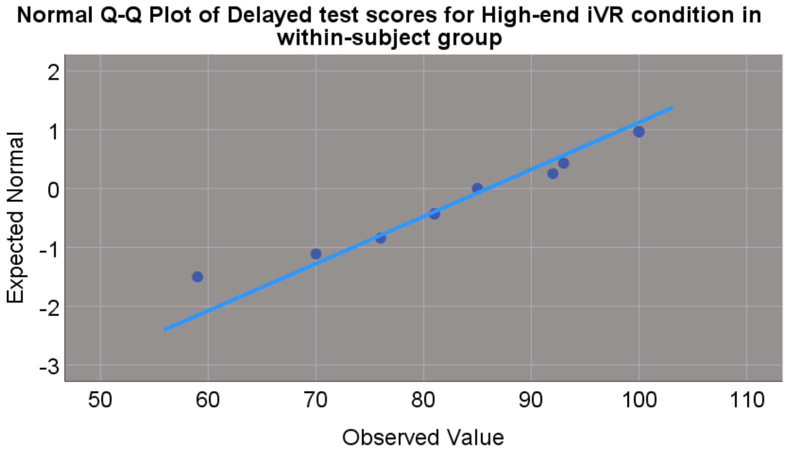
C.6.9 **Q-Q plot showing the distribution of post-test scores in the within-subject group for the high-end iVR condition.**



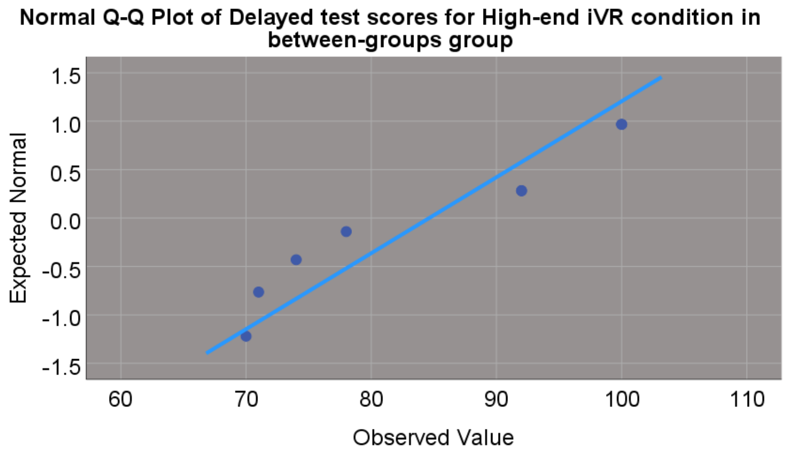
C.6.10 **Q-Q plot showing the distribution post-test scores in the between-groups group for the high-end iVR condition.**



C.6.11 **Q-Q plot showing the distribution of delayed test scores in the within-subject group for the high-end iVR condition.**



C.6.12 **Q-Q plot showing the distribution delayed test scores in the between-groups group for the high-end iVR condition.**



Appendix D: Illustrative animated GIFs

Appendix overview

This appendix consists of animated GIFs illustrating behaviour that participants engaged in whilst performing the experiments and during interviews.

GIFs are labelled according to the figures to which they relate throughout this research:

- **Figure 5.1 (a/b)** Screen capture illustrating the surrounding virtual environments in Labster (2018) and HoloLAB Champions (Schell Games, 2018).
- **Figure 5.3 (a/b)** Screen capture illustrating the kinaesthetic mechanisms used to elicit and support active engagement in Labster (2018) and HoloLAB Champions (Schell Games, 2018).
- **Figure 5.4 (a/b)** Screen capture illustrating plausibility illusion or experienced realism in Labster (2018) and HoloLAB Champions (Schell Games, 2018).
- **Figure 5.6** Locomotion in HoloLAB Champions (Schell Games, 2018).
- **Figure 5.7** Screen capture illustrating the use of the Valve Index controllers in HoloLAB Champions (Schell Games, 2018).
- **Figure 5.8** Illustration of embodied congruency of gestures in Labster (2018).
- **Figure 5.9** Illustration of embodied congruency of gestures in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.1*** Participant 13 describes the congruency of movements in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.2*** Participant 17 discusses interaction in Labster (2018).
- **Figure 9.3*** Participant 17 discusses the use of pipettes in Labster (2018).
- **Figure 9.4*** Participant 18 demonstrates the use of a pipette in Labster (2018).
- **Figure 9.5*** Participant 06 describes tactile feeling whilst holding the controllers in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.6*** Participant 04 describes a break in her sense of proprioception in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.7*** Participant 06 describes expectations of touch in HoloLAB Champions (Schell Games, 2018). 206

- **Figure 9.8*** Participant 24 demonstrates her proximity to manipulatives in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.9*** Participant 13 illustrates consequences of careless behaviour in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.10*** Participant 13 spills a substance in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.11*** Participant 13 describes the realism of interaction in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.12*** Participant 13 throwing a scoop across the laboratory in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.13*** Participant 13 discusses how he adjusted to the conditions of HoloLAB Champions (Schell Games, 2018).
- **Figure 9.14*** Participant 13 transfers and spills a substance in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.15*** Participant 13 describes changes in body posture to engage with manipulatives in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.16*** Participant 13 comparing volumes in cylinders in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.17*** Participant 13 picks up a scoop from the floor in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.18*** Participant 04 conceptualising measuring mass in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.19*** Participant 08 explains what a serial dilution is in Labster (2018).
- **Figure 9.20*** Participant 06 explains what a meniscus is in HoloLAB Champions (Schell Games, 2018).
- **Figure 9.21*** Participant 14 explains how a sample gets contaminated in Labster (2018).
- **Figure 9.22*** Participant 04 explains how to measure liquid substances in HoloLAB Champions (Schell Games, 2018).