Exploring Mixed Reality in Distributed Collaborative Learning Environments

Anasol Carmina Peña Rios

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Abstract

Society is moving rapidly towards a world, where technology enables people to exist in a blend of physical and virtual realities. In education, this vision involves technologies ranging from smart classrooms to e-learning, creating greater opportunities for distance learners, bringing the potential to change the fundamental nature of universities. However, to date, most online educational platforms have focused on conveying information rather than supporting collaborative physical activities which are common in university science and engineering laboratories. Moreover, even when online laboratory support is considered, such systems tend to be confined to the use of simulations or pre-recorded videos. The lack of support for online collaborative physical laboratory activities, is a serious shortcoming for distance learners and a significant challenge to educators and researchers.

In working towards a solution to this challenge, this thesis presents an innovative mixed-reality framework (computational model, conceptual architecture and proof-of-concept implementation) that enables geographically dispersed learners to perform co-creative teamwork using a computer-based prototype comprising hardware and software components.

Contributions from this work include a novel distributed computational model for synchronising physical objects and their 3D virtual representations, expanding the dual-reality paradigm from single linked pairs to complex groupings, addressing the challenge of interconnecting geographically dispersed environments; and the creation of a computational paradigm that blends a model of distributed learning objects with a constructionist pedagogical model, to produce a solution for distributed mixed-reality laboratories.

By way of evidence to support the research findings, this thesis reports on evaluations performed with students from eight different universities in six countries, namely China, Malaysia, Mexico, UAE, USA and UK; providing an important insight to the role of social interactions in distance learning, and demonstrating that the inclusion of a physical component made a positive difference to students' learning experience, supporting the use of cross-reality objects in educational activities.

Acknowledgements

I owe my deepest gratitude to Professor Vic Callaghan whose generous guidance and support helped me to through this research and beyond. His expertise, understanding, enthusiasm and encouragement were invaluable to complete this project, and I will be forever thankful for his trust, advice, and help; including issues that were beyond this research. I greatly enjoyed our ”short” conversations about work and life accompanied by a cup of tea.

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Chapter 1

Introduction

"The whole purpose of education is to turn mirrors into windows."

— Sydney J. Harris (1917 – 1986)

Technology is constantly changing the way we experience everyday life, transforming many aspects of human interaction. One of the biggest changes we have experienced so far is the possibility of moving between two different dimensions: a virtual dimension and a physical dimension. We are constantly jumping from one another, for example, when communicating with people that are not physically in the same location using a chat application in our mobile device whilst interacting with individuals that share a physical space with us. In doing so, we are *consciously* deciding when to switch from one context to the other. However, it is not possible to consciously be in both at the same time. This problem, namely the vacancy problem (Lifton, 2007), is a problem of humans' capacity to be immersed in just one space/dimension at a time. Whilst this phenomenon is not new and occurs even with non-technological items involved (e.g. the degree of *immersion* that an individual can reach when reading a book, making him/her ignore the surrounding environment), it is more visible nowadays, due to factors such as the constant use of mobile devices and ubiquitous technology in combination with

Internet resources.

Figure 1.1: Old depiction of mixed reality, image courtesy Brosterman (2000)

The possibility of merging virtual and physical worlds is an idea that has been addressed from different points of view and disciplines, such as computer science, psychology, sociology, and even science fiction (as illustrated in fig. 1.1), among others. Concepts introduced in science fiction, such as Gibson's Cyberspace (Gibson, 1995) or Stephenson's Metaverse (Stephenson, 1992), have depicted virtual interfaces which although do not replicate all aspects of the physical world, they facilitate interactions in physical environments, enabling possibilities for social interaction between several users at the same time.

Mixed-reality allows the merging of physical and virtual worlds creating environments where physical and digital objects co-exist and interact in real-time. It has been used in different areas, ranging from entertainment and health applications to military training. This research explores the possibilities for creating collaborative mixed-reality in an educational context; more specifically for distance learners, a (growing) sector that faces different challenges.

A survey conducted by The Economist Intelligence Unit (2008) provided an interesting insight on these topics; when participants were asked about likely scenarios in the evolution of higher education during the next 5 years (i.e. the near future). 60% of the respondents thought that the technological changes occurring in education would alter the perception of campuses away from one physical dimension to become multidimensional campuses (physical and online). A similar percentage (60%) stated that online learning would be a fundamental component in the classroom experience. Many of these changes have been already come to fruition in the form of learning management systems (LMS) (e.g. Moodle[1]) or massive open online courses (MOOCs) (e.g. the Khan Academy[2]). Other existing approaches, such as serious games and virtual worlds, have opened resources for active learners to collaborate within simulated environments. Although, these platforms allow collaboration between remote students, there is limited capability for distance learners to do physical hands-on activities; which is a common part of product development or university engineering laboratory activities. Laboratory activities or hands-on classes, are formal learning scenarios where students are presented with a problem that involves the use of physical objects/materials to produce an expected outcome. Such activities foster essential practical skills and knowledge required for work involving building and making physical products, for example, critical thinking, creativity and teamwork, which are essential in many workplaces and real-life settings.

To these ends, this research explores the use of mixed-reality to support collaborative hands-on learning activities for distance learners based on a “learning-by-doing” pedagogy. At this point is important to explain that although this research is situated in the educational field, its aims were not to replace the role of teachers and educators but, rather, to provide an engaging platform to enable students from different regions of the globe working together and exploring creativity and collaboration in ways that were hitherto impossible.

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[1] Moodle - www.moodle.org

[2] The Khan Academy - www.khanacademy.org

1.1 Motivation and approach

The motivation that drives this research can be found in a number of sources; the first one being a creative science prototype story (Callaghan, 2010a) which describes a futuristic high-tech mixed-reality learning environment that changes the nature of traditional learning by combining immersive technology with artificial intelligence; providing 24/7 personalised learning, and competing (or even surpassing!) real-world experiences.

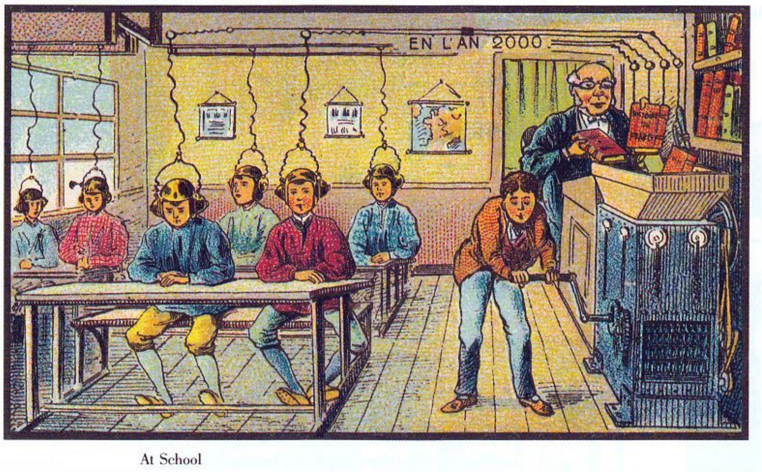


Figure 1.2: France in year 2000 (XXI century). Future school, image courtesy Côté (1899)

A second motivation is related to the affordances of current resources for distance learners. Practitioners, researchers, technologists and educators have been shaping innovative learning environments, conducting cutting-edge science research and devising new educational paradigms and pedagogies which are essential to fuel the current knowledge-based economy. However, current encounters with learning for geographically displaced students are generally limited to web-based and virtualised resources designed for passive learners; following patterns of traditional education, which, when translated to artificial learning environments, limit creativity and collaboration. Figure 1.2 depicts some limitations of artificial learning environments as they were envisaged back in the XXI century.

There is no doubt that online degree programs and distance learning have become important markets for academic institutions around the world, creating wider access to education, content and expanded revenue opportunities. As an example, the Khan Academy, a non-profit educational organisation, reported 15 million registered students in 2014 and nearly 500 million YouTube views, in 70 countries (Husock, 2014). Although these numbers are impressive and reflect the desire (or perhaps need) of people to learn, when compared to other resources on the internet, the numbers are still relatively small. By way of contrast, Statista-The Statistics Portal (2015) reported that social media (i.e. Facebook) had 1.49 billion monthly active users in the second quarter of 2015. Imagine learning environments so engaging that people could stay in them for hours and never get tired of learning! (as described by the Callaghan (2010a) story). Albeit the vision could be considered naïve, as it implies many significant sociocultural, pedagogical and technological challenges, a need for better learning platforms for remote students predominates.

1.1.1 Hypothesis

Based on the motivations described previously, this research poses two main hypothesis:

1. That it is possible to devise a computational model and architecture able to connect locations, that are physically separated, into one unified continuous space by linking elements situated in those locations, using a mix of physical and virtual objects.
2. That such distributed mixed-reality environments (specified in 1) would allow remote users to perform collaborative creative teamwork based on hands-on-activities.

In doing so, a number of secondary hypothesis arose to complement the ones already described:

3. That such distributed mixed-reality environments (specified in 1) would not require specialised technical mixed-reality expertise to be used in collaborative hands-on activities.
4. That using this mix of physical and virtual objects (specified in 1) would be preferred over simulated (virtual) objects.
5. That such distribute mixed-reality environment (specified in 1) would foster engagement and participation of team members.

1.2 Contributions

The major contributions presented in this thesis are as follows:

1. A conceptual architectural model for technology-enhanced learning environments that encompasses personalisation, content creation, assessment and a mixed-reality learning environment (MiReSL model - Chapter 4). This model was complemented with a proposed classification of mixed-reality learning activities (MiReSL-LA classification - Chapter 4).
2. A distributed blended-reality framework composed by a mixed-reality learning environment (the InterReality Portal), and mirrored virtual/physical objects (xReality objects) which can be combined and shared in distributed environments, extending the concept of dual-reality as proposed by Lifton (2007), and addressing the challenge of synchronization of distributed objects. (Distributed blended-reality framework - Chapter 4)

3. A conceptual model that bridges a technical model of distributed mixed-reality objects with a pedagogical model of hands-on laboratories, based on constructionist learning paradigms. (The Deconstructed Model - Chapter 3)

4. A prototype software and hardware architecture which implements the above models and frameworks, facilitating up scaling learning environments by bridging between geographically distributed spaces using a series of shared mixed reality objects, thereby enabling remote users' perception of local environments as blended into one large common environment. (The BReal Lab - Chapter 5)

5. An evaluation of the BReal Lab prototype through user studies in a case study between students of eight different universities in six countries, namely China, Malaysia, Mexico, UAE, USA and UK, including an analysis on collaboration; and a technical evaluation of the prototype performance in terms of latency, proposing methods to estimate synchronisation latency using one or more mixed-reality objects in a distributed architecture. (Chapter 6)

Additionally, a number of secondary contributions are included as follows:

1. The presentation of the combined "Milgram's Reality-Virtually continuum vs Garrison's continue of e-learning" visualisation to situate mixed-reality paradigms in an educational context. (Chapter 3)

2. A definition of Immersive Learning in the context of learning technology. (Chapter 3)

3. Conceptual models to represent single and multiple dual-reality states and how they can be generated in interactions between mirrored virtual/physical objects (xReality objects). (Chapter 4)

4. A definition of adjustable mixed-reality based on the use of mixed-reality objects. (Chapter 4)

5. The creation of an open-source API middleware to connect physical components (BuzzBoards) with 3D virtual representations based on the Inter-Integrated Circuit bus (I^2C) and the use of persistent TPC connections. (Chapter 4)

6. Implementation of a basic collaborative end-user programming tool which extends from single-user to multiple end-user programming, and is suitable for use in distributed mixed-reality learning environments. (Chapter 5)

Finally, this work uncovered a number of additional research challenges such as the classification and identification of actors (i.e. objects and users) in the proposed distributed mixed-reality learning environment, and its use in informal learning settings such as makerspaces, which served as research challenges for colleagues at the Immersive Learning Research Lab at Essex University, which are being addressed in an ongoing PhD research and served as motivation for an EU-funded research proposal.

1.3 List of publications

Part of the contributions described in this thesis have been published and presented in the following publications:

1. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Experiments with collaborative blended-reality laboratory technology for distance learners*≫ on proceedings of 1st Immersive Learning Research Network Conference 2015 (iLRN 2015), Prague, Czech Republic, 2015. (Poster submission and abstract paper).

2. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Using mixed-reality to develop smart environments*≫ on proceedings of 10th International Conference on Intelligent Environments 2014 (IE'14), IEEE Computer Society, Shanghai, China, 2014. (Full paper).

3. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Interactions within Distributed Mixed Reality Collaborative Environments*≫ on proceedings of 10th International Conference on Intelligent Environments 2014 (IE'14), IEEE Computer Society, Shanghai, China, 2014. (Video submission and abstract paper, awarded with Best Video Prize).

4. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Developing xReality objects for mixed-reality environments*≫ on Ambient Intelligence and Smart Environments, Volume 17: Workshop Proceedings of the 9th International Conference on Intelligent Environments, IOS Press, Athens, Greece, 2013. (Full paper).

5. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*xReality interactions within a mixed reality learning environments*≫ on proceedings of 3rd European Immersive Education Summit (EiED'13), London, UK, 2013. (Full paper).

6. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*xReality objects Demonstration – Collaborative laboratory interactions in Immersive Reality*≫ on proceedings of 3rd European Immersive Education Summit (EiED'13), London, UK, 2013. (Demonstration and abstract paper).

7. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Remote mixed reality collaborative laboratory activities: Learning activities within the InterReality Portal*≫ on proceedings of Web Intelligence and Intelligent Agent Technology (WI-IAT), 2012 IEEE/WIC/ACM International Conferences – The Intelligent Campus International Symposium (IC'12), vol.3, no.,

pp.362,366, 4-7, Macau, China, 2012. (Full paper).

8. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*End-user programming and deconstrutionalism for collaborative mixed reality laboratory co-creative activities*≫ on proceedings of 2nd European Immersive Education Summit (EiED'12), Paris, France, 2012. (Full paper).
9. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*BuzzBoards Demonstration - an X-Reality Toolkit for Creating Immersive Reality Educational Laboratories*≫ on proceedings of 2nd European Immersive Education Summit (EiED'12), Paris, France, 2012. (Demonstration and abstract paper).
10. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*Towards the Next Generation of Learning Environments: An InterReality Learning Portal and Model*≫ on proceedings of 8th International Conference on Intelligent Environments 2012 (IE'12), IEEE Computer Society, Guanajuato, Mexico, 2012. (Full paper).
11. **Anasol Peña-Rios**, V. Callaghan, M. Gardner, M. J. Alhaddad, ≪*The InterReality Portal: A mixed reality co-creative intelligent learning environment*≫ on Ambient Intelligence and Smart Environments, Volume 13: Workshop Proceedings of the 8th International Conference on Intelligent Environments, IOS Press, pp. 298-308, Guanajuato, Mexico, 2012. (Full paper).

Additionally, some of the work described here was presented in the following events:

- "*Mixed-reality collaborative environments*" - Guest speaker at "Creativity, Ideas and Innovation" Workshop. Business School – Canterbury Christ Church University, UK. 18 Nov 2014.

- "*Towards blended-reality on collaborative laboratory activities using smart objects*" - Guest speaker at Espacios Educativos Especulares-EEE (Educational Reflected Spaces) Annual Meeting. Universidad Carlos III de Madrid, Spain. 27-28 May 2013.
- "*Mixed-reality and collaboration in learning environments*" - Guest speaker at MobileSummer 2013 (Mobiilikesäkoulu 2013). Mustiala Park, Tammela, Finland. 23-24 May 2013.

1.4 Thesis outline

Chapter one (this chapter) describes, the motivation underpinning this thesis, the hypothesis and the contributions made during this research, as well as the publications that arose from this work. Then, the document presents a review of literature organised in two sections:

- **Chapter two** introduces concepts about multidimensional spaces, which are environments where virtual and physical elements coexist together. The chapter introduces mixed-reality (MR) concepts and delves into different transition points between reality and virtuality, focusing particularly on dual-reality (DR), a key principle underlying this research, which allows synchronisation between virtual and physical worlds. This section presents a discussion of current research towards the creation of mixed-reality spaces, introducing the concept of blended-reality as an environment where virtual and physical are not merely mixed, but blended in a seamlessly way. Finally, this chapter presents collaboration in mixed-reality environments using an educational scenario for distance learners. The section identifies some of the challenges faced by distance learners when using technology-based learning and proposes the use of mixed-reality in a distributed learning environment, establishing possible benefits of using such environments over the use of current alternatives for hands-on engineering-style construction activities.

- **Chapter three** provides an insight on different approaches to the learning process based on philosophical and pedagogical theories. It introduces the concept of deconstructionism, a core unifying principle in the model proposed, which works with a constructionist pedagogy of learning activities that adheres to the dual-reality principles explained in chapter two. Additionally, this section presents a review on different virtual and mixed-reality learning environments and related technology, introducing a definition of immersive learning; and highlighting the importance of designing appropriate learning activities in technology-enhanced learning environments to reach the desired learning outcomes. Finally, the chapter discusses the pedagogical and technical challenges of using multidimensional spaces in education, and presents the Deconstructed Model, in which this research is built upon and unifies mixed-reality technology with pedagogical resources.

Chapter four introduces the Mixed-Reality Smart Learning Model (MiReSL), a conceptual architectural model for content creation, and personalised learning and assessment, based on a mixed-reality learning environment. The MiReSL model serves as a context for the framework proposed in this thesis, which focuses on the creation of a network of geographically distributed interconnected mixed-reality learning environments. Its goal is to allow teams of remote students to execute hands-on activities in collaboration, based on the dual-reality principle of reflecting any change occurring in either one reality, to the other. Particularly, this section introduces conceptual and architectural models for the proposed mixed-reality learning environment (the InterReality Portal); and a conceptual model of physical objects mirrored to its virtual representation (xReality objects) which can be mixed and shared between remote team members. Finally, the chapter proposes a classification of learning activities (MiReSL-LA) that can be implemented in the MiReSL model; focusing on those which are designed for the proposed framework of remote laboratories.

Chapter five starts by describing the implementation of the proof-of-concept demonstrator, the BReal Lab, which is based on the conceptual architectural models, defined in the previous chapter. Additionally, this section explains the implemented distributed architecture which connects multiple implementations of the proposed BReal Lab prototype; ending by describing the strategies for implementing mixed-reality collaborative learning activity based on the MiReSL-LA classification proposed in chapter four.

Chapter six discusses the different evaluation techniques used for mixed-reality user studies before explaining the specific method used for the evaluation of the proof-of- concept BReal Lab demonstrator. This section describes the experimental design and strategy used in the evaluations. Later, the section presents statistical results for the user evaluations, together with an in-depth analysis. In doing this, the thesis reports on the participant's views of their experience with the BReal Lab prototype and the collaborative task. The premises of these tasks are established at the beginning of this chapter. The collaborative aspects of the study were complemented with an analysis of recorded conversations between participants. A key aspect in the proposed model is the synchronisation between events across the multiple environments, which was evaluated using measures such as network latency and rendering lag. The chapter concludes with an in-depth discussion of the results presented in this section.

Finally, **chapter seven** concludes the thesis by summarising the achievements of the thesis, discussing main educational and technological issues that arose from the research identifying further work and ending with a forward looking vision of the future prospects for this area of research.

Chapter 2

Physical and Virtual Worlds

> *"A mind that is stretched by a new experience can never go back to its old dimensions."*
>
> — Oliver Wendell Holmes, Jr. (1841-1935)

Nowadays, technology is becoming increasingly intertwined with our everyday life. We rely on it for different aspects of our life, such as entertainment, learning or communication. This has added an extra dimension to our reality, transforming it from one dimension to multiple dimensions. Unconsciously we live in a multidimensional world, using technology to help us to connect with both digital and physical spaces.

This chapter examines the diverse paradigms and technologies that facilitate mixing of virtual and physical worlds, introducing the concept of Blended-Reality which is the concept underpinning this research. Finally, this section introduces online education as an application domain of multidimensional spaces, particularly in collaborative activities for remote users (explored in more detail in further chapters), setting the initial context for the research presented in this thesis.

2.1 Mixing realities

Originally virtual and physical reality have been regarded as two diametrically opposite entities. However, the pervasive use of technology in different spheres of human life is blurring the dividing line between them, allowing people to switch from one to another in a conscious (yet not *continuous*) way. A person can be at the same time walking on the street, while communicating with a friend using a *virtual* interface embedded in his/her mobile phone.

According to the Oxford Dictionary (2015), the original meaning of the word *virtual* refers to "possessing certain virtues", which has its roots in the medieval Latin word *virtualis*, from Latin *virtus* ("virtue"). Later, the medieval philosopher John Duns Scotus (1266?-1308) started using the Latin term *virtualiter* ("virtually") to describe attributes contained in things which are not knowable from empirical observations but, rather, existed in the form of attributes apprehensible only through the senses (Yoh, 2001; Heim, 1993). He started using the term *virtual* to "breach the gap between formally unified reality (as defined by our conceptual expectations) and our messy diverse experiences" (Heim, 1993). The term has been adopted in diverse sciences (i.e. Physics), but it is in Computer Science where it has been most widely used. It was first used for software simulations of hardware devices in computers (i.e. virtual memory), which helped overcoming limitations of the hardware and allowed the operating system to view simulated hardware as actually existing. The term, "virtual reality" was first used in 1986 by Jaron Lanier, the founder of VPL Corporation (Steuer, 1992; Mann, 2002; Yoh, 2001), and it is usually referred as "the sense of artificial reality." Thus, Virtual Reality (VR) refers to a highly-interactive computer-generated environment which creates a synthetic experience for the user, allowing him/her to have a sense of being present in an environment other than the one he/she is actually in by substituting the primary sensory input with data received produced by a computer

(Heim, 1998; Schroeder, 1996; Kim, 2005; Ijsselsteijn, 2006). Virtual reality systems normally refer to high-tech interconnected input/output devices (e.g. head mounted displays (HDM)) for visual simulation, surround sound system for three-dimensional (3D) sound effects, haptic wearable devices such as "data-gloves" and "data-suits" for detecting user movement and for giving haptic feedback) able to create a parallel world which exist separate from the physical world.

Heim (1993) defined seven different characteristics of virtual reality:

- *Simulation* states the ability of generate images, objects, places, etc. with a high degree of realism.
- *Interaction* refers to any communication or contact between one or many subjects/objects situated in the same environment, in this case within a virtual situation.
- *Artificiality* is related to a world that is largely a human construct, altered from the original form.
- *Immersion* refers to a mental state of consciousness where the person awareness is diminished or lost by being surrounded by an artificial environment.
- *Tele-presence* is the sense of presence in the computer mediated environment, rather than in the immediate physical environment (Steuer, 1992).
- *Full-body immersion* is a characteristic that allows participants to explore and experience immersion in a physical way, with the help of technology.
- *Network communication.* Virtual reality can enable different ways of sharing. This characteristic refers to the communication and sharing of information within different objects/subject in a virtual environment.

Virtual reality has been used in industry along with computer-aided design (CAD) to create 3D visualizations, simulations and virtual prototypes for research and development. Similarly, it has been used in simulators for medicine and military training. However, the most known use is in entertainment where it is commonly linked to video games and online gaming. It is in this area and with the growth of broadband Internet access that multi-user games known as massively multiplayer on-line games (MMOs) enabled large numbers of simultaneous players to collaborate and compete on a large scale. This infrastructure also allowed the growing of a different type of general-purpose virtual environments, which worked as open spaces for users to interact and generate content. The most representative of this being Second Life which reported in 2013 more than one million visits monthly Linden Labs (2013).

Weiser (1999) in his essay "*The computer for the 21st century*", described virtual reality as perhaps the "most diametrically opposed" concept to his vision of ubiquitous computing, in which technology integration into physical world's everyday life makes it indistinguishable from it; whereas virtual reality "attempts to make a world inside the computer [...] focusing on simulating the world rather than on invisibly enhancing the world that already exists". Weiser concerns reflect two limitations, a) the separation that VR imposes to reality; and b) humans' capability to be present and fully engaged in one reality at a time. Lifton (2007) defined this as the *vacancy problem*, "a noticeable and profound absence of a person from one world, either physical or virtual, while they are participating in the other". Mixed-reality tries to solve the challenge of physical/virtual world's exclusion from one another by combining physical and virtual elements in a shared environment. Milgram and Kishino (1994) proposed a continuum to represent the different degrees between virtuality and reality, defining anything amid the ends as mixed-reality (fig. 2.1). Mixed-Reality (MR) is the spectrum that connects physical environments, absent from virtual representations of any kind, to completely virtual ones, allowing the co-existence of physical and computer-generated elements in real-time. Its potential relies on the possibility of enhancing reality, making invisible things visible (Pastoor and Conomis, 2005) and sometimes, due to its synthetic nature, modifying the physical laws governing reality implementing diverse metaphors (visual, auditory and haptic) not available in the physical world (Ellis, 1994).

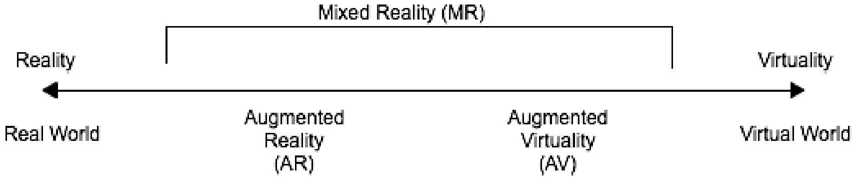


Figure 2.1: Reality-Virtuality Continuum (Milgram and Kishino, 1994)

Within the Reality-Virtuality Continuum's scope, MR is formed by Augmented Virtuality (AV) and Augmented Reality (AR). In Augmented Virtuality (fig. 2.2a), the primary environment is virtual, and is enhanced by adding physical objects and physical world's data. This is generally done by adding raw video data onto markers within a virtual environment (Tamura et al., 2001; Pastoor and Conomis, 2005). A virtual environment is a computer-generated interactive space, based on visual and non-visual mechanisms such as auditory and haptic, to convince users that they are immersed in a synthetic space (Ellis, 1994). A three-dimensional virtual environment (3D VE) can be defined as an environment that "capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions" (Wann and Mon-Williams, 1996), and it has three main characteristics (Dalgarno et al., 2002): a) the illusion of three dimensions; b) smooth temporal and physical changes and; c) a high level of interactivity. In contrast, Augmented Reality (fig. 2.2b) describes an environment where the physical world is enhanced by adding computer-generated objects using computer vision methods to make them appear as if they co-exist in the same dimension (Pastoor and Conomis, 2005). Therefore, AR supplements reality rather than completely replacing it. It displays information useful that is not directly detected by user's senses, helping him/her to perform real-world tasks, and facilitating the understanding of complex scenarios (Azuma and Azuma, 1997).

(a) Augmented Virtuality (b) Augmented Reality

Figure 2.2: Mixed Reality

Mann and Nnlf (1994) noticed that the term Augmented Reality did not explicitly encompassed the possibility of reusing and replacing elements of the physical environment (in opposition to adding new data), thus they proposed a more general framework (fig. 2.3) as a way to describe various aspects of mixing virtual and physical elements that were not considered in Milgram's taxonomy (i.e Diminished Reality (fig. 2.4) (Mann and Fung, 2001a,b)). Mediated Reality is defined as "a general framework for artificial modification of human perception by way of devices for augmenting, deliberately diminishing, and more generally, for otherwise altering sensory input" (Mann and Nnlf, 1994; Mann, 2002).

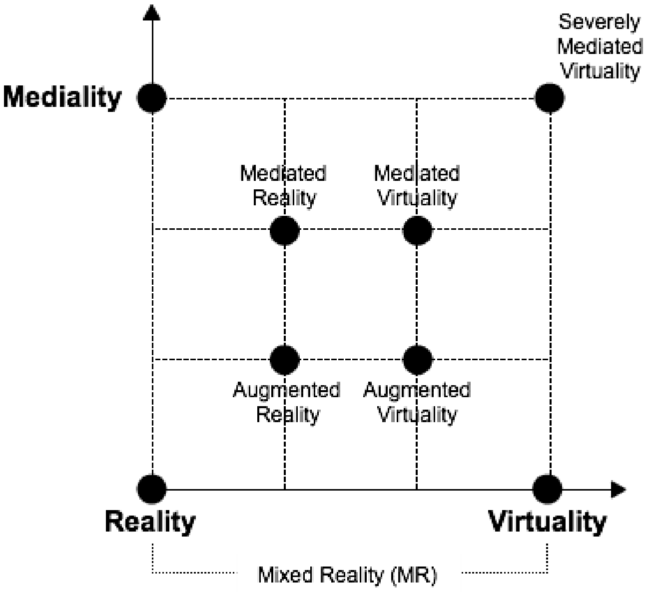


Figure 2.3: Mann's Mediated Reality Framework (Mann and Nnlf, 1994)

(a) Normal vision (b) Diminished Reality vision

Figure 2.4: Diminished Reality, image courtesy Mann and Fung (2001b)

2.1.1 Dual-Reality

The categories defined by Milgram and Kishino (1994) within its taxonomy could be considered as static points within the continuum; where each one represents by itself a single, complete, and consistent world, regardless of which components are physical and which virtual. Lifton (2007) proposed the term Dual-Reality as “an environment resulting from the interplay between the physical world and the virtual world. While both worlds are complete unto themselves, they are also enriched by their ability to mutually reflect, influence, and merge into one another”. In his definition, each environment is complete by itself and the lack of the other does not pose a problem for it to work, however when both environments exist, any element within the physical world is directly linked to another in the virtual world, reflecting any change in either of them in real-time. Figure 2.5 shows dual-reality’s data flux within Milgram’s continuum, reflecting interaction between physical and virtual worlds.

Dual-reality might seem a modification of AV or AR, or even a mix between

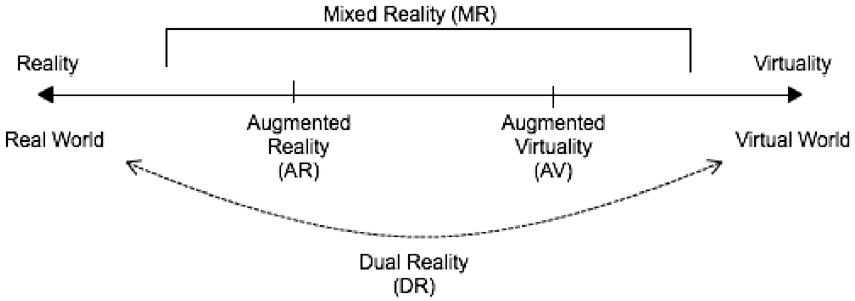


Figure 2.5: Dual-reality within Milgram's Taxonomy

them, however as figure 2.6 shows, AV consists of a virtual environment complemented with physical elements; in comparison to AR, which is mainly based of a physical environment enhanced with virtual elements. In contrast, each DR environment is complete by itself, but elements inside the virtual environment are directly linked with its physical counterparts, interchanging a flux of data that allows them to react *simultaneously* (fig. 2.7).

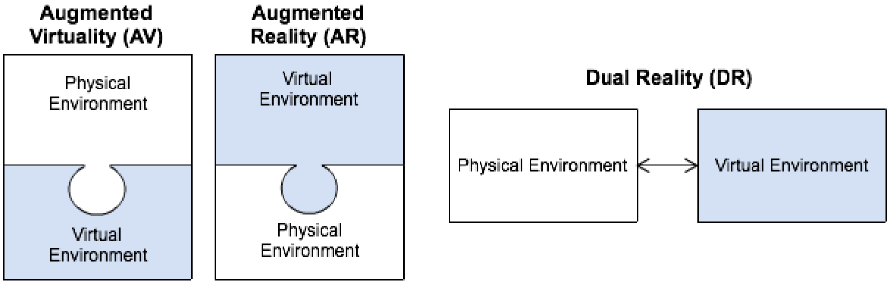


Figure 2.6: Differences between AR, AV and DR

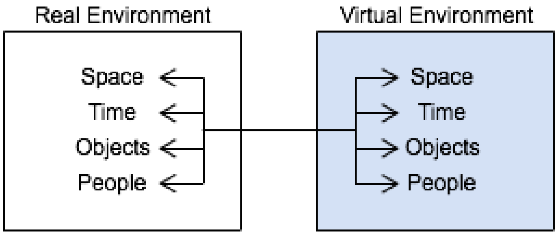
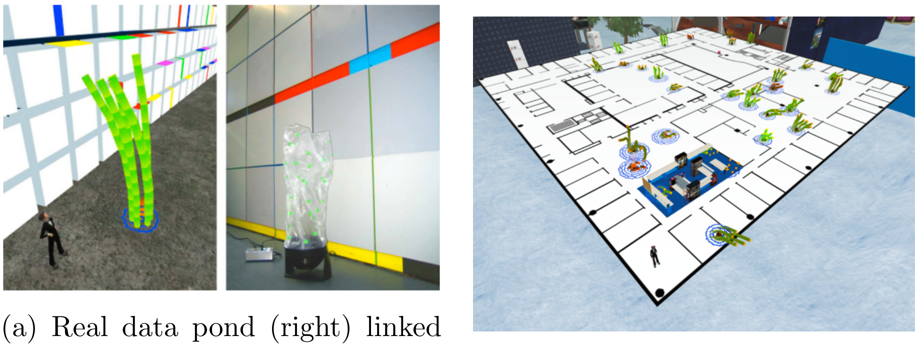


Figure 2.7: Fundamental mappings in dual-reality (DR) (Lifton, 2007)

2.1.2 Related work

The dual-reality principle has been implemented in different projects, although is commonly classified as augmented reality. In his work, Lifton (2007; 2009; 2010) used a bespoke sensor/actuator node as embedded in a power strip (called PLUG) to link virtual and physical worlds. This, sent the data collected to the virtual world, creating different metaphors that showed the data in real-time (fig. 2.8a). Finally, multiple PLUGs were distributed within a physical building, creating a ubiquitous networked sensor/actuator infrastructure of interconnected nodes that reflected their current status on a virtual map of the building (fig. 2.8b).

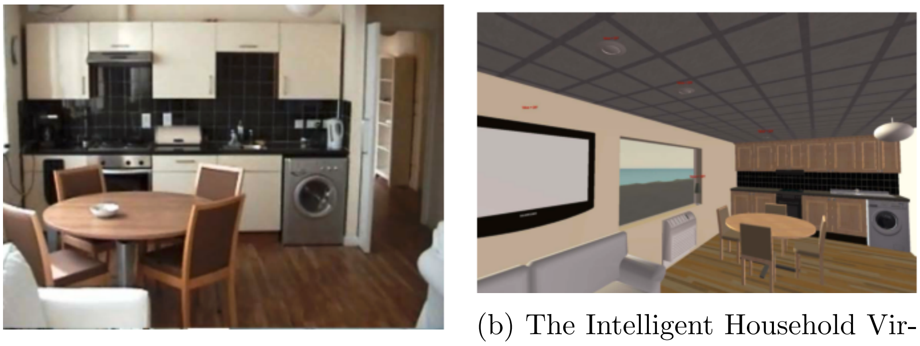

(a) Real data pond (right) linked to a virtual metaphor (left)

(b) DualReality Lab

Figure 2.8: Cross-Reality implementations, image courtesy Lifton (2007)

Paradiso et al. (2009; 2009; 2010) called cross-reality (xReality) to this ubiquitous mixed reality environment that comes from the fusion of sensor/actuator networks and, which tunnels dense physical-world information into virtual worlds, where this data is interpreted and displayed to dispersed users. Projects such as MIT's Dual Reality Lab (MIT Media Lab, 2007), Ubiquitous Sensor Portals (MIT Media Lab, 2009), and the DoppelLab (MIT Media Lab, 2010), are based on the cross-reality architecture. An interesting aspect of these projects is that although sensors/actuators were linked to a virtual representation, these representations were *metaphors* of an environmental variable (fig 2.8a), not a mirrored copy of the object that was capturing this values.

Davies and Callaghan (2010) presented a related project that connected the University of Essex iSpace (fig. 2.9a), a purpose-built test-bed flat for pervasive computing research, with a virtual copy of the household (fig. 2.9b). Here, the contents of the virtual household were controlled using iSpace's Universal Plug and Play (UPnP) embedded middleware infrastructure, replicating the physical iSpace as possible, and creating mirrored mixed-reality objects (e.g. light switches controlled from the virtual world and from the physical world). However, authors stated that identical object replication was not a strict requirement, and some virtual devices had a completely different appearance to its physical counterpart, (e.g. a physical telephone represented as a floating orb).



(a) The University of Essex iSpace

(b) The Intelligent Household Virtual World

Figure 2.9: Mixed Reality Intelligent Household, image courtesy Davies and Callaghan (2010)

MIT's Dual Reality Lab and Essex' Intelligent Household Virtual World implemented the principle of dual-reality allowing single users to interact with a cross-reality environment, however creation and collaboration was limited. In (2013; 2013; 2009), Vallance presented a remote collaboration project between teams of students in two remote locations using LEGO Mindstorm robots[1] (fig. 2.10b), its proprietary programming language (NXT) and a 3D virtual world. In this project, students in one place firstly built a roadmap in the physical world using LEGO blocks and other type of materials (e.g. cardboard) to satisfy a previously provided task specification. As a second step, they replicated the roadmap using virtual objects in the 3D world. After that, using LEGO's proprietary software, they created a program to allow LEGO robots to manoeuvre within the physical roadmap created. Once the solution was created and tested, it was communicated to the team in the other location, using virtual world's communication

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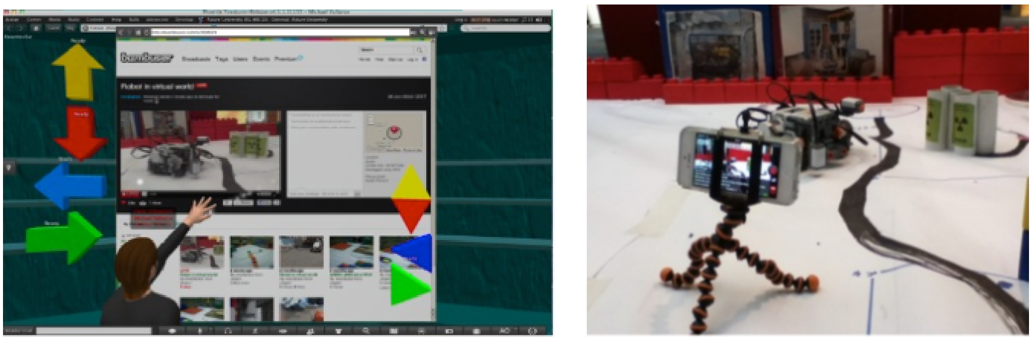
[1] LEGO Mindstorm - `www.lego.com/mindstorms`

tools (verbally using a microphone or in written using a chat window). After this, the team on the other side proceeded to replicate the physical construction of the roadmap in their local environment, and finally, using a video streaming of the robot embedded in the virtual world via a web browser (fig. 2.10a), they showed the result. Additionally, some basic controls were included inside the virtual world to allow users to move the robot independently of the location of the user. This project, although it did not implement the dual-reality principle, as the robot was not linked to a virtual representation of itself, and the virtual world was merely used as a user communication medium; it showed the possibilities of collaboration in a mixed-reality environment.



(a) 3D Virtual world controls (b) LEGO robot

Figure 2.10: Collaboration through virtual worlds, image courtesy Vallance et al. (2013)

The Virtual Collaboration Arena (VirCA) project (Galambos et al., 2014, 2011; Galambos and Baranyi, 2011), developed by the Institute for Computer Science and Control, Hungarian Academy of Sciences [2], added the possibility of doing collaborative work between distributed users, synchronizing physically existing entities (e.g. robots, fixtures, machine tools, workpieces, etc.) with their corresponding virtual counterparts. Networked modular robot control software was built upon the Robotics Technology Component Standard (generally referred to as RT- Middleware) via its open source implementation OpenRTM [3]. This project implemented the principle of dual-reality using a physical object at one

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[2] MTA SZTAKI - `www.sztaki.hu`

[3] OpenRTM - `www.openrtm.org`

environment and allowing users in the other to control it via its virtual representation (fig. 2.11).

(a) VirCA virtual robot (b) VirCA physical robot

Figure 2.11: VirCA Project, image courtesy Galambos et al. (2014)

Kokswijk (2003) described the phenomenon of “interreality” as the user perception of total integration between the physical and the virtual world, “a hybrid total experience between reality and virtuality”, blurring the boundaries between physical and virtual. In recent years, this concept has been applied to personalised immersive e-therapy focused on how behaviour in the physical world influences the experience in the virtual one and vice-versa. This therapy uses a) role-playing experiences in virtual worlds, b) physiological and activity sensors used to track the emotional/health/activity status of the user and to influence his/her experience in the virtual world (aspect, activity and access) and, c) mobile internet-based appliances to link and track social and individual user activity (Riva, 2009; Pioggia et al., 2010).

The increasing possibilities to mix physical and virtual worlds were defined by the Metaverse Roadmap project [4] as Metaverse. The Metaverse, term taken from 1992 Neil Stephenson’s *Snow Crash* novel (Stephenson, 1992), is formed by the fusion of: a) virtually-enhanced physical reality and b) physically persistent virtual space, allowing users to experience it as either (Smart et al., 2007). In their definition, there is no single, unified entity called the Metaverse; rather, there are multiple ways in which physical and virtual worlds can be connected.

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[4] The Metaverse Roadmap project - `www.metaverseroadmap.org`

The Metaverse Roadmap project (Smart et al., 2007) proposes a spectrum of technologies and applications ranging from augmentation to simulation; and from intimate (identity-focused) to external (world-focused) as two continua that are likely to influence the ways in which the Metaverse unfolds in future research; defining four scenarios of application: Virtual Worlds, Mirror Worlds, Augmented Reality and Lifelogging (fig. 2.12).

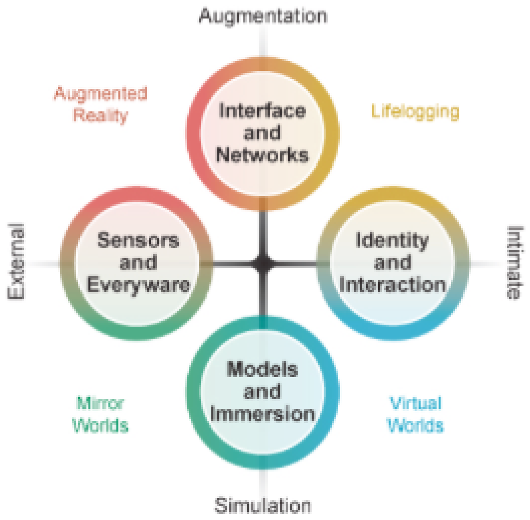

Figure 2.12: Metaverse framework, image courtesy (Smart et al., 2007)

Within this context, mirror worlds are defined as “informationally-enhanced virtual models (or ’reflections’)” of the physical world. Their construction involves sophisticated virtual mapping, modelling, and annotation tools, geospatial and other sensors, and location-aware and other lifelogging (history recording) technologies. These worlds are based on geographic information systems (GIS) to capture, store, analyse and manage data and associated attributes that are spatially referenced to the Earth (e.g. Google Earth).

The Moving Picture Experts Group (MPEG) combined the work done by the Metaverse project and the Single Media Multiple Devices (SMMD) project (later renamed as Representation of Sensory Effects (RoSE)), whose objective was to represent sensory effects for new types of media services (Yoon et al., 2015), into the ISO/IEC 23005 standard[5], (MPEG-V or MPEG for Virtual Worlds). This standard, whose latest version was published in 2014, provides an architecture and specifies associated information representations to enable interoperability between virtual worlds (e.g. virtual worlds, (serious) games, simulations) with the physical world (e.g. sensors, actuators, vision and rendering, robotics) (Oh and Woo, 2013; International Organisation for Standardisation, 2014; Yoon et al., 2015). Films or video sequences (particularly 3D and 4D films) are considered into the standard as another depiction of the physical world, thus classifying as virtual worlds. 4D films are those that include sensory effects (e.g. vibration, wind, lightening) produced by actuators (e.g. fan, motion chairs, scent generators) (Yoon et al., 2015).

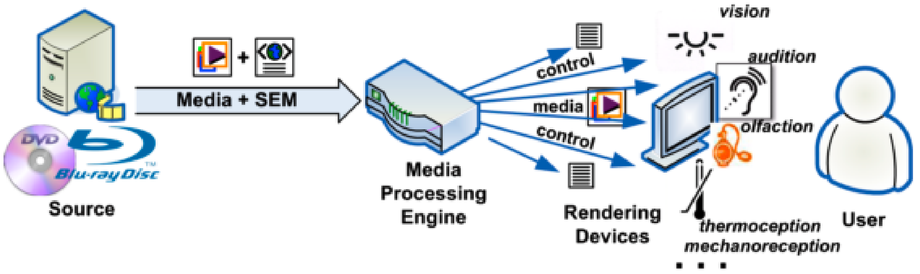

Figure 2.13: Concept of MPEG-V Sensory Effect Description Language, image courtesy The Moving Picture Experts Group (MPEG) (2014)

Figure 2.13 illustrates the proposed Sensory Effect Description Language (SEDL), a XML schema-based language which enables the description of the so-called sensory effects (e.g. light, wind, fog, vibration) that trigger human senses (The Moving Picture Experts Group (MPEG), 2014; Timmerer et al., 2009). The language includes two extra components: a) the Sensory Effect Vocabulary (SEV) which describes the sensory effects produced, and b) the Sensory Effect Metadata (SEM) which may be associated to any kind of multimedia content (e.g., movies, music, websites, games). The SEM is used to steer sensory devices like fans, vibration chairs, lamps, etc. via an appropriate mediation device in order to increase the

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[5] ISO/IEC 23005 Specification - `https://www.iso.org/obp/ui/#iso:std:iso-iec:23005:-1:ed-2:v1:en`

experience of the user (Timmerer et al., 2009).

2.2 Understanding multidimensional spaces

Multidimensional spaces traditionally are referred in the physics and mathematics fields as spaces with more than three dimensions explained using quantum physics and Einstein's theories. Within the scope of Computer Science, the term *multi-dimensional space* could be defined as a hybrid environment where physical and virtual worlds couple together to create the seamless illusion of continuity. Woo (2009) described some technologies that illustrates a paradigm shift bridging virtual and physical worlds; table 2.1 summarises them and extends its classification adding other identified technologies.

Paradigm	Characteristics
Cyber-Physical Systems (CPS)	Bridge computing and communications with the physical processes using embedded systems. Based on physical variables (i.e. temperature, humidity) represented as two-dimensional (2D) abstract objects (e.g. graphs, tables).
Tangible User Interfaces (TUI)	Use everyday physical spaces, surfaces and objects as both controls and representations by coupling digital information to them.
Smart Objects, Internet-of-Things (IoT), Web-of-Things (WoT)	Union between the virtual world of "information" with the physical world of "things". Dynamic global network infrastructure.
Anywhere Augmentation	Acquiring and presenting content for mobile AR. Mobility, collaboration, interactive visualization.
Ubiquitous VR (U-VR)	Augmentation of the physical world with the virtual world. Collaborative wearable context-aware mixed reality with multimodal feedback. Immersion.

Table 2.1: Paradigm shift towards the creation of multidimensional spaces

The term cyber-physical systems (CPS) refers to systems with integrated computational and physical capabilities that bridge the cyber-world of computing and communications with the physical world (Rajkumar et al., 2010; Baheti and Gill, 2011). Embedded computers and networks monitor and control physical processes, usually with feedback loops where these processes affect computations and vice versa (Lee, 2008). CPS are usually implemented to monitor and control applications in physical and engineered systems using embedded computing. Information taken from the tangible world is based on physical variables (i.e. temperature, humidity) and represented as two-dimensional (2D) abstract objects (e.g. graphs, tables).

A more end-user oriented paradigm was proposed by Ishii and Ullmer (1997) using tangible user interfaces (TUI) to "augment the real physical world by coupling digital information to everyday physical objects and environments". In this paradigm, computer systems detect user's manipulation of physical objects, altering its state within the system to give feedback accordingly (Fishkin, 2004). The central characteristic of TUIs is the coupling of tangible representations to underlying digital information and computational models (Ishii, 2007). TUI design introduced challenges such as the mapping of physical objects and their manipulation to digital computation and feedback in a meaningful and comprehensive manner; and user's perceptual "spatial continuity of tangible and intangible representations" (Sears and Jacko, 2007) that allows work on real-time.

The increasing use of the Internet fostered the challenge of connecting those everyday physical/virtual objects in a global network. The Internet-of-Things (IoT) allow objects to be recognizable by sending information among themselves and capable to collect the same information from any other device. It can be defined as union between the virtual world of "information" with the physical world of "things" allowing numerous interesting applications to be constructed with "smart objects", creating a dynamic global network infrastructure with self-configuring capabilities (Uckelmann et al., 2011; Sundmaeker et al., 2010; Gershenfield et al., 2004). Smart objects can be defined as *"autonomous physical/digital objects aug-*

mented with sensing, processing, and network capabilities" which can interpret their local situation and status, and can communicate with other smart objects and interact with human users (Kortuem et al., 2010). The Internet-of-Things is based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network (Sundmaeker et al., 2010). The Web of Things (WoT) emerged proposing the use of web standards to integrate physical-world things into the existing Web, changing physical objects into web services (RESTful resources) which can be used directly over the Hypertext Transfer Protocol (HTTP). Guinard et al. (Guinard and Trifa, 2009) described two types of mashups on the Web of Things: 1) physical-virtual mashups (or cyber-physical systems) and 2) physical-physical mashups. The first category refers to a combination of physical devices and different services available through and end-user interface. The second category refers to a physical user interface that uses physical-world services without requiring an end-user interface, such as a computer or HTTP browser.

Mobile devices and augmented reality gave rise to the term "Anywhere Augmentation", which refers to the idea of linking location-specific computing services with the physical world, making them readily and directly available in any situation and location, such as arbitrary environments with no prior preparation, mainly using mobile and wearable computing commonly combined with augmented reality (AR) (Höllerer et al., 2007; DiVerdi et al., 2009), integrating computer-mediated interaction with real-world activities (Johnston and Clark, 1999). The use of such technology allows systems to give multi-modal feedback, pointing the importance of creating adequate user interfaces, that does not necessarily involve visual feedback (Newman and Clark, 1999; Gellersen et al., 2000), but can work more as a "personal assistant" achieving a more natural human-computer interaction (Clark et al., 2003).

Ubiquitous Virtual Reality is a paradigm that combines Virtual Reality (VR) with ubiquitous computing, extending VR capabilities into a physical space, not confining it within a simulated space (Jang et al., 2005; Lee et al., 2008; Oh and Woo, 2013). Some of its characteristics are (Suh et al., 2007; Lee et al., 2008):

- Ability to enable users to share contents and devices to carry out tasks; understanding contents as realistic multimedia contents able to stimulate human senses, and devices as pervasive smart objects in a physical environment. Collaboration is achieved using non-conventional VR interfaces, which include multimedia sharing and multi-modal interaction, creating collaborative environments that share time and space.
- The use of wearable devices that provide services without the constraints of time, place and device. It considers users' privacy and transparency of user interfaces to allow tasks achievement.
- Mediation that allows responsive personalised multimedia contents supported by context-aware technology and ambient intelligence (AmI), creating a seamlessly integration between physical and virtual worlds (Mediated Reality).

These paradigms show shifts on the technology approach towards multi-dimensional spaces, with CPS focusing on intangible variables to control systems, TUIs focusing on using objects to interact with systems, IoT connecting those objects on a global network, anywhere augmentation adding mobility to multidimensional spaces and U-VR creating immersive multi-modal spaces. Different authors (Holloway, 1995; Pastoor and Conomis, 2005; Suh et al., 2007; Smart et al., 2007) have highlighted different challenges in the creation of multi-dimensional spaces:

- Precise spatio-temporal registration, to align virtual objects with their physical counterparts, fundamental to not compromise the illusion of its co-existence in the same environment.

- Comprehensive photometric and geometric model of the mixed reality environment, required to create appropriate visual integration between environments (e.g. appropriate calculation of illumination, to show shades and highlights of the virtual objects, and occlusion to decide which objects are located in first plane and which ones are behind).

- Identification and sharing of distributed resources and contents for the creation of a Community Space, which must include information of available objects, resources and users, creating a community able to achieve user collaboration.

- MR interfaces able to support relevant mechanisms of perception with multimodal feedback (visual, auditive, haptic) providing to human sensory channels a seamlessly blend of virtual and physical worlds. In this context, humans collect over 70% of the environmental information through the visual channel, consequently visual representations are very relevant in MR implementations.

- User interfaces that allow users to concentrate on their tasks without the necessity of being conscious of the user interface.

- Realistic virtual contents able to be integrated seamlessly into a physical environment to provide seamless presence to users.

- Adequate infrastructure able to build up the invisible bridge between contents and users.

2.2.1 Blended-Reality

From a human perspective, one of the challenges of creating multi-dimensional spaces is achieving a full degree of interaction and immersion, avoiding the so-called “vacancy problem”, the noticeable and profound absence of a person from one world, either physical or virtual, while they are participating in the other (Lifton, 2007). Csikszentmihalyi (1991) defined as “flow” to the optimal state of consciousness characterized by a state of concentration so focused that it amounts to absolute absorption in an activity, leading to ignore or even forget about any other event happening in our surrounds. This absence of mind happens when consciousness is minimally concerned with the situation occurring in one of the environments involved (Riva et al., 2004), and is a consequence of having virtual and physical worlds existing in parallel, not seamlessly integrated into one another. Thus, this integration is one of the biggest challenges, because any break in the continuity between the two spaces would immediately destroy the illusion of a unified environment to human senses (Pastoor and Conomis, 2005).

Blended-Reality (BR) seeks to implement an interactive mixed-reality environment where the physical and the virtual are seamlessly combined (blended not merely mixed) and affect each other, in the service of interaction goals and communication aims (Huynh et al., 2006; Hoshi and Waterworth, 2009).

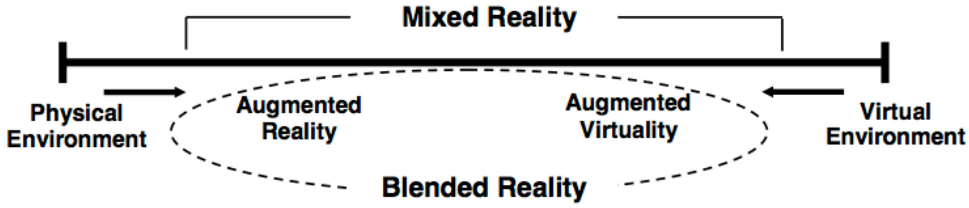


Figure 2.14: Location of blended-reality within Milgram’s Continuum (Bower et al., 2010)

Bower et al. (2010) located it within Milgram’s Continuum as a synchronisation between an augmented reality and augmented virtuality space (fig. 2.14).

Benyon et al. (Benyon et al., 2012; Benyon and Mival, 2012; Benyon, 2012b) uses the term *Blended Space*, to define a broader concept between a physical space and a digital space that have been brought together to create the opportunities for new experiences. In his definition, he incorporates the use of augmented reality and augmented virtuality focusing in the mix of both from the user experience point of view. Hoshi and Waterworth (2009) argue that in a true blending of the physical and the virtual, objects should have both physical and virtual presence, experienced by users as a tangible presence in the blended environment. “Through this physical-virtual combination, the physical objects provide users with clues about the virtual environment and help them develop skills in their environment, such as picking up, positioning, altering, and arranging objects” (Hoshi and Waterworth, 2009). This definition is more aligned with the multi-dimensional paradigms described in the previous section. Moreover, Bower’s definition collides with Milgram’s Mixed Reality definition, which is defined as anything between the two extrema of the Virtuality-Reality continuum. Thus, we should distinguish between a *Blended Space* and *blended-reality*. Figure 2.15 presents a proposed interpretation of blended-reality showing how elements exist in both environments at the same time.

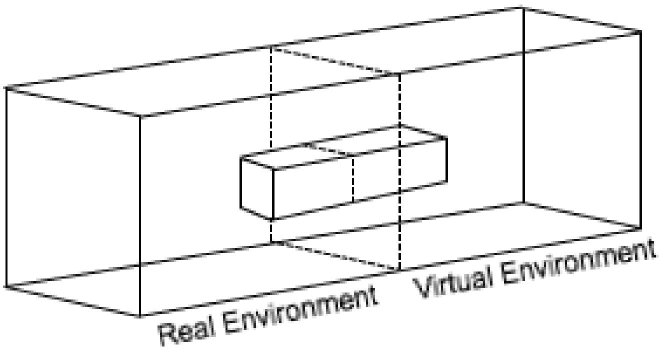


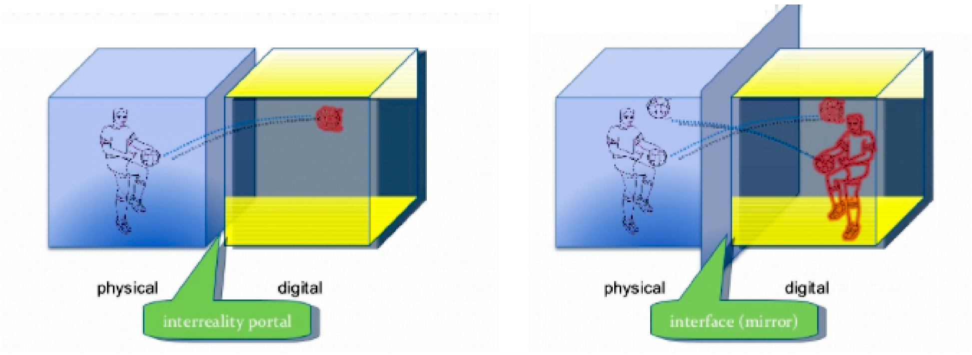
Figure 2.15: Blended-reality

Robert and Breazeal (2012) presented an example of a blended-reality character, the “Alphabot”, which simulated a fluidly transitioning from a computer graphics character on screen, to a mobile robot in physical reality within an immersive environment. The experiment presented a unified coordinate space which smoothly interpolated an animated movement which began in the virtual environment and ended in the physical space (and vice-versa) as one continuous movement, moving the character off/on the screen (fig. 2.16).

Figure 2.16: The Alphabot, image courtesy Robert and Breazeal (2012)

The "Alphabot" represents one of two possible implementations of blended-reality (Delgado-Kloos, 2011): a) as an extended space (fig. 2.17a), in which an action is initiated in the physical environment and continued in the virtual environment (and vice-versa) and, b) as a reflected space in which an action initiated in either the virtual or the physical world is mirrored in its counterpart (fig. 2.17b). In here, an interreality portal acts as an enabler that glues together both realities. These implementations have of course limitations related to the physics of the tangible world. As Ishii pointed out (2007) "unlike malleable pixels on the computer screen, it is very hard to change a physical object in its form, position, or properties (e.g. color, size) in real-time".

From a sociocultural perspective, the Institute for the Future (2009) defined blended-reality as the blending of physical and digital information and processes that permeate every area of human lives (i.e. health, social, financial, recreational, civic, and personal) engaging people in new kinds of deeply immersive digital sensory experiences. A person in a blended-reality environment interacts in real-time with two interconnected environments (physical/local and virtual/distant) extending them to work as if they were one, by blending traces of one into the



(a) Extended space (b) Reflected space

Figure 2.17: Blended-reality implementations, image courtesy Delgado-Kloos (2011)

other unconsciously (often seem as simultaneously) (Applin and Fischer, 2011). The way to achieve this is through the creation of immersive experiences.

Classification	Description
Tactical immersion (sensory-motoric)	Happens when performing tactile operations that involve skill without reasoned thinking.
Strategic immersion (cognitive)	Associated with mental challenges to optimise a situation.
Narrative immersion (emotional)	Happens when individuals care about the characters in a story and would like to know how it ends.
Actional immersion	Enables an individual to have experiences which have novel, intriguing consequences.
Symbolic immersion	Involves the triggering of semantic and psychological associations via the content presented. Similar to narrative immersion.
Sensory immersion	Replicates the experience of a remote location via haptic feedback
Spatial immersion	When an individual feel that a simulated world looks and feels “real” and he or she is really “there” (known as Presence)

Table 2.2: Types of Immersion

Immersion has been described in many different ways and contexts (table 2.2). Dede (1995) defined immersion as the “subjective impression that a user is participating in a ’world’ comprehensive and realistic enough to induce the willing suspension of disbelief”. Ijsselsteijn (2006) stated that is as “a set of physical properties that give rise to presence”. Slater and Wilbur (1997) described immersion in terms of the technology used to create an inclusive (the extent to which physical reality is shut out), extensive (the range of sensory modalities accommodated), surrounding (the extent to which this virtual reality is panoramic rather than limited to a narrow field) and vivid (the resolution, fidelity, and variety of energy simulated within a particular modality (e.g. the visual and colour resolution)) illusion of reality to the human senses. This definition is more focused to exclusive environments (i.e. virtual reality), that exists on top of the physical world, rather than mixed reality environments. At a physiological level, immersion can be classified in three categories (Adams, 2004; Bjork and Holopainen, 2005; The Immersive Learning Research Network, 2015):

- **Tactical immersion (sensory-motoric)** is defined as performing tactile operations that involve skill without reasoned thinking. Similar to when a person is concentrated in a task and his body response is immediate via reflex movements.
- **Strategic immersion (cognitive)** is associated with mental challenges to optimise a situation. Chess players are an example of this type of immersion.
- **Narrative immersion (emotional)** depends on narrative, and it happens when individuals care about the characters in a story and would like to know how it ends. Books and films are example of this type of immersion.

Additionally, Dede (1995) classified immersion in three types:

- **Actional immersion** enables an individual to have experiences which have novel, intriguing consequences. For example, when a baby is learning to walk.
- **Symbolic immersion** involves the triggering of semantic and psychological associations via the content presented. For example, reading a horror novel

at midnight in a strange house builds a mounting sense of terror, even though one's physical context is unchanging and rationally safe. This is similar to narrative (emotional) immersion described before.

- **Sensory immersion** replicates the experience of a remote location via haptic feedback.

Sensory immersion, could be compared to **spatial immersion**, which occurs when an individual *feel* that a simulated world looks and feels "real" and he or she is really "there" (known as Presence) (The Immersive Learning Research Network, 2015).

Presence, or the sense of being in a place or environment has been widely discussed in the literature (Loomis, 1992; Sheridan, 1992; Steuer, 1992; Schroeder, 1996; Slater and Wilbur, 1997; Lombard and Ditton, 1997; Witmer and Singer, 1998; Yoh, 2001; Ma and Nickerson, 2006; Ijsselsteijn, 2006). Is the key concept that allows defining virtual reality in terms of human experience rather than technological hardware; however, it is directly dependant on the perceptual feedback the user receives via the appropriate technology (Steuer, 1992; Ijsselsteijn, 2006). Presence and immersion are logically separable, yet several studies show a strong empirical relationship, as highly immersive systems are likely to engender a high degree of presence for the participant (Ijsselsteijn, 2006). Lombard and Ditton (1997) based on the commonalities of different conceptualisations of presence, define it as "the perceptual illusion of non-mediation". This illusion can occur in two distinct ways: a) the medium can appear to be invisible or transparent and function as would a large open window, with the medium user and the medium content (objects and entities) sharing the same physical environment; and b) the medium can appear to be transformed into something other than a medium, a social entity.

Sheridan (1992) identified three types of presence: physical, telepresence, and virtual. Physical presence is associated with physical environments and understood as "physically being there." Telepresence is "feeling like you are actually there at the remote site of operation" (Ijsselsteijn, 2006), and virtual presence is "feeling like you are present in the environment generated by the computer" (Ma and Nickerson, 2006).

In multidimensional spaces, such as the ones presented in figure 2.17, it might be possible to experience two or more types of presence at a time. For example, in an extended space such as the one presented in figure 2.17a, an individual can experience physical presence when touching the physical object, and virtual presence when the object "crosses" to the virtual side. In a reflected space (fig. 2.17b) this feeling could be simultaneous as all the actions, and even the user itself, are reflected in real-time in both spaces, creating a dual physical/virtual presence feeling. This creates an extended presence, from their physical location into digital worlds (Benyon, 2012a).

2.2.2 Collaboration in distant multidimensional spaces

In collaborative activities in which two or more people share one common virtual world but different local realities and, possibly additional virtual environments, interoperability becomes more complex. Applin at al. proposed the term PolySocial Reality (PoSR) for this situation from the human interaction group perspective (Applin and Fischer, 2011). PoSR describes the aggregate of all the experienced "locations" and "communications" of all individual people in multiple networks at the same or different times (Applin and Fischer, 2012). Slater and Wilbur (1997) suggested that presence may be even more essential for interpersonal interactions in shared virtual environments than for single-user applications. In this regard, presence can have two classified conceptualisations: physical presence and social presence. Co-presence (fig. 2.18) is the sense of "being together in a shared space at the same time", combining physical and social presence (Lombard and Ditton, 1997; Ijsselsteijn, 2006). Lombard and Ditton (1997) present the importance of the commonalities between the two groups, however Ijsselsteijn (2006) points an important difference: communication. Communication is a key point to social presence, unnecessary for creating a sense of physical presence. A medium can provide a high degree of physical presence without having any features for communication between individuals (e.g. a film). Conversely, an individual can experience a certain amount of social presence (or the "nearness" of communication partners) using applications that supply only a minimal physical representation (e.g. telephone, chat software, instant messaging applications). Thus, providing with communication features is indispensable to achieve co-presence in multidimensional spaces.

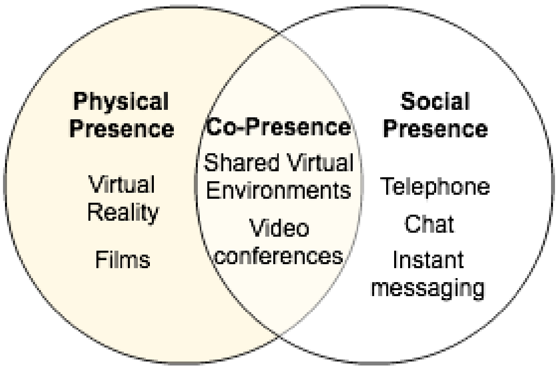


Figure 2.18: Co-presence (Ijsselsteijn, 2006)

From the technological point of view, collaboration in blended-reality spaces represent an important challenge, especially when connecting users in distant environments. To do so, it is necessary to describe the physical and virtual world in terms of the elements that will share the blended-reality environment (i.e. objects, users), the structure of the objects' relationships (topology of the space) (fig. 2.19), and the changes that take place in the space (dynamics of the space), creating recognizable and understandable correspondences between the physical and digital (Benyon, 2012a; Benyon et al., 2012).

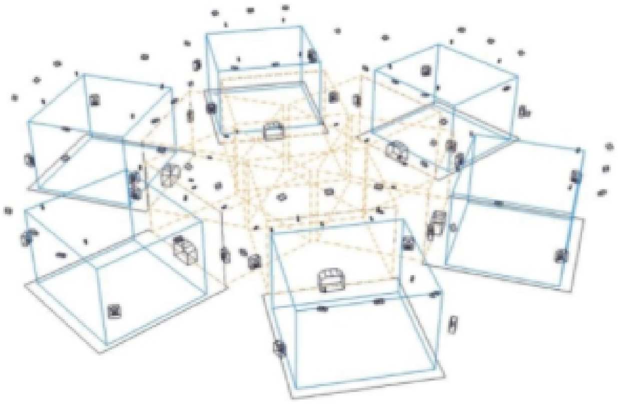


Figure 2.19: Multiple multidimensional spaces interconnected, image courtesy Delgado-Kloos (2011)

2.3 Discussion

The examples of multidimensional spaces presented in this section represented different interactions between users/objects and the environment they belong, either virtual or physical. Figure 2.20 summarises those interactions. Unidirectional communication happens when actions from one environment are reflected in the other (affecting one or more users) but the feedback is not reciprocal. One example is the ISO/IEC 23005 standard specification, as it reflects haptic feedback based on actions happening in the virtual world, but it does not allow the modification of virtual environments (e.g. 4D movie), thus no dual-reality exists in such environments. Another example can be found in traditional TUIs (e.g. a joystick), where the action executed in the physical (e.g. pressing a button) has an effect in a virtual environment (e.g. a video game) and can be followed by all the players in the session, but an event in the virtual world would not modify the physical space. Moreover, such implementations try to create immersion in one (usually virtual) space only.

Bidirectional communications between virtual and physical worlds, involve the creation of blended-reality spaces where interaction happens in both worlds reflecting the changes in both. Those changes can be represented as 2D elements

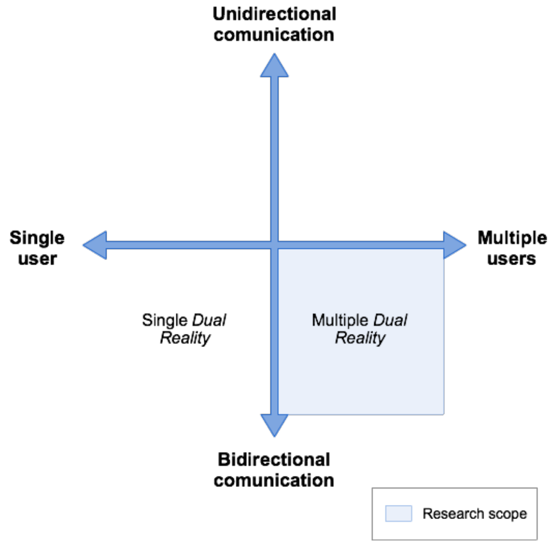


Figure 2.20: User-environment interactions

such as graphs or charts (e.g. smart home applications such as Samsung's Smart Home [6] or the Phillips Hue system [7] allow to change the physical status of objects via a software application), metaphors (e.g. data pond at MIT's DualReality Lab) or mirrored to 3D virtual objects (e.g. VirCA project's virtual robot or the appliances at Essex' Intelligent Virtual Household). In these examples the relationship one-virtual object mirrored to one-physical object allows the creation of dual-reality states. A benefit of implementing these mirrored objects in collaborative environments with multiple users, is that the physical object can be remotely controlled via the virtual mirrored element as presented in VirCA's robot or Vallance's LEGO robots. This represents an advantage for collaborative work between dispersed teams, where the use of specialised equipment might be restricted to specific geographical locations. However, some limitations for the use of current shared physical-virtual object implementations are:

- They have no possibility of modification or being regrouped into new shapes/services by end-users, or adding additional virtual/physical parts to change their configuration (i.e. additional sensors/actuators).

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[6] Samsung Smart Home - http://www.samsung.com/uk/smarthome/

[7] Phillips Hue - http://www2.meethue.com/en-gb/

- They are configured to execute just particular actions, such as activate/deactivate single functionality (e.g. switch on/off a light, moving from A to B in the case of the robots), limiting possibilities of collaboration and creation.
- They represent either an object (e.g. a robot) or ambient variables (e.g. wind and lightening in a 4D movie) but not both.
- Collaborative work in current implementations is represented only by remote users following the actions of the mixed-reality object via the virtual representation, or triggering a pre-programmed behaviour as object's programming is done separately using traditional 2D GUI tools (e.g. LEGO's NXT programming IDE).
- When the virtual world is used to connect two distant environments, there is only one physical object available in one of the environments.

This thesis explores collaboration between multiple dispersed users through the creation and combination of multiple physical-virtual mirrored objects, managing and synchronising more than one dual-reality state at a time, and creating relationships between one-virtual object mirrored to multiple-physical objects simultaneously in different locations. Additionally, it explores possibilities for creation by enabling the combination and use of disaggregated services/functions into new functionalities created by end-users. To contextualise this research, the next subsection describes a scenario that situates this research in an educational context where remote students can benefit from the proposed distributed blended-reality environment.

2.3.1 A learning scenario

In the science fiction prototype "Tales from a Pod", Callaghan (2010a) presented "a speculative look at how artificial intelligence and virtual environments might change the nature of future education" (Callaghan, 2010b). Using a collection of small vignettes, the story depicts a future era in which the technological *singularity* has been reached, and machine intelligence and interaction is equal or surpasses that of people; while the world develops in a *hyperreal* environment. Hyperreality is a vision that mixes virtual reality (VR) with physical reality (PR) and artificial intelligence (AI) with human intelligence (HI) allowing seamless interaction between all the parts (Tiffin and Terashima, 2001). In the story, education evolved by merging virtual and physical worlds in immersive personalised experiences supplied by small "cocoons", isolated immersive learning environments enhanced with multi-modal pervasive technology (sound, vision and haptics). Students are provided with engaging (and even addictive) interactive contents within a social network with inter-personnel haptics. Whilst the story delves in the social risks and benefits of such technology, it reflects a number of current trending topics in education, in which the use of technology has increased in recent years, with analysts predicting a global E-Learning market reaching 107 billion dollars by 2015 (Global Industry Analysts Inc., 2015).

Learning environments have evolved from the traditional classroom to the web (e-learning) providing on-demand content allowing learners to gain greater understanding of a topic, stimulating discovery and learning. Learning Management Systems (LMS) such as Moodle[8] or BlackBoard[9], and Massive Open Online Courses (MOOCs) provided by platforms such as FutureLearn[10] supported by University College London, Coursera[11], founded by academics from Stanford University, and edX[12], created by Harvard University and the Massachusetts Institute of Technology (MIT), allow people from all around the world to educate themselves and get official certificates without the need to attend a particular physical

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[8] Moodle - `www.moodle.org`

[9] BlackBoard - `www.blackboard.com`

[10] FutureLearn - `www.futurelearn.com`

[11] Coursera - `www.coursera.org`

[12] edX - `www.edx.org`

location. According to Horn et al. (2011), in 2009 more than 3 million K-12 students in the United States took an online course, compared with approximately 45,000 that did in 2000. Forbes (Husock, 2014) reported in 2014 that the Khan Academy [13], a non-profit educational organisation, had 15 million registered students and nearly 500 million YouTube[14] views, in 70 countries.

The use of video games for education (serious games) and virtual worlds have also increased, with educators and parents using games such as MinecraftEdu [15], a version of the digital game that promotes imagination as players build various structures out of cubes, or SimCityEDU [16], an educational version of SimCity the popular city-building game, to teach biology, physics, mathematics, social studies, foreign languages among other topics (Short, 2012; Lim and Kho, 2013; Schifter and Cipollone, 2013; Ekaputra et al., 2013; Gaber, 2007; Squire, 2003). These trends do not represent the end of classroom education, as schools and universities provide social interaction and professional skills that technology has not been able to replicate yet, however, with the use of innovative virtual and mixed reality environments, the gap is getting closer, represent better opportunities particularly for distance learners.

The New Media Consortium (NMC), a non-profit association of more than 250 higher education institutions, museums and companies that conducts research into emerging technologies, presented its 2016 Horizon Report in Higher Education (Johnson et al., 2016) long-term, mid-term and short-term trends in education (fig.2.21). Augmented and Virtual Reality, along with adaptive technologies in learning and makerspaces are among the trends' list that reflect the mixing of realities experimented in other aspect of our society, such as communication and entertainment.

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[13] The Khan Academy - `www.khanacademy.org`
[14] YouTube - `www.youtube.com`
[15] MinecraftEdu - `www.education.minecraft.net`
[16] SimCityEDU - `www.simcity.com`

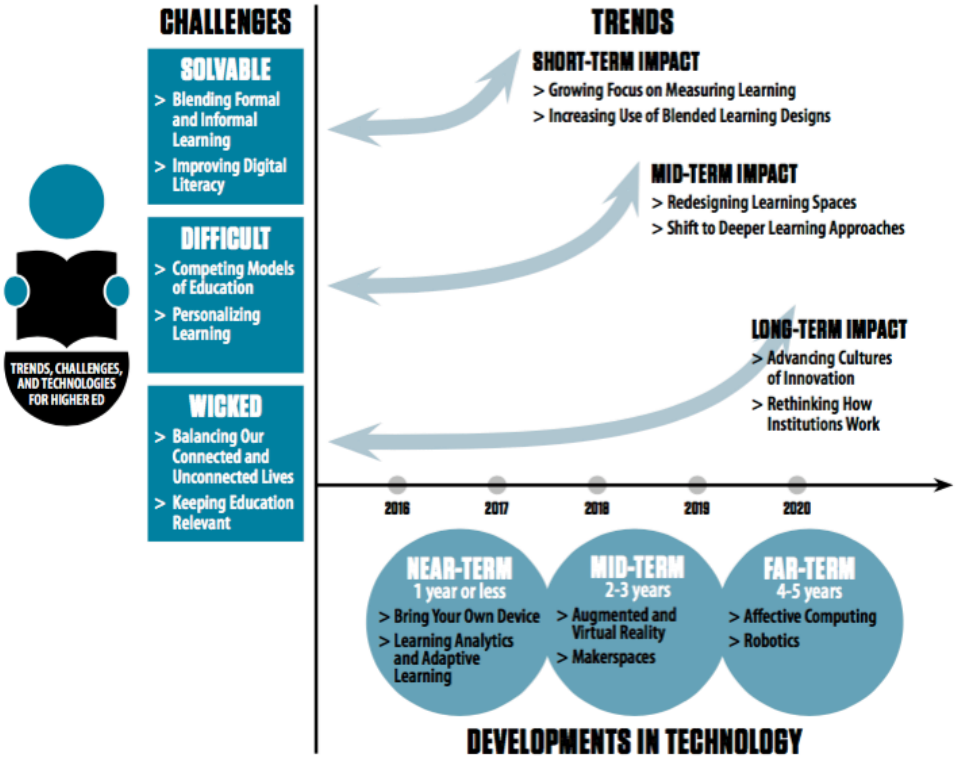


Figure 2.21: Trends, challenges and technologies for higher education, image courtesy Johnson et al. (2016)

An important aspect of education, particularly in science and engineering, involves hands-on experimentation (Ma and Nickerson, 2006; Gomes and Bogosyan, 2009; Magin and Reizes, 1990; Clough, 2002; Nersessian, 1989). Current options for virtual laboratories involve: a) watching online videos of experiments, b) remote off-site experiments that can be triggered using software interfaces, and c) three-dimensional (3D) simulations and microworlds, understanding this last as a virtual environment in which a student can explore alternatives, test hypotheses, and discover facts that are true about that world (Rieber, 2005).

Whilst physical and virtual laboratories can achieve similar objectives, such as exploring the nature of science, developing team work abilities, cultivating interest in science, promoting conceptual understanding, and developing inquiry skills (Bonde et al., 2014), yet they also have specific affordances (de Jong et al., 2013). Physical laboratories provide students with the possibility of working with physical equipment, which emphasize design and problem-solving skills, dealing with unanticipated events, such as measurement errors (de Jong et al., 2013). Additionally, they offer the possibility to engage in teamwork and collaboration with peers and colleagues. However, they are not accessible for distance learners, and usually the monetary cost of setting up specialised laboratories is very high.

Virtual experiments offer cost-effective alternatives to physical laboratories giving students the opportunity to use experimental systems that are beyond their reach. Additionally, they can simplify learning by highlighting specific information and removing confusing details (Trundle and Bell, 2010), such as aberrations in the equipment or unanticipated consequences; or modifying model characteristics, such as the time scale, making the interpretation of certain phenomena easier (de Jong et al., 2013).

Although many well-controlled comparison studies report no differences between physical and virtual laboratories (de Jong et al., 2013; Triona and Klahr, 2003; Klahr et al., 2007; Wiesner and Lan, 2004), due to its nature, virtual experiments are more focused in supporting the acquisition of conceptual knowledge whereas physical laboratories have advantages in allowing students acquire some practical skills such as problem-solving thinking and teamwork (Ma and Nickerson, 2006; de Jong et al., 2013).

Research in different topics such as microbiology (Huppert et al., 2002), physics (Zacharia et al., 2008; Olympiou and Zacharia, 2012), engineering (Jaakkola et al., 2011; Kolloffel and de Jong, 2013), chemistry (Martínez-Jiménez et al., 2003) have shown that students who conducted both physical and virtual experiments outperformed those in the physical alone and virtual alone conditions, capitalising on the benefits of each approach (de Jong et al., 2013). These experiments allowed classroom-based students to alternate classes, with one in the virtual setting testing conceptual knowledge and one in the physical laboratory with tangible equipment. Although this approach of alternate realities (virtual lab / physical lab) it seems to be an optimal solution for classroom-based students, it does not consider students with limited access to the physical classroom, such as distance learners, which in 2012 represented one in 10 at postgraduate level, and around 16% at undergraduate level in the UK (Chalabi, 2014). The Open University (2015) reports around 200,000 students currently enrolled in their programs.

A possible scenario for distance learners to have access to the physical laboratory and the virtual activities, could be the integration of both in a blended-reality laboratory able to connect identify elements in the environment and map them back to their virtual representations in real-time, enabling global learning sessions and cross-cultural collaboration, and taking the advantages of both learning settings.

2.4 Summary

This chapter started by introducing fundamental concepts in mixed-reality and related paradigms (i.e. augmented reality, augmented virtuality, dual-reality), identifying the differences between them, and presenting current research in multidimensional spaces. Multidimensional spaces, were defined in this chapter as hybrid environments where physical and virtual worlds couple together to create the seamless illusion of continuity. Is this illusion of continuity what represents one of the biggest challenges to create blended-reality spaces where users can achieve a true feeling of immersion, addressing the absence of mind from one world when being in the other (”vacancy problem”).

A great number of multidimensional spaces are primarily designed to be operated between users situated on the local space, adding a constraint to physical resources and limiting possibilities of collaboration with remote users. Is the creation of this community spaces with real-time shared content and resources what motivates this research, extending one local mixed-reality space into one large interconnected blended-reality space able to allow users to perform activities in virtual/real-local/distant dimensions at the same time. To illustrate the use of such environment, this chapter described a learning scenario for remote students, allowing collaboration on physical laboratory activities.

The following chapter explores in detail educational concepts, which along with the theory introduced in this section, represent the foundations for a mixed reality framework that enable the use of physical and virtual devices for science and engineering collaborative laboratories, allowing distance learners to work in hands-on activities, based on a blended-reality approach.

Chapter 3

Technology-based Learning and Collaboration Environments

> *"For the things we have to learn before we can do them, we learn by doing them."*
>
> — Aristotle (384 – 322 BC)

Chapter 2 presented a background on mixed-reality and related terms; additionally, it introduced an educational scenario for collaboration in multidimensional spaces. Based on that scenario, this chapter explores the current use of technology in education, reviewing theories involved in the process of learning and affordances of technology-enhanced learning environments, focusing on laboratory activities for distance learners. This section also introduces the concept of Immersive Learning and the applications of mixed-reality in learning. Finally, it presents the pedagogical challenges in the use of collaborative mixed-reality learning environments for remote participants, highlighting the importance of deconstruction as a core element of this research.

3.1 Different approaches to the Learning paradigm

Learning is an innate characteristic of human beings that involves the processing of cognitive, emotional, and environmental influences and experiences for acquiring, enhancing, or making changes in personal knowledge, behaviours, skills, values, and world views (Ormrod, 2011; Illeris, 2004).

Throughout the years several philosophers, psychologists and educators had elaborated diverse hypotheses describing the learning process. Three epistemological theories had been recognised as the main basis for other schools of thought:

- In **Behaviourism**, learning is the result of the acquisition or change in behaviour, modified through a conditioning process. The bases of the conditioning process are the principles of contiguity (the proximity in time of two or more conditioning event necessaries for construct a learning bond) and reinforcement (the repetition of a "stimulus" immediately or shortly after the occurrence of the behaviour to increase the likelihood of behaviour repetition).
- The **Cognitivist** paradigm focuses on brain-based learning, where the functioning of human memory is the main base to promote learning. The memory is an active system which organises and processes information. This theory emphasizes the learner over the environment, as the behaviourists do.
- For **Constructivism**, learning is seen as an active personal process in which the learner actively constructs or builds ideas and internalises concepts, rules, and general principles which may consequently be applied in a practical real-world. The role of the teacher is to be a facilitator, encouraging students to discover principles for themselves and to construct knowledge by working to solve realistic problems.

The work presented in this thesis focuses on constructivist approaches, which explains that the environment is a key factor in the construction of knowledge, especially because learning occurs on real-life social situations and is based on problem-solving and critical thinking, integrating pre-existing theoretical constructs with new experiences. Constructivism, as a philosophy of education, is based on three fundamental principles (Dalgarno, 2002):

- "Each person forms their own representation of knowledge and consequently that there is no single "correct" representation of knowledge", based on Kant's work and adopted later by Dewey (Von Glasersfeld, 1984).
- "Learning occurs when, during active exploration of the knowledge domain, the learner uncovers a deficiency in their knowledge or an inconsistency between their current knowledge representation and their experience", a principle attributed to Piaget's studies of children's cognitive development (Piaget, 2003).
- "Learning occurs within a social context, and that interaction between learners and their peers is a necessary part of the learning process", a principle attributed to Vygotsky (1980) (social constructivism).

Driscoll (2005) and Almala (2006) summarises Constructivism using five components: a) a complex and relevant learning environment, b) social interaction, c) multiple models of learning, d) ownership of learning and e) self-awareness and knowledge construction.

Thus, in Constructivism, students need to be self-motivated and responsible of their learning process, giving them the role of producers of their own knowledge by challenge them with tasks that are appropriate to their skill level. Here, learning is produced by trying different solutions, experimenting possible outcomes and making their own conclusions. Another important aspect is that learning is a social process, where collaboration among learners takes much importance, and the role of teachers changes, making them facilitators instead of instructors, and where context is important in learning activities. Constructivism has been the foundation of other learning theories, such as Constructionism, proposed by Papert et al. (1991), in which the acquisition of knowledge is generated by active behaviour, embodied in the construction of meaningful tangible objects in the physical world, and related to personal experiences and ideas; this opposed to learning in the traditional classroom, in which transmission of knowledge goes from teacher to student based on isomorphic theoretical concepts (described as Instructionism) (Papert et al., 1991; Driscoll and Rowley, 1997). Some critics of constructivist approaches had pointed out that it is heavily focused on individual person's interactions with objects (not people). These observations led to the development of social constructivism (Holton, 2010), which is heavily rooted in Vygotsky's views about the existence of an inherent social nature in learning, representing a shift away from the traditional teacher-centred or lecture-centred education, and is considered as a co-construction in which active participation of the learner is essential (Holton, 2010). Smith and Macgregor (1992) defined Collaborative Learning (also known as co-creative learning) as an umbrella term for a variety of educational approaches that encourage the creation and reinforcement of learning involving joint intellectual effort by students, or students and teachers together, mutually searching for understanding, solutions, meanings, or creating a final deliverable. Is based on the constructivist view of shifting away from the typical teacher-centred or lecture-centred education, however, they remark that instructional learning usually does not disappear and instead it provides material for students' discussion and active work (Smith and Macgregor, 1992). The use of mixed approaches between structured teacher-centred instruction and student-centred learning is a response to an "idealised" vision of constructivism in which learning occurs as a "pure unguided discovery" (Holton, 2010). Holton (2010) pointed that constructivist-inspired educational approaches such as problem-based learning (a learning strategy that implements the constructionist approach of learning as a side-effect of creative problem solving (Ngeow and Kong, 2001)), or laboratory activities still require a significant amount of guidance and structure, either from the instructor/facilitator (Hmelo-Silver and Barrows, 2006) or embedded in the learning environment (De Jong and Van Joolingen, 1998; De Jong et al., 1999). Another problem found in constructivism is the difficulty of assessing student learning, and knowing what students understand (Holton, 2010; Von Glasersfeld, 1984). Other criticism of this theory point that cognition and perception are active processes such as learning, and therefore all of them represent some kind of construction (Noddings, 1995).

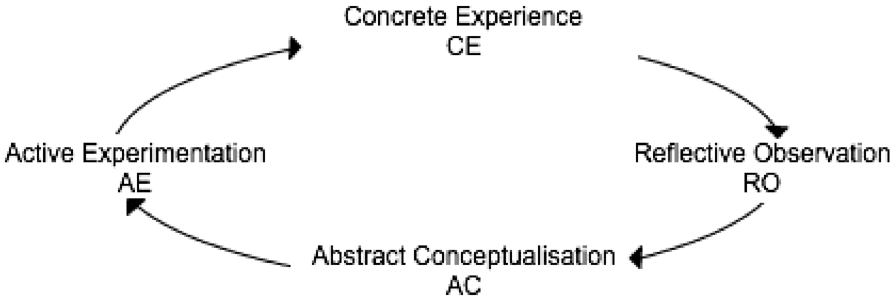
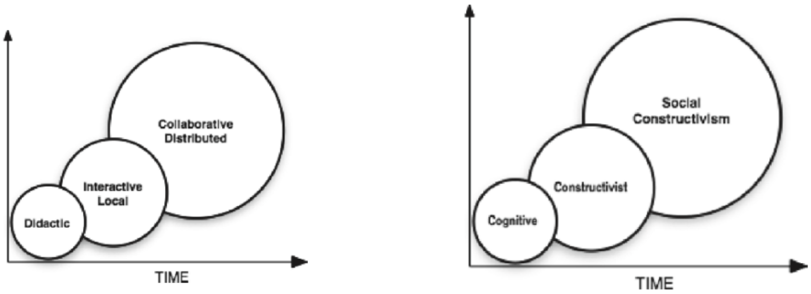


Figure 3.1: Kolb's Learning Cycle (Kolb, 1984)

Experiential Learning (Kolb, 1984) (also known as "learning by doing"), Enactivism and Embodied Cognition (Rosch et al., 1992) are other theories grounded on the premise that knowledge is created through the experience or interaction with the environment, having learning as outcome. In enactivism, thinking and cognition are grounded in bodily actions rather that in objects ("it is not knowledge-as-object but knowledge-as-action" (Begg, 2013)). Some authors (Holton, 2010; Proulx, 2008; Barsalou, 2008; Pecher and Zwaan, 2005) have suggested that enactivism combines concepts from cognitive science and constructivism, and thus could be considered an extension of constructivism. Embodiment is the enactment of knowledge and concepts through the activity of learners' bodies (Lindgren and Johnson-Glenberg, 2013). Holton (2010) points that embodied cognition and enactivism are usually oversimplified in the design of learning environments, by using anthropomorphic representations (e.g. avatars), making something "hands-on," using gestures, or being physically active during learning and teaching.

To Kolb (1984), learning is considered as a “process whereby knowledge is created through the transformation of experience” (Experiential Learning). He described the learning cycle in four stages (fig. 3.1), pointing that effective learning requires experience a phenomenon (concrete experience (CE)) and reflect about the causes and consequences (reflective observation (RO)), before create abstract concepts to represent it (abstract conceptualisation (AC)), which later on need to be tested to assure their validity (active experimentation (AE)). A key factor that differentiates Constructionism from Experiential Learning, is that it favours learning by building with *concrete materials* rather than abstract propositions, adding then the importance of the context where the learner is consciously engaged in constructing (Papert et al., 1991).

Figure 3.2 illustrates the trends in learning paradigms over time, changing from local cognitive, to the current era of collaborative distributed social constructivism, impulsed by the open possibilities that technology-enhanced learning environments provide.



(a) Trends in pedagogical stances over time

(b) Development of learning paradigms over time

Figure 3.2: Paradigm shifts, images courtesy Nicholson (2008)

For instructors and learning designers, being aware of learning theories is important because they situate the learner and learning environment. Furthermore, they guide designers in identifying what is important to consider for the design of learning activities and environments (Kirkley and Kirkley, 2004).

3.2 Deconstructionism

Deconstructionism is based on Papert's Constructionist (1991) ideas of creating tangible artefacts helps to create understanding of the world. Deconstructionism is focused on the opposite process, of the deconstruction of real-life artefacts to gain knowledge. It is important not to confuse this term with the philosophical stream of the same name, created by the French philosopher Jacques Derrida, or with Deconstructivism which is a branch of postmodern architecture that began in the late 1980s.

Deconstructionism is a familiar behaviour in people, an example of it happens when a child breaks in pieces a toy just out of curiosity to see what is inside and/or how it works. Similarly to the relation between constructivism and constructionism, deconstructivism in education, is about the decomposition of ideas and relations, while deconstructionism is about the deconstruction of a tangible artefact (Boytchev, 2014).

It can be seen as a problem-solving technique, formed by two activities: analysis and design. The process of analysis involves decomposing problems into simpler sub-problems, typically with the help of formalized rules (Resnick and Ocko, 1990). The design process seeks to satisfy a given set of constraints rather than obtaining an optimal solution, due to the ill-structured nature of the problem goals, which needs to be defined as part of the solving task (Resnick and Ocko, 1990). An example of its use as a problem-solving technique can be found in software engineering, where functional decomposition, and modularisation are strategies to deal with the cognitive complexity of software systems, and involve recursively breaking down a problem into sub-problems until these become simple enough to be solved directly (Bjø rner, 2007; Wang, 2007).

Deconstruction has been used extensively in education for teaching and learning. On the teaching perspective, Macdonald (2012) suggested that considering teaching as dividable tasks would help students to gain better understanding of those tasks. The design of learning activities using standards such as the one proposed by the Instructional Management Systems (IMS) Global Learning Consortium[1] is a practical implementation of this idea, dividing tasks into smaller components to implement them in the classroom.

On the learning perspective, Self (1997; 2005) explored deconstructionism applied to learning computer science fundamentals. He explained that the deconstructionist perspective emphasises that learning comes from "differences between the model and the situation where it is applied, rather than from similarities, which the abstractions of rationalism emphasize" (Self, 1997). In another example, Resnick (1990; 1990a) presented a computer-based robotics environment (LEGO/Logo) focused on learning through the design phase of the problem solving process. Using LEGO[2] blocks, and "Logo blocks" (code snippets) students could build tangible objects. Logo blocks are based on Papert's Logo Programming Language (Papert, 1980; Harel and Papert, 1991), a text-based computer language designed specifically for children. LEGO/Logo evolved later into Scratch[3] a visual programming environment focused on children and teenagers designed to teach computer programming using animated stories and games (Resnick et al., 2007, 2009; Maloney et al., 2010).

Boytchev (2014) presented the process of learning through construction in two phases: a) Deconstruction (Analysis), when a piece of knowledge about an object or a phenomenon is decomposed into meaningful-for-the-learner smaller entities

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[1] IMS Global Learning Consortium - `www.imsglobal.org`

[2] LEGO Education - `www.education.lego.com`

[3] Scratch - `www.scratch.mit.edu`

and; b) Construction (Design), using those entities as building blocks to construct the personal knowledge. An optional phase happens when the learner rearranges the entities in a different form to the initial one, producing new knowledge (Creativity) (fig. 3.3). This process is an iterative process, as usually it is necessary to repeat it several times before reaching a final result. Boytchev reported that problems occur predominantly in the deconstruction phase, due to "the excess cognitive load or a cognitive barrier", having as a result a failure of students to relate a new concept to their previous knowledge, thus failing in decomposing that new knowledge (Boytchev, 2014). The same problem has been reported by Resnick and Ocko (1990) with learners having difficulties of decomposing problems into simpler entities ("decomposition bugs").

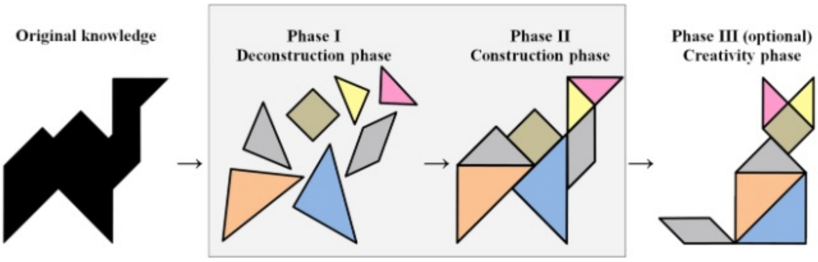

Figure 3.3: Phases of learning through construction, image courtesy Boytchev (2014)

Boytchev (2014) listed three key factors that could allow deconstructionism reshaping how people teach and learn: digitality, ubiquity and transparency.

- Digitality/Digitalism - Digitality (Negroponte, 1995) refers to the condition of living in a digital culture, where most of the human activities are supported by technology due to its immediacy, ubiquity and participatory nature (e.g. digital communications, digital media, etc.). In Education, the dominance of learning by manipulation of virtual entities deposes key principles of Deconstructionism. Ironically, advances in technology could allow the merging of both, physical artefacts with digital entities.

- Ubiquity - Ubiquitous learning can span not only over space and time, but also through any media, allowing students to have their own imprint on the learning process. Ubiquitous learning (u-learning) ”enables anyone to learn at anyplace at any time”, with adaptive learning environments based on context-aware technology (Bruce, 2007; Yahya et al., 2010; Zhao et al., 2010), supported mainly by the increasing use of mobile devices in education (Wang and Ng, 2012). The phenomenon of u-learning creates a similar shift in teaching, becoming it ubiquitous (u-teaching). The relation between u-teaching and u-learning shares the same relation of deconstructionism and constructionism. The main goal of u-teaching is the decomposition of learning content that renders it u-learnable, a challenge of unknown complexity.
- Transparency - Technology is getting more transparent and less obtrusive, as predicted by Weiser (1999), encapsulated in small, yet smart devices. Boytchev (2014) states that “the current model of education creates an image of the world through which people learn about the world. In a transparent future education people will learn directly from the world around them using all their senses”. The use of technologies such as virtual, augmented and immersive realities have the potential of allowing students to create learning *experiences.*

3.3 Learning and collaboration in technology-enhanced environments

Technological innovation is present in every aspect of our life, and currently it is enabling and promoting a change in teaching and learning methods. The use of technology in education, is experiencing rapid change transitioning from the traditional classroom-based schema to distance learning, media learning and recently and with the exponential growth of internet to electronic learning (e-learning), ubiquitous learning (u-learning) and smart learning; understanding the term e-learning as all forms of electronically supported learning and teaching (Rosenberg, 2000); u-learning as the possibility of having access to adaptive learning environments in various contexts and situations (Bruce, 2007; Yahya et al., 2010; Zhao et al., 2010); and smart learning as the combination of u-learning with a cloud computing infrastructure able to offer on-demand ubiquitous personalized everywhere at any time (Scott and Benlamri, 2010; Kim et al., 2011). According to the National Institute of Standards and Technology, cloud computing is a model which allows on-demand access to massive computing resources by virtualisation (Mell and Grance, 2011). Table 3.1 summarises some of this changes.

Dede (2005a) analyses this from the socio-cultural perspective, where he defines individuals born between 1946-1964 (Baby Boomers) as passive observers or "consumers", with television being the dominant medium shaping their characteristics, providing a just one-way channel of communication (or "push" approach as defined by Brown (2000)); whereas, individuals born after 1982 (Millenials) are portrayed as active seekers of information or "creators", due to the influence of computers and primarily the Internet (the two-way "push and pull" approach (Brown, 2000)), which has allowed the creation of different forms of self-expressing and social interaction among individuals via the *cyberspace*.

E-Learning has also experienced similar changes, from web 1.0 where passive learners consumed content previously created and unalterable, such as web pages, online courses or audio podcasts, to a co-creative web 2.0 where remote learners work actively on the creation of collaborative learning resources (e.g. blogs, wikis, forums, etc.)(McLoughlin and Lee, 2010) shared freely through new open licence models such as the Creative Commons licence[4]. This change reflects the general constructivist (not constructionist, as the deliverables produced are virtual rather

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[4] Creative Commons - `www.creativecommons.org`

Era	Focus	Educational characteristics
1975-1985	Programming; Drill and practice; Computer-assisted learning – CAL.	Behaviourist approaches to learning and instruction; programming to build tools and solve problems; local user-computer interaction.
1983-1990	Computer-Based Training; Multimedia;	Use of older CAL models with interactive multimedia courseware; Passive learner models dominant; Constructivist influences begin to appear in educational software design and use.
1990-1995	Web-based Training	Internet-based content delivery; Active learner models developed; Constructivist perspectives common; Limited end-user interactions.
1995-2005	E-Learning	Internet-based flexible courseware deliver; increased interactivity; online multimedia courseware; Distributed constructivist and cognitivist models common; Remote user-user interactions.
2005 - to date	U-Learning	3D multi-user virtual environments, mixed-reality and augmented reality in learning, multi-dimensional spaces and intelligent contexts
2010 - to date	Smart Learning	U-Learning with a cloud computing infrastructure; High availability of services; Accessible regardless of the physical location of the user

Table 3.1: The changing focus of educational technology (adapted from Nicholson (2008))

than tangible objects) perspective of using self-motivated collaboration in meaningful settings, in this case virtual environments, to create knowledge; whilst the web 1.0 has some similarities with the traditional Instructionism paradigm, where the learning is distributed in one-way, from teacher (or in this case e-learning resources) to student, as can be experienced in a number of online courses.

A survey presented by The Economist Intelligence Unit (2008) showed that although online courses were the most used resource (71%), respondents estimated an increase in the use of web 2.0 tools (wikis, blogs and collaboration software) within the next 5 years. In 2012, the US National Center for Education Statistics confirmed that tendency, reporting that one in ten students were enrolled exclusively in online courses (Ginder and Stearns, 2012; Johnson et al., 2015). More recently, FutureLearn[5], a Massive Open Online Course (MOOC) platform owned by the Open University in the UK, had 370,000 students enrolled for an English online course, making it the biggest online course to date (Coughlan, 2015). However, the use of web 2.0 tools, such as social media in educations is constantly increasing. Similarly, the report “Learning in a Digital Age” presented by JISC[6], a non-public organisation that supports research in educational technology for higher-education within the UK, discussed the growing use of blogs, wikis, podcasting, social networking, and other tools as vehicles to deepen learning (Jisc, 2012; Johnson et al., 2015). Social media has transcended its initial purpose of building social connections due to people increasingly rely on their newsfeeds to get information from the real world, such as major global events, and using it as a way for sharing and garnering feedback on personal creative works (Johnson et al., 2015; Boller, 2014).

The use of online technology has opened up opportunities for students, regardless time or space. On-demand content allows learners to have 24/7 access

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[5] FutureLearn - `www.futurelearn.com`

[6] JISC - `www.jisc.ac.uk`

to materials and resources, and collaborating in synchronous (e.g. chat, video conferences, etc.) and asynchronous (e.g. forums, wikis, etc.) way with their peers, giving distance learners possibilities for social interaction, a key element on the learning process (Smith and Macgregor, 1992; Dillenbourg et al., 2009; Nicholson, 2008). This sense of community and belonging provides conditions for free and open dialogue, critical debate, negotiation and agreement, foundations of education (Garrison and Kanuka, 2004).

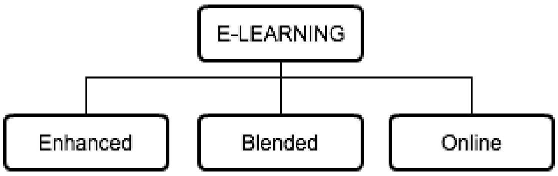

Figure 3.4: A continuum of e-learning (Garrison and Kanuka, 2004)

Thus, the traditional learning paradigm has shifted to a *blended learning* scenario, with the possibility of combining traditional classroom methods with computer-mediated activities. Garrison and Kanuka (2004) defined a continuum of e-learning (fig. 3.4) with face-to-face (F2F) enhanced classrooms in one end and complete online experiences on the other, where Blended Learning is situated on any point that mixes these two approaches. The term Blended Learning, has been defined in many contexts, from the combination of various pedagogical approaches, to the combination of any form of instructional technology (e.g., educational television, online courses, etc.) with F2F instructor-led training (Driscoll, 2002; Graham, 2004). However, the current shift in Education towards the constructivism paradigm, along with the change in learners, following the creative possibilities of the web 2.0, should lead us to define a broader definition for Blended Learning, mixing both meanings, and including the possibility of students' creation of their own learning materials. Thus, within this thesis the term Blended Learning is understood as the thoughtful integration of F2F instructional learning experiences with computer-mediated learning experiences. This computer-mediated experiences can include: a) technology-based instructional material (e.g. online courses or videos) and/or b) constructivist activities that involve the creation of student-owned learning materials. It also includes what Dede (2005a) calls "Distributed learning", which describes educational experiences that combine F2F teaching with synchronous and asynchronous mediated interaction. Here, is important to remark the term *learning experiences*, because the use of modern technologies, such as virtual reality or mixed-reality, has opened up limitless design possibilities and applicability to so many contexts. Therefore, the use of Blended Learning in the learning design represents a fundamental reconceptualization and reorganisation of the teaching and learning dynamic (Garrison and Kanuka, 2004), and introducing the great amount of complexity in the creation of *learning experiences*.

When participants of the The Economist Intelligence Unit (2008) survey were asked about likely scenarios in the evolution of higher education, they confirmed this paradigm shift in education with 60% stating that online learning will be a fundamental component of the classroom experience, and the same percentage said that the perception of the college campus will shift from one-dimensional (physical) to multi-dimensional (physical and online), modifying the learning environment. Technologies such as mobile and wearable devices, virtual reality, the Internet-of-Things, augmented reality, context-aware among others are changing the learning environment, understanding a learning environment as the place, location or setting, not limited to a physical location, in which learners have the opportunity to conceptualize information that is useful within the real world (Chen et al., 2008; Crawford et al., 2010). The 2015 New Media Consortium Report in Higher Education (Johnson et al., 2015) states that the increasing use of Blended Learning is redesigning the learning spaces, estimating an adoption of wearable devices between a time span of two to three years, and the use of adaptive learning technologies and the Internet-of-Things in between four to five years. Figure 3.5 illustrates the changes in the use of technology towards the creation of multi-dimensional learning environments by showing the relation between modes of learning and the Milgram's Reality-Virtually continuum (Milgram and Kishino, 1994) within an adapted version of Garrison's continuum of e-Learning, which includes traditional F2F education, located at the "Reality" extreme of the continuum, and online learning at the "Virtuality" side. This figure also suggests a relationship between enhanced learning with mixed-reality technologies which will be explored in the following subsections.

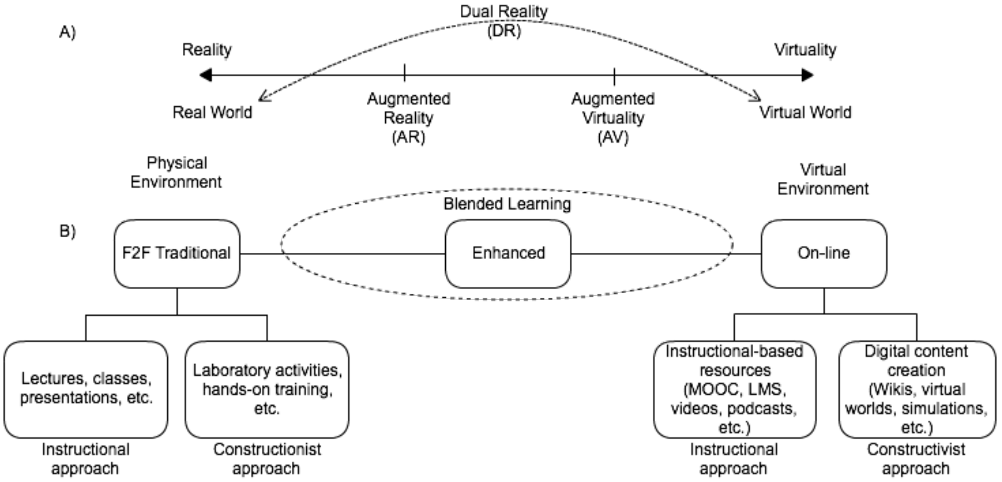

Figure 3.5: Milgram's Reality-Virtually continuum vs Garrison's continue of e-learning (adapted)

3.3.1 Virtual Learning Environments (VLE)

A Virtual Learning Environment (VLE) is any technology-based platform designed to manage and facilitate students' learning activities, through the provision of appropriate content and resources (Stiles, 2000). Dillenbourg (1999; 2000) identified the following characteristics of a VLE:

- They have a delimited set of designed information.
- Educational interactions occur in the environment, turning spaces into places.
- The information/social space is explicitly represented. This representation varies from text to 3D immersive worlds.

- Students are not only active, but also actors. They co-construct the virtual space.
- VLEs are not restricted to distance education. They also enrich classroom activities.
- VLEs integrate heterogeneous technologies and multiple pedagogical approaches.
- Most virtual environments overlap with physical environments.

Virtual learning environments (VLE), used with rich teaching templates and teaching content, help to improve learners' ability for analysing problems and exploring new concepts (Pan et al., 2006). Moore (1995) classified VLEs into three major categories: text-based, desktop and "sensory-immersive VR". Dede (2005a) created a similar classification defining three types of virtual learning interfaces:

- "*World to the desktop*" interface, based on familiar text-based and/or video-based interfaces such as Learning Management Systems (LMS), Massive Open Online Courses (MOOCs), forums, video recorded conferences, etc. which provide instant access to distant experts and archives, enabling collaborations, mentoring relationships, and virtual communities-of-practice.
- "*Alice-in-Wonderland*" multi-user virtual environments (MUVE) interfaces, based on three-dimensional models, in which participants' represented as avatars interact with computer-based agents and digital artefacts in virtual contexts. Additionally, Dalgarno et al. Dalgarno et al. (2002) differentiate them based on the hardware used, calling "desktop virtual environments" those who can be explored using standard PC hardware; and "immersive virtual environments" to those who require specialised hardware (i.e. head-mounted displays). In education, they are commonly known as

three-dimensional Virtual Learning Environments (3D VLEs) (e.g. serious games, virtual worlds in education, etc.).

- Interfaces for "*ubiquitous computing*", based on augmented and mixed-reality, linking virtual resources back to the physical world. These interfaces are characterised the role of "smart objects" and "intelligent contexts" in learning and doing.

Dede (2005a) argues that immersion is the crucial factor that is moving education towards the use of virtual environments and augmented reality, a characteristic that is not attained with "world-to-the-desktop" interfaces, moreover Fowler (2015) affirms that it may bridge technology with pedagogical requirements. However, immersion should not be treated as a unique property, as it is achieved from a complex interaction of representational fidelity and learner interaction, holding a dependency on other aspects of the environment (Dalgarno and Lee, 2010; Hedberg and Alexander, 1994).

3.3.2 Immersive Learning

Teachers and learners have adopted the use of digital tools in education, and they expect to increase their use. The vast majority of tools used in education are text-based, however the use of virtual reality, augmented reality and other immersive technologies are opening opportunities to create new learning experiences combining both ends of the physical - digital spectrum.

Immersive Learning could be defined as the combination of Blended Learning with diverse immersive technology (e.g. interactive 3D graphics, commercial game and simulation technology, virtual reality, augmented reality, rich digital media, etc.) that can support self-directed and collaborative group-based learning activities. The previous chapter, presented the concept of immersion in different contexts and degrees, however, the most commonly used is spatial immersion, which occurs when an individual *feels* that a simulated world looks and feels ”real” and he or she is really ”there” (also known as Presence) (The Immersive Learning Research Network, 2015). This feeling of ”being there” is the key element that allows constructivist approaches to be used in Immersive Learning (e.g. experiential learning, exploratory learning and problem-based learning).

Schrader (2008) described the use of technology in education based on the role it takes on a learning activity. He defined four types of interaction:

- *About* technology - when the end goal is to learn how it works or how to use a particular technology (e.g. programming languages).
- *From* technology - when technology is the teacher and/or provides the content (e.g. online courses).
- *With* technology - when technology frees cognitive space for attention to higher-level skills (e.g. calculator).
- *Within* technology - when technology is the context, creating a mechanism of interaction between content and experience (e.g. virtual worlds).

Immersive learning happens when creating experiences that focus on learning *within* the technology. This can be from technology embedded in the physical space (i.e. intelligent classrooms) to virtual learning spaces (i.e. virtual worlds). When immersive learning experiences are designed for collaboration, they can take advantage of learners’ immersive feeling of “being there with others” (co-presence), allowing them to participate and interact in a more natural way, even when the participants are not in the same geographical place, enhancing the learning experience. Therefore, is important to identify and match a learning environment with the needs of the learners and the learning goal. The benefits of such environments are related to the feeling of immersion, which can shape participants’ learning styles beyond "what using sophisticated computers and telecommunications has fostered thus far, with multiple implications for higher education" (Dede, 2005a), particularly for distance learners, promoting solutions to the problems of presence (and co-presence) in learning activities (Wang et al., 2011b; Callaghan et al., 2010).

An immersive learning environment can be defined as a technology-based educational setting that deeply involves learner's senses giving a realistic sense reality even when the situation is virtual enhancing the user experience. This type of environments usually include sensory stimulus feedback (visual, haptic, auditory) and occasionally the possibility of combining virtual and physical spaces or integrate mobile capabilities to engage and motivate differentiated learner groups. Smart classrooms, 3D VLEs and mixed-reality learning environments are some implementations of immersive learning environments.

Smart Classrooms

Smart classrooms are teaching spaces enhanced with context-aware technology (Dooley et al., 2011; Augusto, 2009; Yau et al., 2003; Gligorić et al., 2012) and Internet-of-Things objects (Muñoz Organero et al., 2011; González et al., 2008; Yan-lin, 2010) among others, to support teaching and learning activities. Although some implementations based on these technologies can include some type of immersive user-interface, their action field is more restricted to the physical environment.

3D Virtual Learning Environments (3D VLEs)

A three-dimensional virtual environment (3D VE) is a computer-generated environment that creates the human perception of three spatial dimensions, supporting the usage of avatars to represent human users, and different communication and interaction tools (Dickey, 2005). When these are used in education they are commonly known as three-dimensional Virtual Learning Environments (3D VLEs). According to Hedberg and Alexander (1994), 3D VLEs have the potential to offer "a superior learning experience", increased "immersion", increased "fidelity" and a higher level of "active learner participation".

There are a number of circumstances where the use of 3D VLEs may be preferable to physical environments, such as exploration of places that cannot be visited (e.g. historical places, outer space, etc.) or where the tasks to be learned are expensive or dangerous to undertake in the real world (e.g. nuclear plant training, spaceship repairing training, etc.) (Dalgarno, 2002). Additionally, 3D visualizations enable the use of visual metaphors to present data, showing information from different angles. They can be classified in: simulation interfaces, serious games, 3D virtual worlds and microworlds.

- Simulation interfaces are a non-linear exploratory environment that allow learners to rehearse different scenarios, tasks, problems or activities or make predictions about the behaviour of computer-modelled real-world situation by altering its variables (De Freitas, 2006; Aldrich, 2004). Its use is common in Research & Development areas in public and private institutions, and in laboratory activities as they can represent physical or natural phenomena with small variations in a repetitive way.
- Serious games can be defined as "games in which education (in its various forms) is the primary goal, rather than entertainment" (Michael and Chen, 2006). This category includes all types of games specifically aimed at educational audiences (De Freitas, 2006). They have defined goals and use approaches such as gamification and storytelling to motivate and guide students through the tasks.

- Virtual worlds can be defined as a general purpose (or no-purpose) computer-generated representation of an environment, that allow users to navigate through the world, and interact with virtual objects just as they would in the real world (Wu et al., 2011). A key difference between them and a serious game is the lack of specific goals or gamification elements. They have been extendedly used to recreate virtual images of physical spaces (e.g. museums (Garnier et al., 2011; Carrillo and Herrera, 2012; Voutounos and Lanitis, 2012), classrooms and universities (López-Hernández, 2011; Davies et al., 2008; Livia et al., 2014), historical places (Kennedy et al., 2012), etc.), or used together with scenarios and role-playing activities (Gardner and O'Driscoll, 2011; Gardner and Horan, 2011) (e.g foreign language learning (Gardner and Williamson, 2010; Gardner et al., 2011), science and engineering (Scheucher et al., 2009; Mattila et al., 2012; Occhioni, 2013), health and medicine (Christopoulou et al., 2013)), using platforms such as Open Wonderland[7], Second Life[8] or RealXtend[9].
- A microworld is a small, but complete, version of some domain of interest, that can be found in the world or artificially constructed (or induced) (e.g. a child's sandbox) (Rieber, 1996). People do not merely study a domain in a microworld, they "live" the domain, as it embeds important ideas in a form that students can readily explore (Rieber, 2005). According to Rieber (2005), microworlds generally have three characteristics: a) they offer a way to understand and explore concepts and principles underlying complex systems; b) they focus primarily on qualitative understanding based on building and using concrete models; c) there is a deliberate attempt to reduce the distinction between learning science and doing science; some examples of microworlds include Logo (Papert, 1980) and StarLogo (Resnick, 1997).

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[7] Open Wonderland - `www.openwonderland.org`

[8] Second Life - `www.secondlife.com`

[9] RealXtend - `www.realxtend.org`

Table 3.2 presents the educational approach most commonly associated with this 3D VLEs. Simulations and serious games, due to the use of limited phenomena and data to achieve specific goals can be considered as mechanisms that apply instructional approaches (Gredler, 2004, 1996). Rieber (2005) argues that virtual worlds, usually come from the constructivist thinking; however due to their flexibility they could be used in a constructivist approach (e.g. Minecraft for Education [10], or when used as a communication medium between participants replicating a formal setting (e.g. classroom, gallery, museum) they could be considered as following an instructional approach. Finally, microworlds due to their emphasis on understanding based on building physical models, follow a constructionist philosophy.

3D Virtual Learning Environment	Educational approach
Simulations	Instructionism
Serious games	Instructionism
Virtual worlds	Instructionism/Constructivism
Microworlds	Constructionism

Table 3.2: Educational approach in 3D VLEs

Dalgarno and Lee (2010) identified five affordances of 3D VLEs as follows, understanding affordance as “the functional properties that determine the possible utility of an object or environment” (Gibson, 1979):

- Facilitation of learning tasks that lead to the development of enhanced spatial knowledge representation of the explored domain.
- Facilitation of experiential learning tasks that would be impractical or impossible to undertake in the real world.
- Facilitation of learning tasks that lead to increased intrinsic motivation and engagement.

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[10] Minecraft for education - `www.minecraftedu.com`

- Facilitation of learning tasks that lead to improved transfer of knowledge and skills to real situations through contextualisation of learning.
- Facilitation of tasks that lead to richer and/or more effective collaborative learning than is possible with 2-D alternatives.

Multi-user 3-D environments allow learners to carry out tasks together rather than just communicate, sharing and generating knowledge without having to travel out of their local setting, thus they are popular in remote education, supporting collaboration and enhancing the following factors (Wang, 2009):

- Immediacy: is the perception of physical or psychological closeness between communicators (Mehrabian, 1966; Wang, 2009).
- Social presence (co-presence): is the feeling that other persons are present even though the characteristics and behaviours of those persons may be represented and observed via mediated communication rather than physical proximity and direct observation (Wang, 2009).

Mixed-Reality Learning Environments

A Mixed-Reality (MR) Learning Environment combines physical and virtual resources to enhance the learning process. This includes a broad range of applications in which some elements of the physical world (e.g. physical space, physical objects, students, etc.) can be blended with digital objects (Kirkley and Kirkley, 2004), creating multidimensional spaces.

The use of ubiquitous computing, mobile wireless devices and wearable devices allow participants' use of virtual interactive resources as they move through the physical world, fostering an increasing number of educational applications. Most of the implementations focused on teaching conceptual knowledge are based on Augmented Reality (AR) (e.g. science & technology (Alrashidi et al., 2013b; George et al., 2011; Chong et al., 2005), medicine and health, art & design, language learning (Liu et al., 2007)); whereas the use of Augmented Virtuality (AV) in education has been more concentrated in students' telepresence to join remote classrooms or learning environments as in (Torrejon et al., 2013). However, a number of applications mixing different approaches have arisen in recent years, an example is Shanghai Jiao Tong University's Online Learning System (Zhang et al., 2011). This project utilises two main learning approaches: a) live classroom broadcasting, delivered in real-time (e.g. audio, lecture video, presentation video) to remote multi-modal receivers (e.g. 'standard natural classrooms', home computer, IPTV, mobile phone, etc.) via Internet; and b) web-based learning, providing lectures and material on demand.

(a) MiRTLE, image courtesy Gardner and O'Driscoll (2011)

(b) Holodeck, image courtesy Schmidt et al. (2013a)

Figure 3.6: Use of mixed-reality in instructional approaches

A different approach is exemplified in projects such as University of Essex' MiRTLE (fig. 3.6a) (Callaghan et al., 2008; Gardner and O'Driscoll, 2011; Davies et al., 2008), or University of Hawaii's Holodeck (fig. 3.6b) (Schmidt et al., 2013b,a), which were used to reunite students who were in a physical classroom with students who were in a different geographical location, with the goal of fostering a sense of community amongst remote and physically-present students (Horan et al., 2009). These mixed-reality learning environments are based on an instructional "push" approach that allows remote students sharing a lecture with students located in a physical classroom, and participate in the class asking questions through chat/voice tools in the virtual world. The mix between the physical world space (where students meet in-person) with a virtual world (where students meet as avatars) is made through live video streaming, presented inside the virtual world.

Tolentino et al. (2009) presented the Situated Multimedia Arts Learning Laboratory (SMALLab), a semi-immersive learning environment that incorporated gesture recognition in a 15-foot-by-15-foot space projected on an interactive floor surface (fig. 3.7a). Their approach is based on the concept of embodied learning, where the interface is to certain extent responsive to students' movements, capturing their gestures and tracking their position. A similar project, the MEteor simulation game (Lindgren and Moshell, 2011), a 30-foot-by-10-foot interactive environment with both wall and floor projection displays, allows students to predict asteroid's movement using their bodies (fig. 3.7b).

(a) SMALLab, image courtesy Birchfield and Johnson-Glenberg (2010)

(b) MEteor simulation game, image courtesy Lindgren and Moshell (2011)

Figure 3.7: Use of mixed-reality in embodied learning

Ibáñez et al. (2011) presented an application for teaching Spanish as a foreign language, where students could make a phone call by touching a 3D mobile phone to a teacher's smartphone. Using geotagged information sent by the physical smartphone, students were able to "walk" with the teacher via a virtual representation of the street. The project created mirrored connections between 3D objects inside the 3D VLE with physical objects. Similarly, the PhyMEL project (Physical, Mental and Emotional Learning) (Fernández Panadero et al., 2014), a wheelchair simulator to train and promote awareness between different stakeholders (medical staff, people with disabilities, architects and general people), allowed interaction between virtual and physical worlds by controlling the wheelchair simulator. All these implementations exemplify different mappings between elements in their environments (fig. 2.7), as defined by Lifton (2007). MiRTLE and Holodeck created a bi-directional environment-environment mapping via the video streaming; the language learning mixed-reality implementation presented by Ibañez et al. exemplified two different one-directional mappings, a) object-environment (geo-tagged info in physical phone to virtual street) and b) object-object (virtual phone to physical phone), finally the PhyMEL project presented an object-object bi-directional mapping represented in the wheelchair simulation.

These projects show some of all the possible combinations in mixing virtual and physical environments. From here it is also possible to identify that instructional and embodied learning approaches create mappings in a more abstract way, connecting environments and participants, whereas constructivist approaches focus on uni-directional or bi-directional mappings between objects. A diversity of resources may be available for the creation of innovative learning environments to enhance the learning process; however, this process cannot be completed without establishing learning goals based on correct designs to ensure that the activities are properly structured with clear learning objectives, regardless of the pedagogical methods utilised. To achieve this, it is important to consider two main elements (fig. 3.8): a) infrastructure of the environment, which can help to create the sense of presence and b) the type of activities that can be performed within the learning environment. The combination of both can lead to a degree of immersion in different degrees; achieving spatial and sensory immersion via the technology, and strategic, narrative and actional immersion through the learning activities.

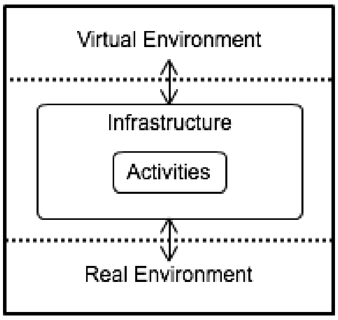

Figure 3.8: Mixed-Reality Learning Environment

3.4 Designing learning activities in technology-enhanced environments

Fowler (2015) warns about the use of term immersion in pedagogy, as it risks being confused with a similar term already being used in technology and psychology. Pedagogical immersion has the ability to identify and empathise with the concept, which is critical to understanding it. Thus the ability to make the concept to be learnt more concrete is a key component to task immersion. Moreover, the enforcement of collaboration in technology-enhanced learning environments requires the management of learning workflows and the coordination of interactions that lead to collaboration (Dillenbourg et al., 2009).

Learning design is “a description of a method enabling learners to attain certain learning objectives by performing certain learning activities in a certain order in the context of a certain learning environment” (Koper et al., 2003). It describes a pedagogical scenario, using a more formal description (also called educational script or storyboard) that may or may not follow an instructional design model (Schneider, 2007). In other words, is the process of structuring the learning into a sequence of activities to teach and reinforce the subject or topic to be learnt by the student. It has its roots on instructional design, which is defined as “the systematic process of translating general principles of learning and instruction into plans for instructional materials” (Tattersall et al., 2003). As a general approach, Stiles summarises (2000) the design of learning activities in the following steps:

- Identify learning outcomes (what is the point of the course?), and relate learning activities and assessments to them.
- Design realistic or authentic learning opportunities for learners, which should be related to the Learning Outcomes.
- Apply Deconstruction on learning opportunities to make them appropriate to the level of the learner.
- Consider Group or Individual Learning opportunities.
- Identify or Create Resources based on the previous points.

In technology-enhanced learning environments, it has been applied to some extent in LMS (e.g. Moodle[11] or Blackboard[12]), however, learning design is more commonly applied using modelling languages, such as the eLesson Markup Language (eLML) [13] or IMS LD (proposed by the Instructional Management Systems (IMS) Global Learning Consortium [14]). These have been used for the design of learning activities to be performed by students during a session in order to achieve specific learning goals. Dessus and Schneider (2006) identified four kinds of objectives of modelling languages:

- Definition of pedagogical scenarios
- Exchange of learning units (learning objects, scenarios)
- Execution of learning units in a platform
- Sketch, design, plan and discussion of pedagogical scenarios

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[11] Moodle - `www.moodle.org`
[12] Blackboard - `www.blackboard.com`
[13] eLesson Markup Language - `www.elml.org/website/en/html/index.html`
[14] IMS Global Learning Consortium - `www.imsglobal.org`

A benefit of its use is the standardisation on the design of learning activities, and the portability and re usability of the learning sessions created (Dessus and Schneider, 2006; Schneider, Daniel K., 2014), however, its proper implementation depends on the technical ability of the teachers, and its use is more common in instructional learning rather than constructivist approaches.

IMS Learning Design is a modelling language specification used to describe learning scenarios for online learners, which can be shared between systems. It can describe a wide variety of pedagogical models, or approaches to learning, including group work and collaborative learning Jeffery and Currier (2003). It is based on a formal XML specification for modelling Units of Learning (UoL), which are "the smallest unit providing learning events for learners, satisfying one or more inter-related learning objectives" (Tattersall et al., 2003), which can be aggregated into larger units (e.g. from lectures to courses) Fowler et al. (2007). A Learning Object (LO) can be defined as any entity, digital or non-digital, which can be used, re-used or referenced for learning, education or training (Barker, 2005). The IEEE defined an open standard for Learning Object Metadata (1484.12.1 – 2002) for the description of "learning objects" based on the IMS LD specification (Barkman et al., 2002; Committee, 2002; Barker, 2005). The instructionist perspective, considers as a learning object to any small piece of instruction that can be assembled and reused into some learning structure (Wiley, 2000). Learning objects are encapsulated within Units of Learning (UoL) as structured sequences of activities that poses a defined learning goal. These UoL and can be preceded by zero or more conditions that need to be accomplished before starting or completing the tasks (McGreal, 2004). Learning objects are grounded in the object-oriented paradigm of computer science (Wiley, 2000) using a deconstructed approach (fig. 3.9). By the creation of independent self-contained (encapsulation) small units (modularity) instructional designers can create components (objects) that can be reused a number of times in different learning contexts. Moreover, Learning objects can be utilised simultaneously by a number of people in collaborative activities.

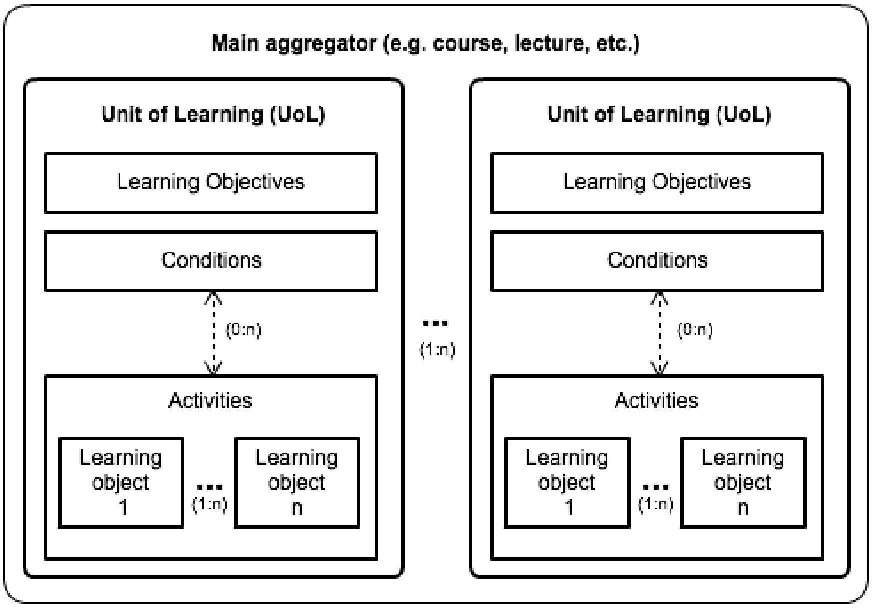

Figure 3.9: Deconstruction of Units of Learning

From the constructivist approach, a learning object has been defined as an object "specifically designed to promote learning through hands-on interaction" (Zuckerman, 2007). Zuckerman (2007) classified constructivist learning objects in three categories:

- Construction kits and building materials, which promote activities that involve design and model building. These artefacts help learners understanding the physical world by making models of physical things; engaging learners and fostering creativity through design and construction ("Experimenting" movement).
- Objects that represent a simplification of real life. For example, objects that help children feel a part of the adult world, such as children-size real-world artefacts (e.g. kitchen appliances, kitchen tools, play food) ("Simplified Reality" movement).
- Artefacts carefully designed to represent a single abstract concept, not the physical world; where the hands-on manipulation process will help learners

"absorb" the abstract concept through physical interaction alone, without any real-world analogy ("Intelligent Hand" movement).

Figure 3.10 shows a simplified diagram of interactions between the three principal components in the IMS Learning Design specification: people, activities and environment. People involved in the learning activity, has different roles (e.g. instructor, learner, etc.) and work towards specific objectives by performing learning activities, which are conducted within an environment consisting of learning objects and services. The learner is the person who performs this sequence of actions in order to fulfil one or more particular interrelated learning objectives.

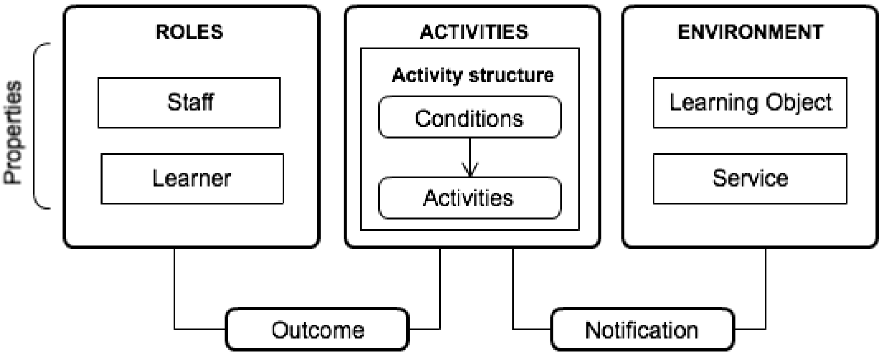

Figure 3.10: IMS Learning Design. Main components (Pena-Rios et al., 2012a)

Implementations of this specification have been used in e-Learning using specific learning design tools (e.g. LAMS[15] or OpenGLM[16]), authoring tools (De-la Fuente-Valentín et al., 2011), or through its integration with 3D Virtual Learning Environments (Ibáñez et al., 2013; Maroto et al., 2011; Joshi and Gardner, 2012; Livingstone and Kemp, 2008; Fernández-Gallego et al., 2010) following an instructional approach. A different integration involves the use of serious games (Moreno-Ger et al., 2007; Westera et al., 2008; Hendrix et al., 2012; Marfisi-Schottman et al., 2010), proposing a blended learning approach, using instructional and constructivist elements. Some other bespoke frameworks for the design of learning activities in 3D Environments have been made (Persa et al., 2014), however in-

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[15] LAMS Foundation - `www.lamsfoundation.org`

[16] OpenGLM - `www.edutechwiki.unige.ch/en/OpenGLM`

tegration and portability remains difficult due to specific characteristics of their particular implementation.

3.5 Scenario: Mixed-Reality in laboratory collaborative activities for distance learners

A challenge being faced by educational institutions in today's technology-enabled knowledge economy is that they should be able not only to teach students with an adequate education in their field of study, but also to arm them with the wider skills and knowledge required for work in real life scenarios. Some of the required skills nowadays involve critical thinking, creativity, lifelong learning, the ability of communicate effectively and collaborate with others (Friedman, 2011). Laboratory activities and practical classes are an ideal scenario to foster these skills.

Laboratory activities or practical classes, are formal learning scenarios where students are presented with a problem that involves the use of concrete objects/materials to produce an expected outcome. They can be used to enhance students' interest and knowledge of science concepts and procedures, and knowledge of tools and skills needed in the industry (Lunetta et al., 2013). Laboratory activities can be designed to be conducted by students individually or in groups, however when they are assigned to teams of students, learning occurs due to reasoning and feedback between team members.

For over 200 years, laboratory activities had been reported as an assisting tool for students in making sense of the world (Lunetta et al., 2013). According to Exley (2004), the first hands-on-courses in the UK were offered in Oxford and London in the 1860's. Prior to that, science courses had relied upon the "demonstration lecture" to give insight into experimental processes and procedures. During the 1950's, laboratory activities in the curricula were limited almost exclusively to illustrate information given by the teacher and the textbook. In the 1960's, the science education reform era influenced by Constructivist ideas developed new curricula emphasising student inquiry and hands-on activities (Lunetta et al., 2013). Laboratory and practical classes remain the most characteristic feature of science and engineering courses (Exley, 2004). Experience in these activities is important as it provides the learners with an opportunity to test conceptual knowledge and to work collaboratively, interacting with fellow student, real equipment and performing analysis on experimental data.

Practical classes have been generally designed for learners that have physical access to the laboratory room and instruments, however, the adoption of technology in classrooms has opened opportunities for distance learners to interact with laboratory-like activities, such as:

- Online lab activities based on videos: Some universities and MOOC platforms have full courses available on video, using streaming platforms (i.e. YouTube), such as the introductory Chemistry Laboratory courses offered by Carleton University[17] or MIT OpenCourseWare[18]. A benefit of this implementations is the possibility of having the information in any time, everywhere (Ma and Nickerson, 2006), however there is a lack of interaction between the user and the equipment.
- Use of remote/distance laboratories: A remote laboratory experiment consists in remotely interacting with physical devices over computer networks (IEEE Standards Association, 2012). The experimentation phases involve tele operation of a physical system (e.g. a telerobot) which usually is triggered by remote users via software interfaces (generally web-based) that

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[17] Carleton University's First Year Experiments - `www.youtu.be/olJlbbKtuAU`

[18] MIT OpenCourseWare's Chemistry Laboratory Techniques - `www.youtu.be/EUn2skAAjHk`

includes including visual and data feedback from the remote site (Tzafestas et al., 2006; Foss et al., 2001). These implementations cover various science and engineering fields ranging from basic electronics and engineering concepts (Barros et al., 2008; Gillet and Fakas, 2001; Bhargava et al., 2006; Fjeldly et al., 2002), control (Schmid et al., 2001; Dabney et al., 2003; Sánchez et al., 2004), to a larger variety of mechanical and chemical engineering experimental set-ups (Henry and Knight, 2003).

- Implementation of virtual laboratories (eLabs), which use interactive graphical user interfaces that incorporate simulation techniques generally based on 3D graphics or photo-realistic animations, and with no link to a (remote) physical system (Ma and Nickerson, 2006; Tzafestas et al., 2006). Some examples of simulated labs currently in use are University of Bristol's LabSkills[19], Freie Universitat Berlin's Technology Enhanced Textbook (TET)[20], Amrita University's Virtual Lab[21], University of Leeds' Virtual Labs[22], or Durham University's Interactive screen experiments[23] among others.

In figure 3.11, Gomes and Bogosyan (2009) presented a 2D matrix representing just two of the aforementioned characteristics in the previous table, which covers most of the current implementations to date. Reported issues (Nedic et al., 2003; Ma and Nickerson, 2006) related with these solutions are: a) the lack of interaction with real equipment, thus the activity is commonly performed with idealized data and restricted options. Additionally, each activity setup is associated with limited learning scenarios, thus changing the learning goals sometimes represents restructuring the whole implementation; b) the difficulty in carrying out collaborative work with other learners showing reduced user engagement. For

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[19] University of Bristol's LabSkills - `www.labskills.co.uk`

[20] Freie Universitat Berlin's Technology Enhanced Textbook (TET) - `www.didaktik.physik.fu-berlin.de/IMPAL/show/demo.php`

[21] Amrita University's Virtual Lab - `www.amrita.vlab.co.in/`

[22] University of Leeds' Virtual Labs - `www.virtual-labs.leeds.ac.uk/pres/index.php`

[23] Durham University's Interactive screen experiments - `www.level1.physics.dur.ac.uk/general/index.php`

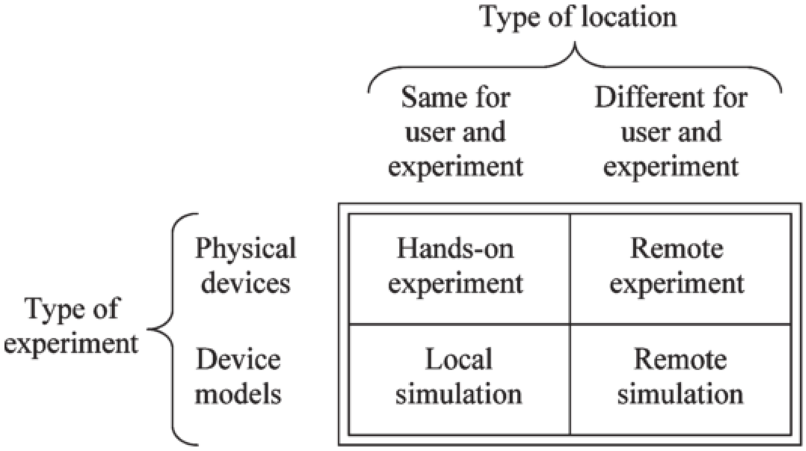


Figure 3.11: Charaterisation of Experiments, image courtesy Gomes and Bogosyan (2009)

example, remote laboratories are generally designed for one student, which triggers the mechanisms to start the experiment. When more students exist, they are limited to a (passive) observer role.

Table 3.3 presents an enhanced classification for laboratory-like activities based on the ones proposed by Gomes and Bogosyan (2009) and Ma and Nickerson (2006). An interesting classification refers to the nature of the learning environment, the 2015 NMC Horizon Report in Higher Education (Johnson et al., 2015) predicts the increment of informal learning environments (e.g. makerspaces) in a time span of two to three years. Makerspaces, also referred to as hackerspaces, hack labs, or fab labs, are community-oriented workshops where tech enthusiasts meet regularly to share and explore electronic hardware, manufacturing tools, and programming techniques and tricks (Cavalcanti, 2013). These type of spaces represents increasing opportunities for collaboration and creativity.

On the pedagogical side, Ma and Nickerson (2006) defined a four-dimensional goal model for laboratory education to measure competing technologies based on the premise that each technology has different learning objectives. The proposed laboratory goals are: conceptual understanding, design skills (i.e. design

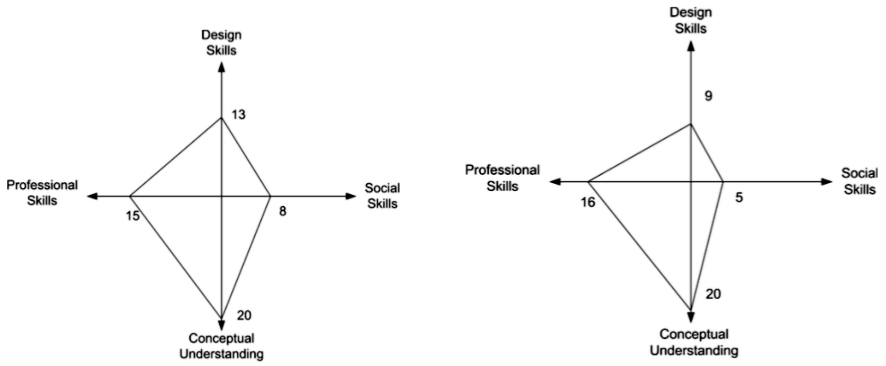
Type	Classification
Interaction between the user and the experiment	• Direct interaction: where the user controls the equipment directly. • Indirect interaction: where the user controls devices and instrumentation equipment through a computer interface. • No interaction.
Nature of the experiment	• Physical devices (and equipment). • Simulated/emulated models for the devices (and equipment).
Location of the user and the experiment	• Same location. • Different locations.
Number of participants	• Individual activity. • Collaborative activity.
Nature of the learning environment	• Formal experimentation environments (e.g. laboratory or practical classes). • Informal experimentation environments (e.g. museums, makerspaces, etc.).

Table 3.3: Laboratory activities classification

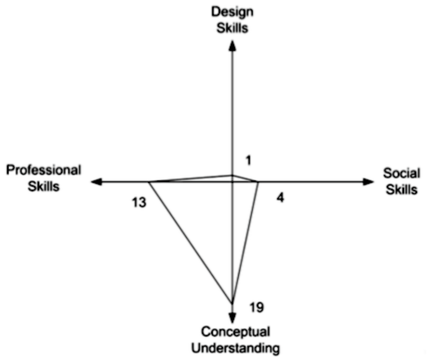
and construction of new artefacts or processes), social skills (i.e. communication, team interaction and problem-solving) and professional skills (i.e. application of knowledge to practice). Traditional laboratory activities focus on these four learning objectives (fig3.12a). Existing virtual and remote laboratories focus more on conceptual understanding and professional skills, although design skills have been considered by a few virtual laboratory projects (fig. 3.12b, 3.12c). Ma and Nickerson (2006) reported that although there is a fair amount of evidence that simulated and remote labs are effective in teaching concepts, the effectiveness of these approaches seems to be correlated to the directness of its link to the real world. Two different aspects in this correlation were observed by Miller (1954): a) the engineering fidelity which concentrates on how realistic the simulated environments are; and b) the psychological fidelity which focuses on the sense of *presence* or “been there”. Other studies (Ma and Nickerson, 2006; Patrick, 1992) confirmed that despite a reduction in engineering fidelity; high psychological fidelity in virtual worlds can lead to a higher learning transfer (Ma and Nickerson, 2006), moreover, some comparative studies between remote and virtual laboratories have shown performance degradation in remote lab students is affected by the lack of physical presence (or realistic virtual presence) (Tzafestas et al., 2006; Lawson and Stackpole, 2006).

Another important aspect is collaboration. Ma and Nickerson (2006) claim that is collaboration, not the technology, which accounts for learning performance differences. In other words, even if remote labs are not as effective as hands-on labs, “the experience of working with geographically separated colleagues and specialised equipment may be educationally important enough to compensate for any shortcomings in the technology” (Ma and Nickerson, 2006).

The use of immersive technologies in laboratory activities, has the potential to promote solutions of some of the reported issues of engineering fidelity, psychological fidelity and collaboration. Currently, augmented reality is the most common technology used in science and engineering hands-on activities, with implementations ranging from a science laboratory for elementary school children (11-12 years old) (Theng et al., 2007), to the use of head mounted displays (HMDs) for physics lab at a university course (Kuhn et al., 2015). However, most of the implementations are based on digital-only artefacts (Barakonyi et al., 2004), considering



(a) Educational goals of hands-on labs (b) Educational goals of simulated labs



(c) Educational goals of remote labs

Figure 3.12: Educational goals of different implementation of laboratory activities, image courtesy Ma and Nickerson (2006)

them as simulated laboratories, which reduces psychological fidelity. Additionally, when considering collaborative teamwork the use of physical devices (which promote engineering fidelity), is restricted to local environments (Billinghurst et al., 2002; Regenbrecht and Wagner, 2002; Henrysson et al., 2005).

Stohr-Hunt (1996) reported that students engaged in hands-on experiences scored better on a standardized test of science. Similarly, Kontra et al. (2015) reported that physical experience enhances science learning. This is particularly relevant in virtual laboratories and areas of science education that lend themselves to physical experiences. Another solution proposed, is the use of smart objects and the Internet-of-Things to create remote laboratories for engineering and science education (Koren and Klamma, 2015). However, the use of network aware technology in distance learning, to support constructionist laboratory activities, is an area with many difficult challenges due to the different physical devices and equipment needed to complete an experiment (Tzafestas et al., 2006), this involve the identification of different physical devices and diverse experimental equipment, the interfaces needed to complete a real physical experiment and diverse pedagogical challenges including the engagement between the learners and the technology, primarily focused on the feeling of increasing the sense of co-presence in the laboratory. Most of the recent efforts to solve this issues have been isolated, due to the lack on standardized or common-practice solutions. Some initiatives in the creation of standards have started with the IEEE P1876™ Working Group on Networked Smart Learning Objects for Online Laboratories (NSLOL WG) [24], the European Association of technology-Enhanced Learning (EATEL) SIG Remote Labs and Online Experimentation [25], or the Global Online Laboratory Consortium (GOLC) [26], however, at this moment, they are still in their infancy.

3.5.1 Microworlds and End-User Programming

Currently, implementations for mixed-reality laboratory activities are either more focused on the identification of objects (smart-objects) or in bespoke implementations designed for a particular activity.

Microworlds are learning environments that implement a metaphor of the classroom, emphasising the “place” or “space” where learning occurs (Wilson, 1995). The space is important as it can give to students room to explore and interact with others. Papert (1980) argued that microworlds promote active learning as they allow “exploration by the learner of a microworld sufficiently bounded and transparent for constructive exploration and yet sufficiently rich for signifi-

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[24] IEEE P1876™ WG - `www.ieee-sa.centraldesktop.com/1876public/`

[25] EATEL SIG - `www.ea-tel.eu/special-interest-groups/sig-remote-labs-and-online-experimentation/`

[26] GOLC - `www.online-engineering.org/GOLC_about.php`

cant discovery. “This is essential for laboratory activities, where learners should have a certain degree of freedom to test different possible solutions to a given activity, achieving the different phases of learning by deconstruction as presented by Boytchev (2014) (Deconstruction, Construction, Creativity). Edwards (1995) mentioned that a microworld is generally formed by:

- A set of computational objects that model the mathematical or physical properties of the microworld's domain.
- Links to multiple representations of the underlying properties of the model.
- The ability to combine objects or operations in complex ways, similar to the idea of combining words and sentences in a language.
- A set of activities or challenges that are inherent or preprogrammed in the microworld; the student is challenged to solve problems, reach a goals, etc.

In mixed-reality learning environments, and particularly for laboratory activities, this also represent the possibility of working with different elements, and create new mappings between virtual and physical worlds, as described by Lifton in his dual-reality mappings (fig. 2.7). An important element to achieve is to provide tools that allow students to create this mix of virtual/physical elements. End-user programming (EUP) have been used in microworlds to allow them combining objects and/or operators to achieve particular goals. It can be defined as a number of techniques that allow non-technical people to create programs to be performed by a particular environment (Cypher and Halbert, 1993), empowering them (Chin et al., 2008). In this context, ”programming” could be defined as the process of transforming a mental plan of desired actions for a computer into a representation that can be understood by the computer (Hoc and Nguyen-Xuan, 1990; Scaffidi et al., 2012). A program usually consists of a sequence of actions structured in a particular way to reach a particular goal. Some of the approaches that have been used to encourage and empower users to create programs are (Rieber, 2004; Goodell, 1998):

- Application-specific Languages, which are relatively simple scripting languages (e.g. HyperText Markup Language (HTML), ActionScript).
- Programming by Example (PBE), also known as Programming By Demonstration (PBD), is a paradigm that allows the computer to capture new behaviour and tasks by demonstrating a sequence of actions on concrete examples (Halbert, 1984) (e.g. macros in an editor). An implementation of this paradigm is the Pervasive Interactive Programming (PiP), a model applied to customise intelligent environments (Chin et al., 2009).
- Visual programming languages (VPL), which is any programming language that uses graphical representations of objects (e.g. an icon of a physical artefact), statements (e.g. an if-then-else conditional expression) and variables are transformed into concrete objects that the user can see and manipulate, making them easier to understand through tinkering and observation (Maloney et al., 2010). Some examples are MIT's *Scratch*[27], Carnegie Melon's *Alice*[28] and Kent University's *Greenfoot*[29]. They are designed to teach programming to individuals without prior experience, supporting rich media (e.g. graphics and sound) to the create of multimedia projects (e.g. animated stories and games) (Utting et al., 2010; Maloney et al., 2010). Scratch targets younger users focusing on tinkerability as a way to foster self-directed learning. Alice and Greenfoot target older students, introducing class-based object-oriented programming. Java-based Greenfoot, allows students to explore high-performance computation (e.g. complex simulations or problems). Alice is the only one of these systems that supports 3-D

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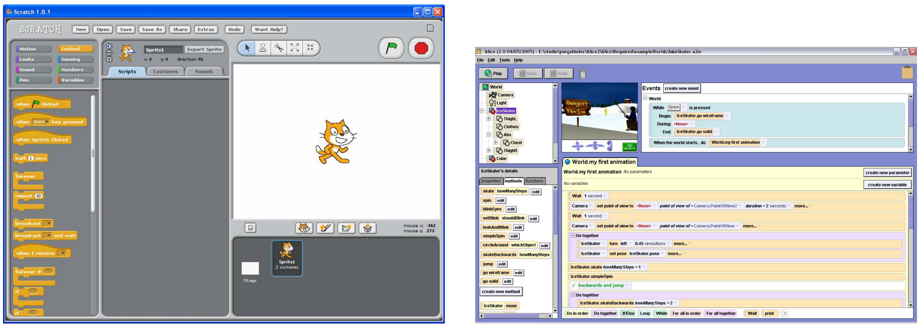
[27] MIT Media Lab *Scratch* - `www.scratch.mit.edu`

[28] Carnegie Mellon University *Alice* - `www.alice.org`

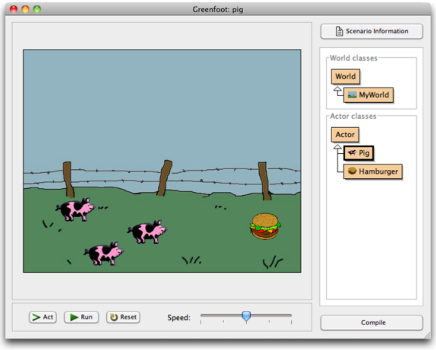
[29] University of Kent *Greenfoot* - `www.greenfoot.org/door`

graphics.

- Natural Programming, is a paradigm that uses different human-centred approaches to reduce the amount of learning and effort needed to write programs for people who are not professional programmers. An example is Carnegie Mellon's Whyline [30], a debugging tool that allows programmers to ask "Why did" and "Why didn't" questions about their program's output (Ko and Myers, 2004).



(a) Scratch (b) Alice



(c) Greenfoot

Figure 3.13: Visual programming environments examples

The best known example of a microworld is Papert's LOGO/Turtle project, based on the text-based programming language LOGO and a small educational turtle robot. The aim was to allow children explore and learn mathematics, based on his constructionist vision of education. Other visual end-user programming environments (e.g. Scratch, Greenfoot, Alice (fig. 3.13)), have been used in physical computing to create interaction between programs and the world outside

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[30] Carnegie Mellon University, The Whyline - `www.cs.cmu.edu/~NatProg/whyline.html`

the computer. This usually incorporates sensors to gather information from the environment; controlling motors, lights, and other devices; and designing, building and programming robots. Some examples include LEGO Mindstorms[31], Arduino boards[32], Raspberri Pi [33], Picoboards[34], Phidgets[35] and even everyday objects that conduct a little bit of electricity (e.g. fruit, water) using the MakeyMakey hardware [36]; allowing learners to create small scale computer projects based on the constructionist approach (Rosenbaum et al., 2010).

The goal of a microworld is to help learners understanding concepts and principles underlying all complex systems (Rieber, 2004). It must be defined at the interface between an individual user in a social context and a software tool possessing the following five functional attributes (Rieber, 2004):

- domain specific;
- provides a doorway to the domain for the user by offering a simple example of the domain that is immediately understandable by the user;
- leads to activity that can be intrinsically motivating to the user (the user wants to participate and persist at the task for some time);
- leads to immersive activity best characterized by words such as play, inquiry, and invention; and
- it is situated in a constructivist philosophy of learning.

It is in particular, the fourth characteristic the one that situate mixed-reality as a suitable approach to create immersive microworlds. It could be argued that

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[31] LEGO Mindstorms - `www.mindstorms.lego.com`
[32] Arduino - `www.arduino.cc`
[33] Raspberri Pi - `www.raspberrypi.org`
[34] Picoboards - `www.picocricket.com/picoboard.html`
[35] Phidgets - `www.phidgets.com`
[36] MakeyMakey - `www.makeymakey.com`

simulations are microworlds, however, Rieber (2004) pointed two important characteristics of microworlds that may not be present in simulations:

- a microworld presents the learner with the "simplest case" of the domain, even though the learner would usually be given the means to reshape the microworld to explore increasingly more sophisticated and complex ideas.
- a microworld must match the learner's cognitive and affective state. Learners immediately know what to do with a microworld (little or no training is necessary to begin using it).

In a microworld, the student is encouraged to think about it as a "real" world, and not simply as a simulation of another world (Rieber, 2004). Figure 3.14 illustrates a mixed-reality microworld, in which the infrastructure of physical objects, allow the creation of activities via an end-user programming tool. Current implementations are based on linking virtual and real using physical computing with 2D visual programming languages; moreover, they are usually designed for individual participation, excluding its use in collaborative activities; and the nature of physical computing implies that the learner has its own physical objects (e.g. sensors, actuators, etc.) which cannot be shared or combined with other students, unless they are both in the same physical space and one of the learners loses ownership of the object to allow the other to use it. A solution to this could be the inclusion of networked elements which would allow people in different locations to share and control physical objects without being in the same room.

3.5.2 Challenges in the shift to multi-dimensional learning environments in education

As described earlier in this section, current trends in educational technology have been trying to create a multidimensional space, where virtual and physical ele-

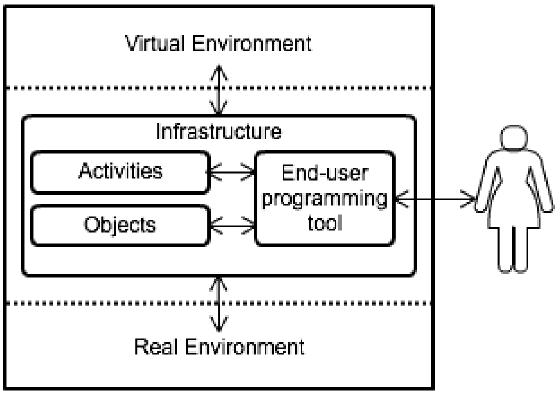


Figure 3.14: Mixed-Reality Learning Environment as a Microworld

ments are combined; allowing them to take the best of both parts: the exposition to real settings and situations enhanced with social integration, along with the possibilities that virtual learning environments and immersive technology. Kloos et al. (2014) classified this shift to multi-dimensional learning environments in three categories (fig. 3.15):

- A physical-digital dimension where students and professors share a common environment, either physical, virtual or mixed.
- A local-global dimension, with students in the same physical location or spread around the world.
- A formal-informal dimension, related to formal learning with defined objectives or informal where outcomes are undefined (e.g. lectures, laboratory classes vs. makerspaces, museums).

This represents a big challenge on the design and creation of functional learning environments, considering the mix of pedagogical approaches along with the the use of technology. As Resnick (1995) affirmed “well-designed computational tools and activities can provide students with new ways of thinking about computational ideas”.

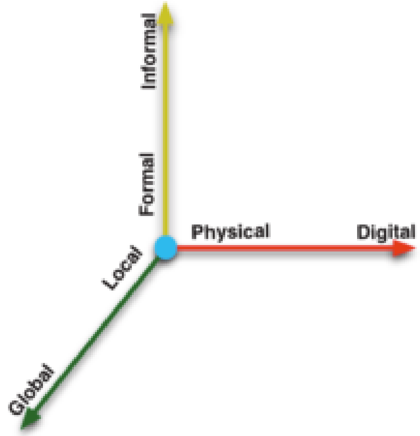


Figure 3.15: Three-dimensional framework of trends in education, image courtesy Kloos et al. (2014)

Besides the adoption of technology by end-users (instructors and students), it is necessary to adapt technologies and pedagogical methods to create solutions for people in geographically dispersed locations (global dimension). Nowadays, most of the opportunities for distance learners focus on emulating the classroom, in doing this, there is a challenge of maintaining the social aspect of it allowing true collaboration between peers. Collaboration can promote creativity, critical thinking, dialogue, assist with deeper levels of knowledge generation, promote initiative and, when conducted internationally, address issues of culture (Vallance, 2009). Vallance (2009) defined this as “collaboration fluency, the teamworking proficiency that has reached the unconscious ability to work cooperatively with virtual and real partners in an online environment to create original digital products”. Additionally, most of the current resources for distance learners focus on simulations or text-based resources, which restrict collaboration and pose an additional challenge for learners to engage and experience hands-on activities such as science and engineering laboratories. Dede (2005a) points the need to create learning environments based on ”mediated immersion” and ”distributed-learning communities”, with “knowledge distributed across a community and a context, as well as within an individual, able to provide a balance among experiential learning, guided mentoring, and collective reflection". He adds that multi-user virtual environments and real-world settings augmented with virtual information can provide the capability to create "problem-solving communities in which participants can gain knowledge and skills through interacting with other participants who have varied levels of skills, enabling legitimate peripheral participation driven by intrinsic sociocultural forces" (Dede, 2005a). However, one of the biggest challenges for distance learners is to change the way to experience education from one-dimensional (physical) to multi-dimensional (physical and virtual) education, yet how to integrate the physical into the virtual in a seamless way remains an unsolved problem. This change from desktop-based interfaces to mixed-reality interfaces is happening due to the psychologically immersive characteristic innate in virtual environments and augmented realities, which induce a strong sense of "presence". This sense of presence is variable and depends on the situation the learner is confronted with. Achieving self-presence (sense that my avatar is me), social presence (sense that others are with me) and spatial presence (sense that I am in the immersive environment) is always a challenge to any mixed-reality learning environment, in particular to hands-on activities for distance learners, where they are restricted to simulations, distance laboratories and videos. These solutions have benefits such as the availability for students to access 24/7 to these resources, and more control of the environment by the teachers/instructors; however they also lack in creating real-life situations as the datasets and interaction is restricted, and collaboration is minimal. Stiles (2000) identified some of the problems when designing technology-based learning solutions:

- Failure to engage the learner.
- Mistaking "interactivity" for engagement.
- Focussing on content rather than outcomes.
- Mirroring traditional didactic approaches on the technology.

- Failure to recognise the social nature of learning, generating a genuine sense of isolation, that leads to less effective learning.

Mixed-reality learning environments, such as augmented reality, have progressed towards tackling some of these issues, situating the learner in interactive environments which may (constructivism) or may not (embodied learning) include physical objects; however, in the particular case of science and engineering laboratories, research has suggested the lack of physical presence have implications in remote lab students (Ma and Nickerson, 2006); and whereas simulated and remote labs are effective in teaching concepts they lack in the acquisition of social and design skills (Ma and Nickerson, 2006). Hands-on activities allow learners to correlate concepts with authentic tasks; and when performed in meaningful realistic settings, they help in developing problem-solving skills.

3.6 Discussion

This thesis proposes the incorporation of smart networked objects in a multi-user virtual environment to achieve a multidimensional laboratory setting for distance learners, enabling collaborative work using physical devices. The proposed solution utilises a *blend* of three dimensions similar to the ones proposed by Kloos et al. (2014), joining the physical-digital dimension (using blended-reality), the formal-informal dimension (using blended learning) and the local-global dimension (using a distributed computational architecture) to design a mixed-reality environment able to allow distance learners to perform co-creative teamwork in Science and Engineering laboratory-like activities.

This presents a technical and pedagogical challenge of creating, organising and synchronising mirrored real-virtual spaces with two or more physical objects connected at each end, to be used in collaborative activities in group-oriented synchronous time. In laboratory activities, the theoretical foundations of collaboration lie in social constructivism where "personal meaning-making is constructed with others in a social space" (Vallance, 2009). Is in the construction/deconstruction paradigm where the possible glue to these challenges, as is the common element present in technological and pedagogical ambit, it helps to teachers and instructors in the in the design of learning activities by decomposing them into resources (Learning Objects) that can be composed (and recomposed) into learning activities to support the learning process; it helps students in solve problems when decomposing it into basic entities to achieve understanding, and from there to compose a solution (problem-solving); and it can help in the creation of multidimensional learning environments by deconstructing virtual and physical elements to be later combined in blended-reality spaces, allowing understanding of the physical world in hands-on activities. Table 3.4 shows a classification of atomic functions (the minimal decomposed element) and nuclear functions (a composed object formed by one or many atomic functions) from the point of view of the three main elements in the proposed deconstructed model: learners, instructors and technical infrastructure.

Role	Atomic function	Nuclear function
Learner	Objects and services (actions) available in the environment.	An Internet-of-Things project
Instructor	Resources available in the environment, activities available (sequence of activities).	A Unit of Learning (UoL)
Technical infrastructure	3D Virtual Environments, immersive environments, smart objects, ubiquitous-VR.	Cross-reality toolkit and system

Table 3.4: The Deconstructed model - unification architecture

3.7 Summary

This chapter presented a review of fundamental pedagogical aspects of technology-enhanced learning environments, as well as related work towards the creation of multidimensional spaces in education. Moreover, it presented a definition of Immersive Learning and a review of current immersive learning environments, including the different pedagogical approaches that support them.

Additionally, it introduced the concept of Deconstructionism and its use in teaching and learning, along with the many challenges in the use of technology-enhanced environments in learning, particularly in collaborative work for distant learners in laboratory activities. Finally, this section introduced the deconstructed model as the medium that unifies pedagogical and technological challenges, arguing that it has the capability to glue constructionist pedagogies seamlessly into the creation of multidimensional learning environments. This can be achieved by decomposing resources into atomic functions that can later be re-composed into nuclear functions from the perspective of the three actors involved in technology-enhanced learning: instructors, learners and the technology that supports it. From the instructors' perspective, deconstruction is present in the creation of Units of Learning (UoL) based on resources available in the learning environment (atomic functions) which can be combined to create nuclear functions (a complete UoL). From the learners' perspective the idea is similar, considering as atomic functions all the objects (physical and virtual) and their functions, which students can re-construct in any combination (nuclear functions) to achieve the learning goals of a hands-on session (e.g. a laboratory activity) prescribed by the instructor. From a technological viewpoint, the deconstructed elements become sets of autonomous networked resources (atomic functions) and virtual elements that may be inter-connected to form different combinations (nuclear functions) supporting the creation and execution of UoL as required by the teacher or the student.

The following sections present the theoretical and architectural framework towards the implementation of a multidimensional learning environment based on the deconstructed model as described in this section.

Chapter 4

Frameworks and Conceptual Models (Architectural and Pedagogical)

> *"Tell me and I [will] forget. Show me and I [will] remember. Involve me and I [will] understand."*
>
> — Xunzi (312-230 BC)

As presented in previous chapters, the use of technology in education poses many challenges, especially to distance learners which often feel isolated and experience lack of motivation in completing on-line activities. The challenge is bigger for students working on laboratory based activities, especially in areas that involve collaborative group-work involving physical entities. Addressing this challenge became the principal focus of this research which sought to create a learning environment, based on collaborative multidimensional spaces, able to connect learners in different geographical locations and foster collaboration and engagement as described in earlier chapters.

This section introduces a conceptual and architectural model for the creation of a learning environment able to support the integration of physical and virtual objects, creating an immersive mixed-reality laboratory that seamlessly unites the working environment of geographically dispersed participants (teachers and students), grounded on the theories of constructionism and collaborative learning.

4.1 Mixed-Reality Smart Learning Model (MiReSL)

The shift from classroom instruction to ubiquitous student-centred learning has provided a number of technology-based platforms designed to enhance the learning ecosystem; understanding ecosystem as "the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space" (Enciclopaedia Britannica, 2015). This vision goes from complete campus implementations, considering educational, administrative and social aspects such as the one introduced by Ng et al. (2010); to specific setups designed for specific stakeholders.

Gütl and Chang (2008) analysed diverse approaches focused on the learning process itself, identifying important aspects which need to be considered in technology-based learning environments:

- A contextual and timely approach able to change, facing learner requirements (Burra, 2002) (adaptable).
- Social and cultural aspects (Bransford et al., 1999).
- Learning community aspects as well as learner-centred, knowledge-centred and assessment-centred aspects (Bransford et al., 1999) (collaborative).
- Individual learner profiles which include task and role-based aspects, interests, knowledge state, short-term learning objectives and long-term career goals (Ismail, 2002; Gütl, 2007) (personalised).

For a mixed-reality learning environment, it should also consider context-aware technology able to identify users, objects, and the physical environment. This section introduces the Mixed-Reality Smart Learning (MiReSL) model, which is a conceptual architectural model proposed as a context for this research. The MiReSL model incorporates a Smart Learning approach (u-learning with a cloud computing infrastructure) with the (De)constructed model of components for teaching (Units of Learning) and learning (physical and virtualised objects) to deliver personalised content enhanced with co-creative mixed reality activities that support the learning-by-doing vision of the constructionist approach. Figure 4.1 presents MiReSL as a computational architecture, which can be divided in four main characteristics:

- A **personalised** learning environment, which keeps track of profiles, preferences, personal scores and learning objectives. Is formed by: a) a Profile Manager, which ensures the integrity of sessions, managing privileges and settings for the environment according to user preferences and roles available (student or instructor); and b) a Personal Content Repository, which maintains the Personal Curricula (all the units of learning assigned or self-selected by the user), the Assessments Scores, and any Content Created. Additionally, it stores information about the learning environment and configuration (needed by the Context-Awareness Agent) in the Environment and Terminal Device Profile.

- **Content creation**, allowing instructors to design and create units of learning (UoL) maintained by the Content Manager in the UoL repository. As defined previously (fig. 3.9), a unit of learning is composed by at least one activity, which in turn, is formed by a number of Learning Objects (LO), which can be any internal (e.g. internal messaging system, internal e-mail, etc.) or external resources (e.g. web search engines, blogs, rss, etc.) located in their correspondent repository.

- **Assessment** of the UoLs, providing feedback and helping to create personalised content suitable for the learner. It is formed by an Intelligent Tutor Agent and an Assessment Agent. The Intelligent Tutor Agent evaluates and suggests new content to the learner based on the feedback received by the Assessment Agent and other variables such as frequency and time dedicated to study, and user preferences. The main objective of this agent is to act as a facilitator, supporting and guiding the learners as they acquire knowledge. The Assessment Agent is the one that evaluates the activities according based on the learning objectives defined on each UoL.

- The **mixed-reality** aspect involves the creation of the mixed-reality learning environment, understood as the human-computer interface (HCI) that allows learners to interact with a mix of physical and virtual objects to achieve specific learning goals. It comprises the Context-Awareness Agent, which obtains real-time information of interactions between elements in the environment (i.e. users, objects, or the environment itself), and passes the information to the Mixed Reality Agent, which process changes on the environment and reflects them in their respective scope. It includes an authentication module and the 3D user interface which allows communication and collaboration between users when performing the mixed-reality learning activities.

Finally, the model is supported by a highly-available technological infrastructure based on cloud computing which provides benefits such as: a) the possibility to store, share and adapt resources within the cloud, b) increased mobility and accessibility, c) and the capacity to keep a unified track of learning progresses, d) the use of resources such as synchronous sharing and asynchronous storage allows the model to be available at any moment that the student requires (Kim et al., 2011; Sultan, 2010).

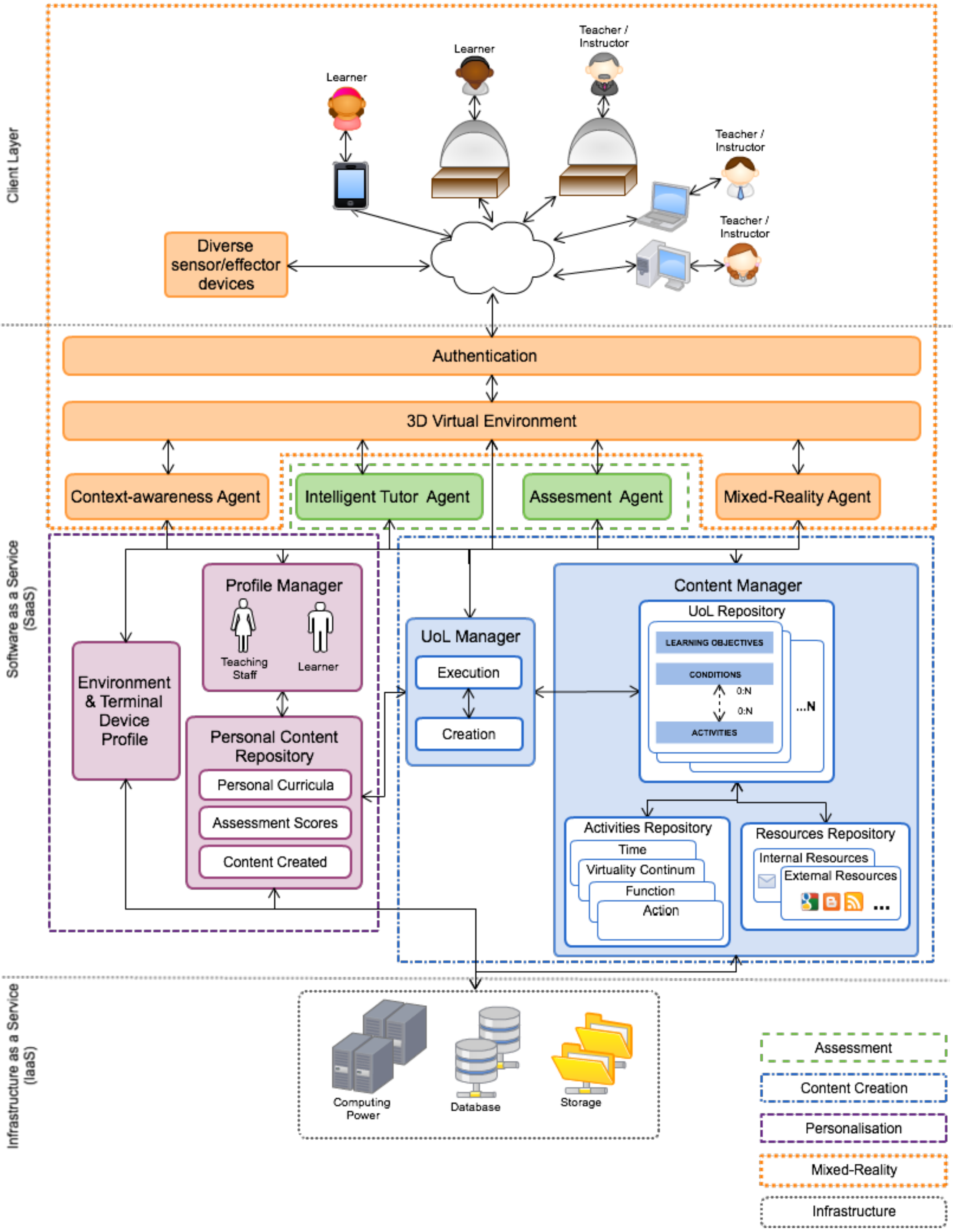


Figure 4.1: Mixed-Reality Smart Learning Model (MiReSL) (Pena-Rios et al., 2012a)

4.2 A distributed Blended-Reality framework

The MiReSL Model was proposed as a complete ecosystem for the use of mixed-reality in learning. However, as PhD time is a limited resource, it was necessary to prioritise and focus the research scope to what I considered to be the most critical element of the model, namely the creation of the mixed-reality learning environment, able to connect environments and learners around the globe in collaborative activities. However, the MiReSL model described has been used as a reference point for colleagues at the Immersive Education Lab Research Group at the University of Essex (Alrashidi et al., 2013a; Alzahrani et al., 2015; Felemban, 2015). Figure 4.2 shows the areas described at the original MiReSL Model encompassed in this research.

Based on this strategy, this thesis proposes a model for interconnecting multiple distant learning environments, allowing bidirectional communication between environments, smart objects and users using a synchronising mechanism to mix distributed physical and virtual devices. The goal of this interconnected learning environment is to enable hands-on activities for distance learners based in a collaborative group-based learning session. Figure 4.3 illustrates the three components of a blended-reality space:

a) The **physical world**, where the user and the physical objects are situated;

b) The **virtual world**, where the physical-world data will be reflected using 3D virtual objects, allowing multiple users/environments to be interconnected;

c) The ***Interreality Portal***, a human-computer interface (HCI) which receives and processes in real-time data generated by the physical environment, so it can be mirrored by its virtual counterpart. The fundamental task of the InterReality Portal is to detect changes in one environment and *translate* them into appropriate actions within the other environment. As

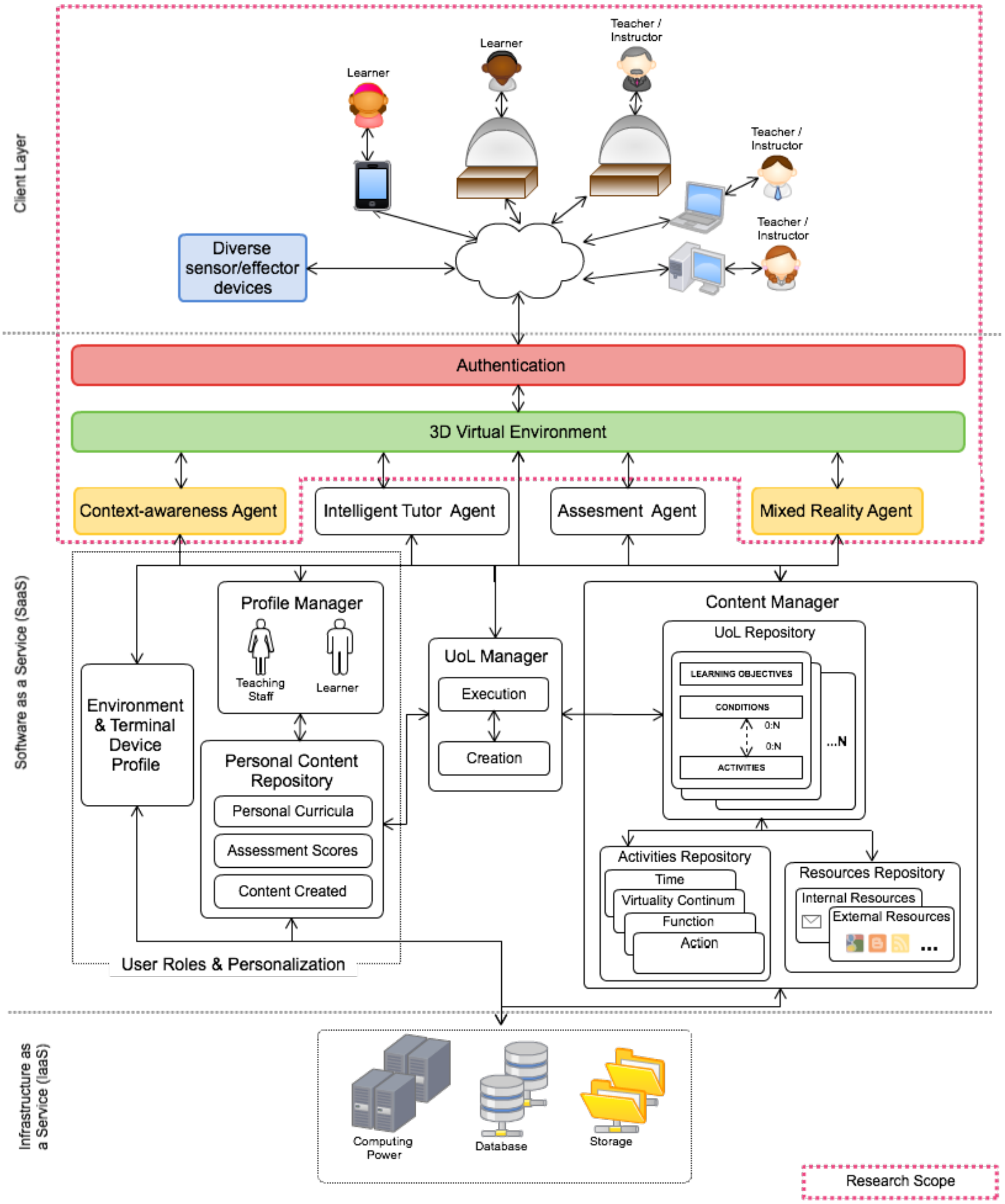


Figure 4.2: Mixed-Reality Intelligent Learning Model (Research Scope)

such the Interreality Portal has been one of the major focuses of this work and has produced many of the thesis contributions.

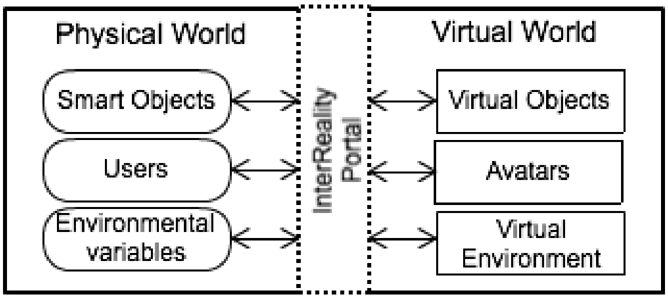


Figure 4.3: Blended-reality space (local)

A blended-reality space can be built upon the dual-reality principle of reflecting actions between elements within a physical and virtual environment (fig. 2.7). Figure 4.3 shows the correspondent mappings to link one physical environment with one virtual environment via the InterReality Portal (i.e. smart objects with virtual objects, users with avatars, and environmental variables with a virtual environment). Smart objects are used for two main reasons: a) its capability to sense and interpret their local situation and status, and b) its ability to communicate with other smart objects and interact with human users. Thus, if an object changes its state either in the physical or the virtual world, the change is immediately reflected in its mirrored object, linking both worlds in real-time; for example, turning on a network-controllable household device (e.g. a TV) would turn on its linked virtual representation (e.g. a 3D virtual object simulating a TV). Similarly, users could be linked to their avatars via wearable devices; tracking physical characteristics such as geographical location, or even emotions via physiological measurements (e.g. heart rate, PH level, etc.) and translating them to their virtual persona (avatar). In this mapping, clearly a change executed in an avatar cannot change the user physical appearance or physiological characteristics, but it could be reflected using multimodal feedback via the wearable device (e.g. a haptic response). Finally, environmental variables within the physical space (i.e. temperature, humidity, light level, etc.) could be captured via networked sensors and reflected in the virtual environment in multiple ways, for example, the value of a light sensor can be mapped to the sun within the virtual world, creating virtual sunsets and sunrises synchronised with the ones in the physical world. A change in the virtual world cannot be directly reflected in the physical environment (e.g. we cannot change the sun position at will), but the change could be translated using diverse actuators within a closed physical smart environment (i.e. a smart room). Figure 4.3 describes the connection between one physical space with one virtual space only, however, it could be possible to connect multiple separated physical spaces, linking them to a common virtual space by interconnecting and synchronising their elements, creating the illusion of one common extended space as showed in figure 4.4.

The work presented in this thesis focuses on the synchronisation between objects and environmental variables across multiple dual-reality spaces. Automated synchronisation between users/avatars (i.e. wearable devices that directly affect avatars in a virtual space) was not explored as represents by itself a body of research; thus the scope of this work was delimited to the creation of a distributed blended-reality space able to allow users in different locations interact and share objects, extending the spaces to allow them to work in collaborative hands-on learning activities.

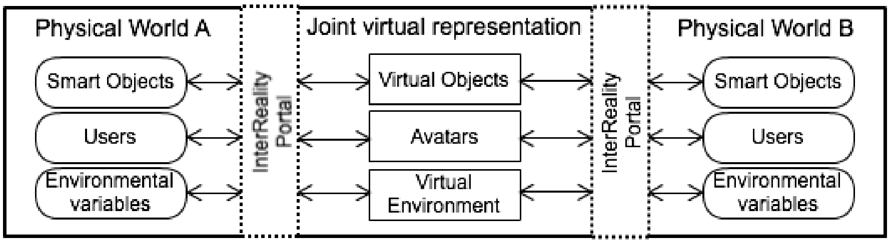


Figure 4.4: Blended-reality space (extended)

The next subsections introduce the proposed mixed-reality learning environment, the *InterReality Portal*, and the distributed architecture of interconnected portals that allow learners in geographically distributed locations work in collaboration, creating a large-scale education environment. As mentioned above this is an important aspect of the thesis that has given rise to important contributions.

4.2.1 The InterReality Portal

The InterReality Portal can be defined as a collection of interconnected physical and virtual devices that allow users to complete activities between the two extreme points of Milgram's Virtuality Continuum. From the educational point of view, and inspired in Callaghan (2010a) Science Fiction Prototype (SFP), it can be defined as a mixed-reality learning environment that allows remote students to do activities together using a mixture of physical and virtual objects, grounded on the learning-by-doing vision of constructivism. It is conceptually formed by four layers (fig. 4.5):

- The **Client layer or physical world**, which refers to the physical environment where the learner, the physical object(s) and environmental variables exist.
- The **Data Acquisition layer**, which is responsible for obtaining real-world information based on network eventing data produced by interactions between: a) the user and the physical objects, or b) the user and the physical environment.
- The **Event processing layer**, which retrieves a set of rules and actions (behaviours) available for the particular object/environment. These rules and actions determine the result in either the physical or the virtual environment, triggered by an interaction.
- Finally, the **Virtualisation layer** contains the 3D virtual environment, 3D virtual object(s) and avatar(s).

To link and synchronise physical and virtual worlds, any interaction/change in the physical world is identified by the Context-Awareness agent (CAag) (in the data acquisition layer); and sent to the Mixed-Reality agent (MRag) (in the event processing layer). Then, the Mixed-Reality agent (MRag) executes a correspondent action on the 3D virtual environment based on the behaviours available for that particular action and reflecting any changes accordingly. Similarly, changes from virtual to physical, are detected by the CAag and passed upon to the MRag, which sends the correspondent behaviour to the physical object (fig. 4.5), achieving bi-directional communication based on mirrored dual-reality states.

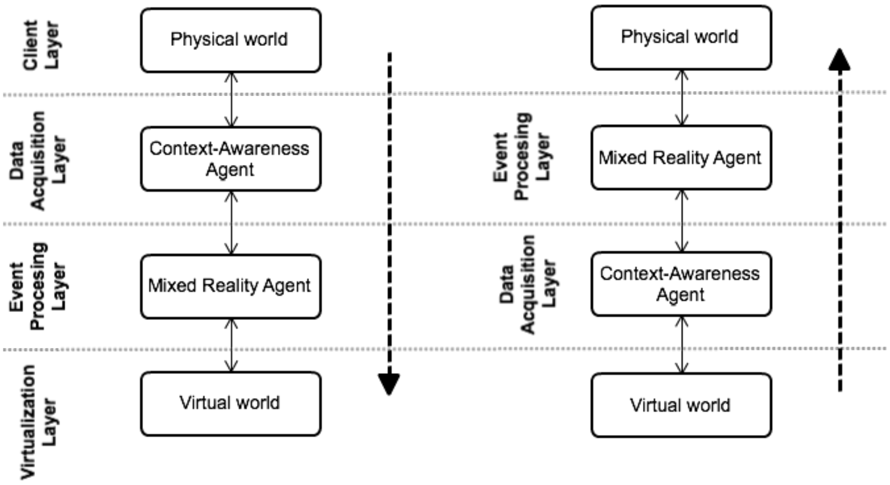


Figure 4.5: InterReality Portal. Conceptual Model (Pena-Rios et al., 2012b)

4.2.2 xReality objects

Cross-reality (xReality) objects are smart networked objects coupled to their virtual representations, updated and maintained in real time within a mixed-reality space. The difference between smart objects and *xReality objects* is that the digital representation of the latter emulates the shape, look and status of the physical object in a 3D virtual environment, and allows bidirectional updates; whereas the digital representation of a smart object, if implemented, is commonly represented as a 2D graphic or table in a graphical user interface (GUI).

Figure 4.6 shows the conceptual construction of xReality objects and the differences between them, physical objects, and virtual objects. **Physical smart objects** have a unique ID, and a list of minimum one available service; understanding as services all the properties inherent to the particular object (e.g. in the case of an internet-controllable lamp, its available services could be *turned on* and *turned off*). In a similar way **virtual objects** have a unique ID and one or more behaviours attached (e.g. in the case of a virtual light, its available behaviours could be *light intensity* and *light shadow*). Thus, **xReality objects** take characteristics of both objects, correlating them to synchronise physical and virtual worlds simultaneously.

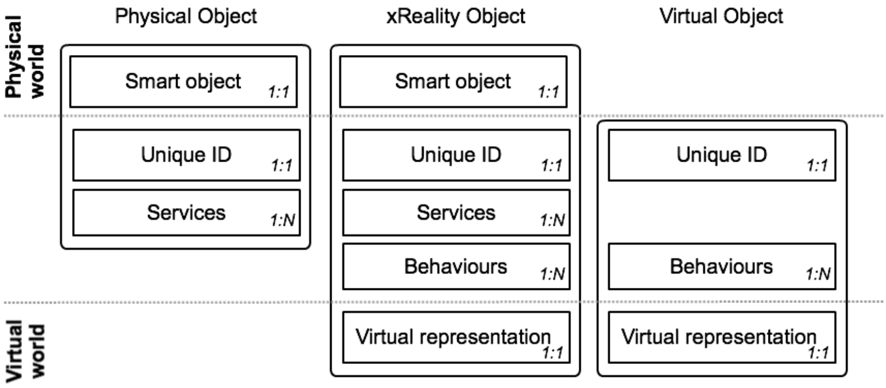


Figure 4.6: xReality Object. Conceptual Model

The synchronisation in real-time between physical objects and their virtual representations is exemplified in figure 4.7. Here, where an action is executed in a smart object within the physical world (e.g. turn Light1 on), the change is detected by the Context-awareness agent (CAag), which proceeds to: a) identify the object via its unique ID (e.g. UniqueID = Box_1), and b) send this information to the Mixed Reality (MRag) agent. The MRag determines which is the behaviour linked to that change in the smart object, and proceeds to update the virtual object (e.g. turn virtual Light1 on) in the visualization layer, and thus synchronising virtual with physical elements of a xReality object and creating a one-to-one interaction, which can be defined as a *single dual-reality interaction*. Therefore, in this example, every time the physical light changes its state, the

InterReality portal reflects this change in its virtual counterpart, and vice versa, linking and synchronising both objects in real-time.

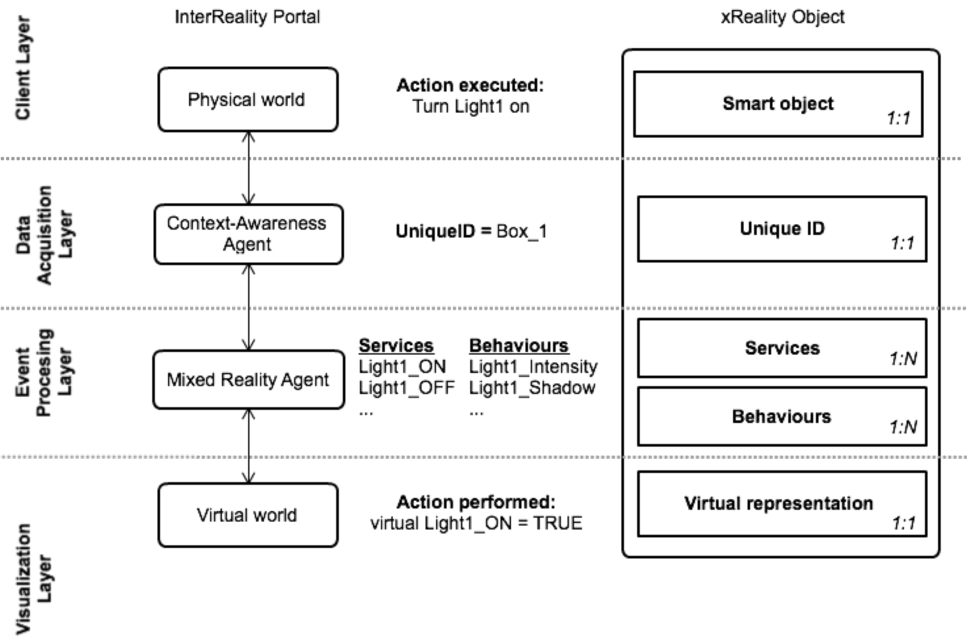


Figure 4.7: Relation between xReality objects and the InterReality Portal. Conceptual Model

4.2.3 Managing multiple xReality objects

As described in the previous section, the synchronisation between one physical object and one virtual object, creates a mirrored xReality object that exists in both worlds simultaneously; this real-time synchronisation that allows object's existence in both worlds is defined as a *dual-reality state*. Figure 4.8 shows the conceptual model of a complete InterReality system composed by the InterReality Portal and one xReality object. The diagram illustrates a one-to-one relationship between one physical object and one virtual object in a local mixed-reality space; however, when connecting a second InterReality system in a remote mixed-reality space, it is necessary to manage *multiple dual-reality states*.

Figure 4.9 shows the connection between two InterReality systems. Here, the

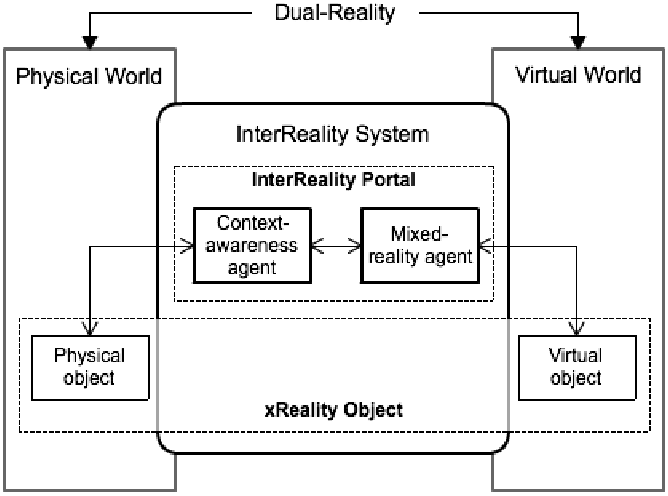


Figure 4.8: Single dual-reality state. Conceptual model

Context-awareness agent (CAag) periodically requests information from the physical object to identify any change on the object, when a change is detected the information is sent to the Mixed-reality agent (MRag) which translates this as an action in the virtual object. When this process is replicated on a second InterReality system, the Dual-reality agent (DRag) coordinates the synchronisation between multiple environments following these predefined rules (Pena-Rios et al., 2012b):

1. A change in a virtual object of a given InterReality system results in identical changes to all mirrored virtual objects in any subscribing InterReality portal.
2. A change in a physical object of a given InterReality system results in changes to the virtual representation of the physical device in all subscribing InterReality portals; and in changes to the physical objects linked to those virtual representations.

Therefore, a change in a physical object "A" is reflected first in its linked virtual representation within the local InterReality system; and then sent via the Dual-reality agent to any remote InterReality system connected at that time. The remote InterReality system first reflects the change in the virtual representation,

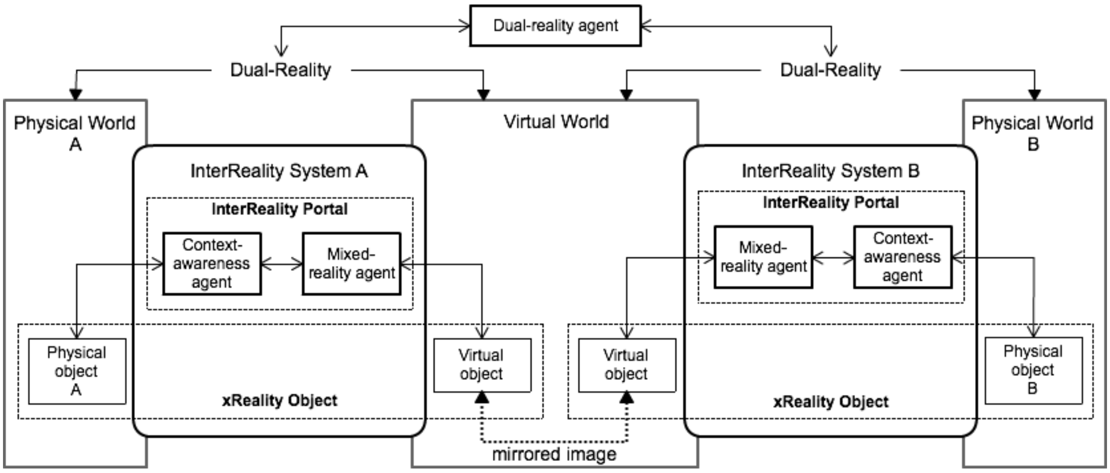


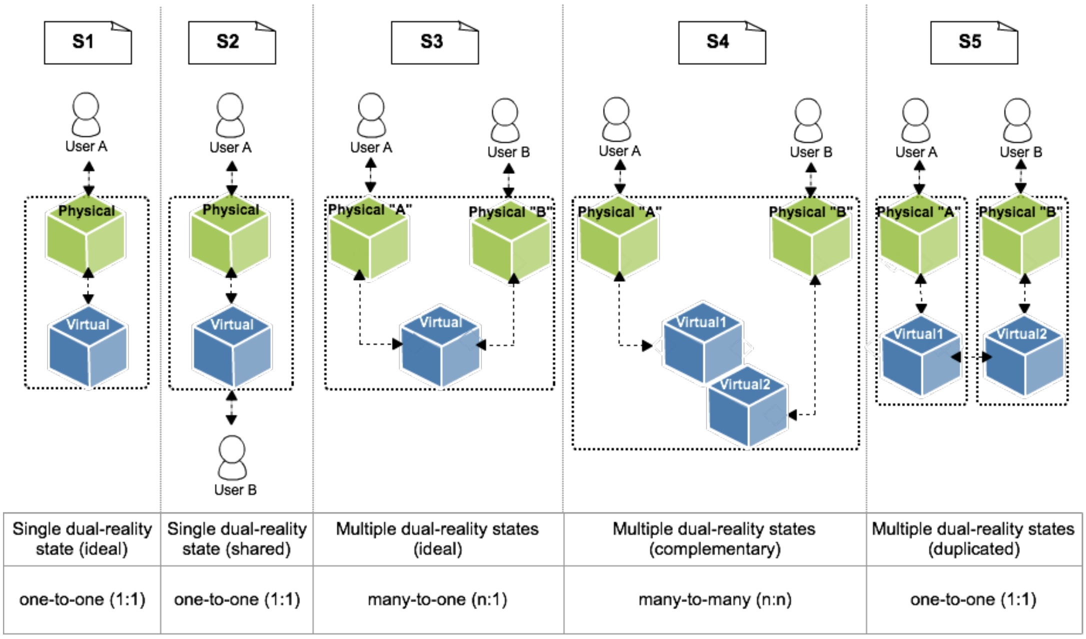
Figure 4.9: Multiple dual-reality states. Conceptual model

and then changes the status in the physical object “B”. When this mechanism is replicated using multiple xReality objects in each physical space, it is possible to mirror distant physical spaces and thus joining multiple distant environments based on a distributed mixed-reality architecture.

4.3 Interactions within distributed mixed-reality collaborative environments

The possibility of having multiple xReality objects in a distributed mixed-reality architecture introduces different scenarios for collaboration between distant users. Moreover, it allows the creation of mashups between local xReality objects and distant xReality objects, or the interaction between complete xReality objects (understanding them as a physical object linked to its virtual representation) with virtual objects (without links to a physical object).

Scenario S1 in figure 4.10 shows a single xReality object owned by one user in a local environment. This represents the ideal single dual-reality relationship that has been described in previous sections, which is formed by the synchronisation between one physical object (situated in the local environment) and one virtual



Single dual-reality state (ideal)	Single dual-reality state (shared)	Multiple dual-reality states (ideal)	Multiple dual-reality states (complementary)	Multiple dual-reality states (duplicated)
one-to-one (1:1)	one-to-one (1:1)	many-to-one (n:1)	many-to-many (n:n)	one-to-one (1:1)

Figure 4.10: xReality interactions (Pena-Rios et al., 2013)

object (described as a one-to-one relationship). Is this one-to-one relationship which creates a local blended-reality environment (fig. 4.11).

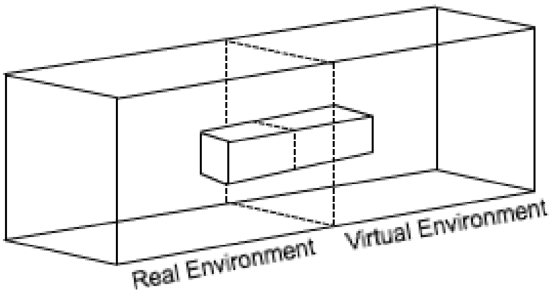


Figure 4.11: Single dual-reality

When an additional user joins, he/she can interact with the remote physical object via the shared virtual representation (scenario S2); or via a local physical object linked to the same virtual representation (scenario S3), creating a many-to-one relationship (many physical objects connected to one virtual representation). The relationship between physical and virtual objects described in scenario S3 represents an extended blended-reality environment (fig. 4.12), in which an element is reflected in the virtual environment and linked using its virtual entity to another object in a remote space, showing a *continuous* shared element within spaces (physical-virtual-physical) with multiple dual-reality states.

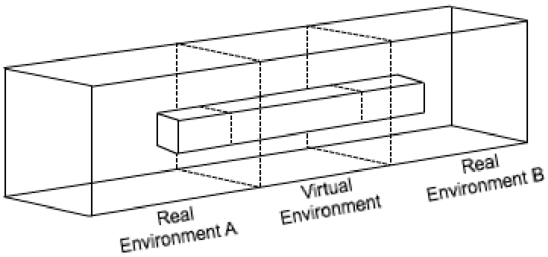


Figure 4.12: Multiple dual-reality

The scenarios described so far use only one physical object in the local environment or one in both, the local and the remote space; however, when adding more physical objects to each environment it is possible to create mashups between multiple xReality objects. Scenario S4 describes a collaborative session where users combine xReality objects that physically exist in the owner's local environment, but can be shared and combined using its virtual representation in the virtual world, creating a complete new object in the virtual. As an analogy, this can be seen as a puzzle where each of the participants have one or more pieces that allows the completion of the final object inside the virtual world (fig. 4.13).

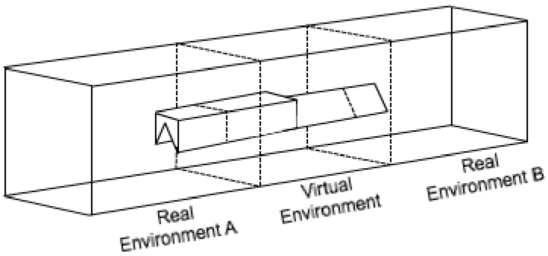


Figure 4.13: Multiple complementary dual-reality

Finally, scenario S5 shows the possibility of having two or more xReality objects that do not complement to each other, but instead, both exist as separate entities inside the common virtual space (fig. 4.14).

By way of an illustration of the different combinations that can be used to create a xReality object, we can imagine that two users (A and B) are collaborating in the creation of a clock alarm (fig. 4.15). User A has the speakers which play the

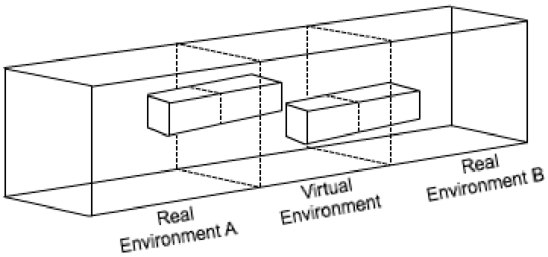


Figure 4.14: Multiple duplicated dual-reality

alarm sound and user B has the "snooze" button and the LCD that shows the time. All the objects have a mirrored virtual representation within the virtual world, therefore all of them are xReality objects by itself. However, when combined, they create a mixed-reality clock alarm that reproduces the sound in space A and can be stopped with the button in space B.

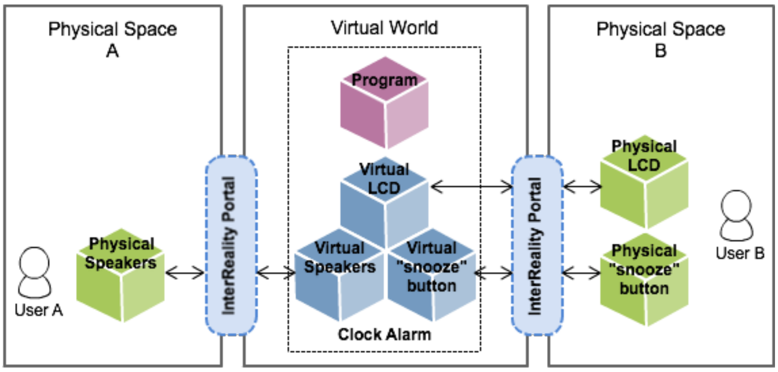


Figure 4.15: xReality object. Example

The final mashup can be seen in the virtual world and users can interact with it from there. For example, user A which only has the speakers could press the virtual "snooze" button with the same effect as if he/she had pressed the physical one. In addition to the communication between pieces (i.e. speakers, LCD, a button), a program needs to be included in the final mashup to add the desired functionality (e.g. stop the sound when pressing the "snooze" button). This program is considered as an additional virtual element (with no physical representation) which allows the combination of available functions for each xReality object (i.e. speakers sound, detection of a button press). Another additional virtual element could be different software processes, threads or apps required for achieving the final functional mashup. Thus, in addition to the combination between mirrored physical/virtual elements, a xReality object includes a combination between soft and hard components that allows it to achieve a desired behaviour.

4.3.1 Adjustable Mixed-Reality

The scenarios described in the previous section introduce the possibility of having different degrees of mixed-reality between two or more interconnected environments based on communication between xReality objects, which can be defined as Adjustable Mixed-Reality. The more xReality objects are used in a shared environment, the less simulated the environment is, and vice versa (fig. 4.16). Thus, by adding or removing xReality objects in the shared blended-reality environment, it is possible to decrease or increase the amount of virtuality or reality, creating dynamic mixed-reality environments, which can be useful for the creation and testing of functional prototypes in distributed teams, or in collaborative hands-on activities, such as laboratory activities for distance learners.

Figure 4.16: Adjustable mixed-reality

4.4 Classification of learning activities

The creation of the proposed blended-reality distributed architecture poses two different types of challenges: firstly, the creation of a technical infrastructure able to work as a link between remote environments by reflecting information of physical/virtual objects in real-time. Secondly, the ability of such environment to allow remote users performing collaborative activities, to generate a specific outcome, depending on the context where the technology is used (e.g. a learning outcome, a functional prototype, etc.).

The first challenge has been addressed widely in this chapter. Regarding the second challenge, it is necessary first to identify the uses and dimensions of distributed mixed-reality. Lee et al. (2009) identified three key dimensions for ubiquitous virtual reality (U-VR) that can be applied to distributed mixed-reality:

- *Reality*, which refers to the point where the implementation is located in relation with Milgram's virtuality continuum (Milgram and Kishino, 1994).
- *Context*, which refers to the flexibility to change and adapt according to time and space. Context can be presented as a continuum ranging from static to dynamic.
- *Activity*, which refers to the number of people that will execute an activity within the implementation, going from a single user to a large community.

Similarly, Alrashidi et al. (2013b) proposed a 4-Dimensional Learning Activity Framework (4DLAT) that classifies learning activities by number of learners and complexity of the task. Thus, as part of the MiReSL model, this thesis proposes a classification of learning activities to identify the affordances of the proposed model, but above all, MiReSL learning activities classification (MiReSL-LA) helps to delimit and design the activities that can be done within the InterReality system (i.e InterReality Portal and xReality objects), which as explained before is the main focus of this research. MiReSL-LA (fig. 4.17) is formed by:

1. *Virtuality Continuum-based activities* classifies activities in base of their interaction with physical and virtual objects.
2. *Timing-based activities* refer to the time when activities are taking place. For example, **synchronous activities** involve the execution of activities

between two or more participants at the same time (e.g. team-based collaboration); whereas **asynchronous activities** may be completed individually, (e.g. research, personal assessment, etc.).

3. *Function-based activities* refer to the nature of the activity itself. For example, if it is a main **Learning Activity** such as lectures or a **Support Activity** such as coursework.

4. *Action-based activities* refer to the main work being undertaken in the activity. **Task-based activities** are events that result in a deliverable. **Simulation/Emulation activities** involve activities with physical-virtual devices. Finally, **role-play activities** refer to role definitions performed within game structures and supported by co-creative rules.

5. *By number of participants* includes activities designed for an individual (**Single-user activities**) or for groups of people (**Collaborative activities**).

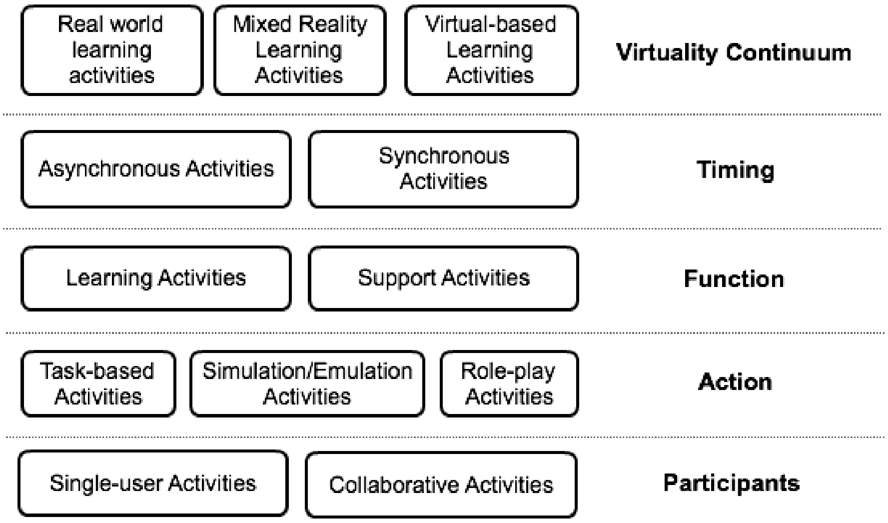


Figure 4.17: Classification of Activities in the MiReSL model (MiReSL-LA)

This is not a strict classification, as many activities can be classified in two or more categories simultaneously and could fuse with one another in order to create new learning experiences. Based on this classification, figure 4.18 shows the activities available within the proposed InterReality system, which allows the execution of MR learning activities via the use of xReality objects, and virtual-based activities by using just virtual objects on the virtual environment; allowing students without a physical object, to participate in learning sessions. The collaborative nature of the activity makes it synchronous, where students need to gather to coordinate and test different options to achieve a final result. Finally, laboratory activities are, by nature, a complement of the main lecture, a hands-on experience that allows students to correlate theoretical knowledge with real-life activities. Taking this into consideration, tasks within the proposed model can be considered as supporting activities, and due to the hands-on factor, they are task-based and simulated/emulated activities due to the nature of the xReality objects.

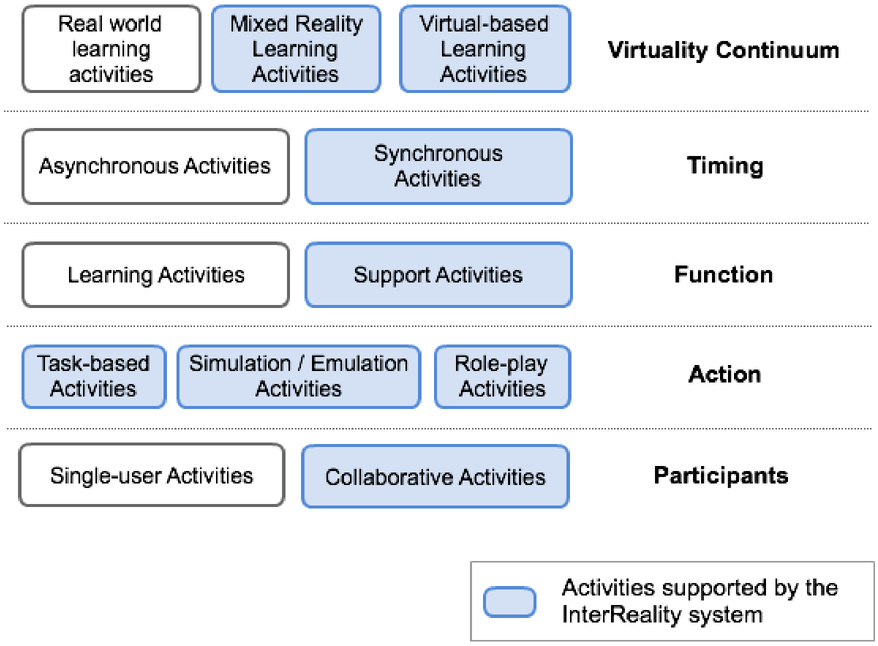


Figure 4.18: Classification of activities available in the InterReality system

In addition to the challenges previously described, the proposed blended-reality distributed architecture presents the challenge of bridging the model of distributed xReality objects with the pedagogical model of constructionist laboratories to produce a solution for distributed mixed-reality laboratories. As discussed in the previous chapter, the use of deconstructionism in a collaborative mixed-reality laboratory architecture can be used to unify a constructionist pedagogy (in which learning is a consequence of the correlation between performing active tasks that construct meaningful tangible objects in the physical world and relating them to personal experiences and ideas), with a set of mirrored physical/virtual objects and their supporting soft components (e.g. programs, software processes, threads, apps), which can be construct/deconstruct in different mashups to support science and engineering hands-on activities. Table 4.1 summarises the affordances of the proposed InterReality System towards the creation of a mixed-reality learning environment formed by multiple interconnected multidimensional spaces, and able to support collaborative hands-on activities within distance learners.

	Affordances	**Description**
1	Simulation of physical objects	Enable the use of virtual objects.
2	Emulation using a mixture of physical and virtual mirrored objects (xReality objects)	Instantiation of diverse scenarios of single and multiple dual-reality states.
3	Creation of physical-virtual mashups using a deconstructionist model	Creation of mashups using services available in static and nomadic xReality objects.
4	Collaborative sessions between 2 or more users	Support the use and sharing of xReality objects within an environment, regardless its physical location.

Table 4.1: InterReality system affordances

4.5 Summary

This chapter, introduced the Mixed-Reality Smart Learning model (MiReSL) which described a learning ecosystem based on a conceptual computational architecture that included aspects such as personalisation, content creation, assessment and mixed-reality learning environment. Along with this model, a classification of learning activities (MiReSL-LA) that can be performed in mixed-reality learning environments was proposed to identify the affordances of such model. The

MiReSL model was introduced to contextualise the research presented in this thesis, which focuses on the mixed-reality aspect of the aforementioned model. Based on this, the chapter also provided a high-level overview of a mixed-reality distributed computing architecture based on two main supporting concepts that form an InterReality system: the InterReality Portal and xReality objects. The InterReality system was proposed as a solution to bridging virtual and physical worlds, and to merging remote spaces towards the creation of a distributed blended-reality space via the synchronisation of their elements. Both, the MiReSL model and its supporting InterReality system are important novel contributions and will be detailed at an implementation level in the following chapter.

As part of the discussion, the chapter described novel combinations of synchronised physical and virtual objects based on the principle of dual-reality and the concept of cross-reality first defined by Lifton (2007); Paradiso and Landay (2009), but which, by way of a contribution to the field, were extended from single one-to-one virtual/physical relationships to multiple combinations in different scenarios, exploring different possibilities for managing, sharing and using objects within a blended-reality space; and allowing users to adjust the degree of mixed-reality based on the number of xReality objects used. Both elements of the InterReality system, the InterReality portal and the xReality objects, presented a simple principle which could be applied to different scenarios of collaboration between geographically distributed teams, such as product design in a Research & Development department, or an educational scenario such as the one introduced in previous chapters.

The following chapter details the implementation of an InterReality system, and the architecture that enables interconnection between multiple InterReality system implementations to create a distributed blended-reality system, following the principle of construction/deconstruction applied to collaborative educational activities for distance learners.

Chapter 5

Experimental Framework

"Life is not a problem to be solved, but a reality to be experienced."

— Soren Kierkegaard (1813-1855)

Previous sections of this document presented a scenario and rationale for collaboration in distance learning based on multidimensional spaces. This included a conceptual framework for the use of cross-dimensional objects in a mixed-reality learning environment. This chapter describes the strategy used for the implementation of the experimental proof-of-concept demonstrator, which was divided into three phases, illustrated on figure 5.1. Phase 1 involved the construction of a functional mixed-reality learning environment (the BReal Lab), formed by an InterReality Portal able to work with xReality objects, implementing detection, identification and management of *dual-reality* states. Phase 2 concerned building a distributed architecture of multiple working InterReality systems, allowing interconnection of xReality objects in separate locations, and managing its multiple *dual-reality* states. Finally, phase 3 explored the design and implementation of a mixed-reality collaborative laboratory activity from learner's perspective.

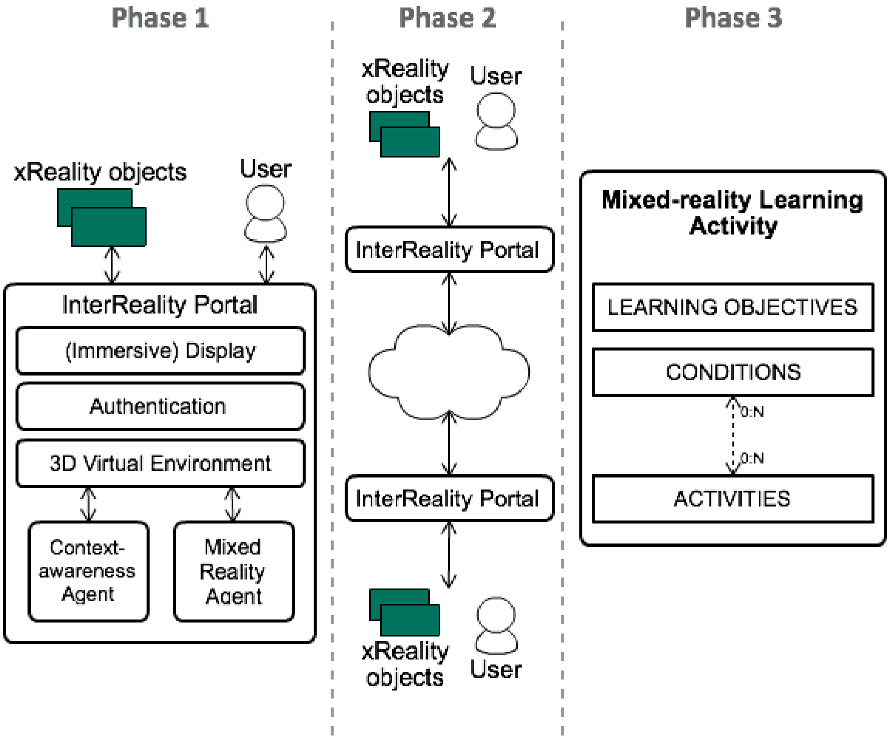


Figure 5.1: Implementation plan

5.1 The Blended-reality Lab (BReal Lab)

The Blended-reality Lab (BReal Lab) is the implementation of the mixed-reality learning environment proposed in previous sections. It is formed by the InterReality Portal and xReality objects; and comprises the mechanisms that allow users to interact between physical and virtual worlds. Figure 5.2 shows the BReal Lab architecture, where the physical component of the xReality object connects via local network to the InterReality Portal, sending information in real time. The InterReality Portal, via the Context-awareness agent (CAag), captures this information and sends it to the Mixed Reality agent (MRag) to represent it in the 3D virtual environment.

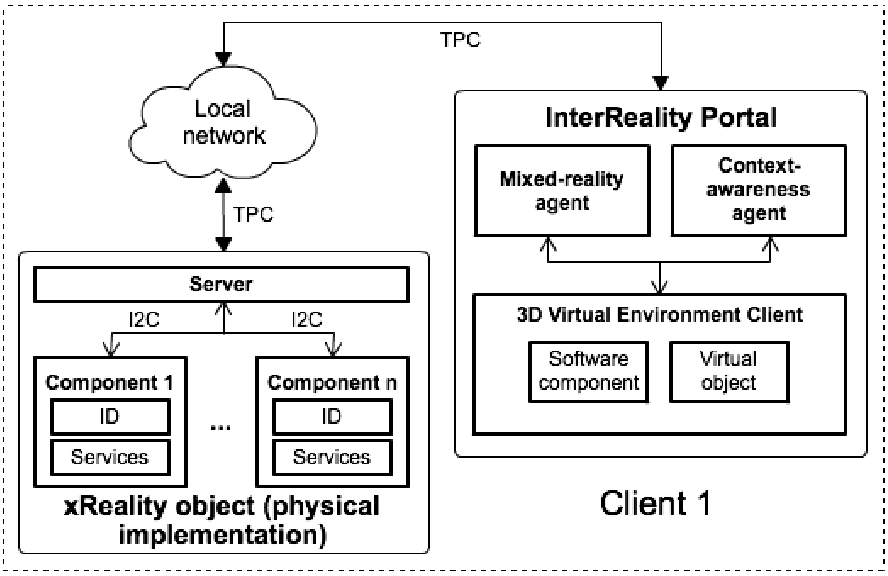


Figure 5.2: The BReal Lab architecture

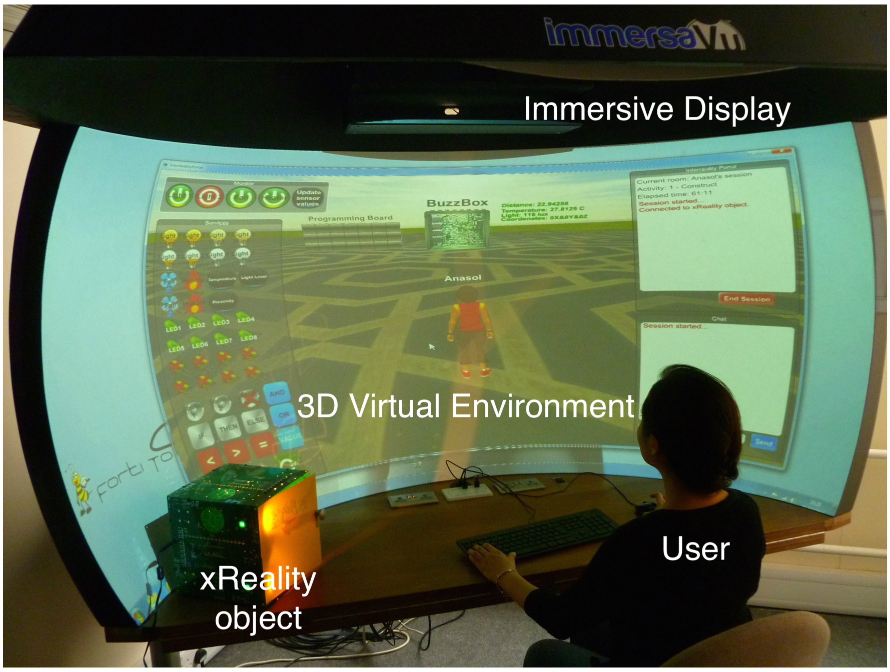


Figure 5.3: The BReal lab implementation

5.1.1 InterReality Portal implementation

The InterReality portal, as defined previously, is an interface that allows the connection between physical and virtual worlds towards the creation of a blended-reality space. Thus, implementation of such interface is formed by components in both, the physical and the virtual world, and should achieve a certain level of psychological *immersion* able to avoid the separation between both worlds. Ideally, according to Slater and Wilbur (1997) definition of immersion, it should be highly inclusive (I) to allow technology to pass unnoticed, highly extensive (E) to include multi-sensory stimulus, with a high degree of surrounding (S) to have a panoramic field of action, and with a high level of vividness (V) to diminish differences between virtual and physical worlds.

These characteristics eliminates the possible use of closed VR HDM as they allow just immersion in the virtual world, keeping the physical world excluded. The use of CAVEs although allows inclusion of physical objects, creates an isolated artificial space with less possibility of incorporate real world situations. Thus, implementation of the physical environment was done using a semi-spherical sectioned screen with a desk attached (fig. 5.3, 5.4), allowing interaction with the physical environment and a natural position for performing learning activities, with a free-range of head movement without the need of any intrusive body instrumentation (e.g. special glasses). A disadvantage in the use of special equipment such as the one described, is that usually it is only available in universities and research centres. Therefore, for experiment purposes, when distant participants had no access to such device, implementation was done using a simpler setting based on a wide screen or when possible a projector.

Implementation of the virtual component was done using a 3D virtual world that acted as GUI between physical and virtual worlds, connecting remote environments. It contained a virtual representation of all the elements of the physical learning environment; namely, representations of the user (personified in an avatar), virtual counterparts of xReality objects and a virtual representation of the environment itself (fig. 5.5). Additionally, it included communication capabilities between users via a chat window; and a mechanism to control and combine services available within the xReality objects with the aim to create virtual-physical

Figure 5.4: Immersive Display Group's ImmersaStation [1]

mashups, which will be described later.

Distance: 19.28424
Temperature: 27.25 C
Light: 0 lux
Coordenates: 0X&0Y&0Z

Current room: Ana's session
Activity: 1 - Construct
Elapsed time: 0:58

Ana said: Hello!

Figure 5.5: InterReality Portal 3D GUI

The virtual environment implementation (fig. 5.5) was developed using Unity3D[2], a cross-platform game engine for creating interactive 3D content which supports C# and JavaScript routines. Unity3D was used instead of existing virtual world

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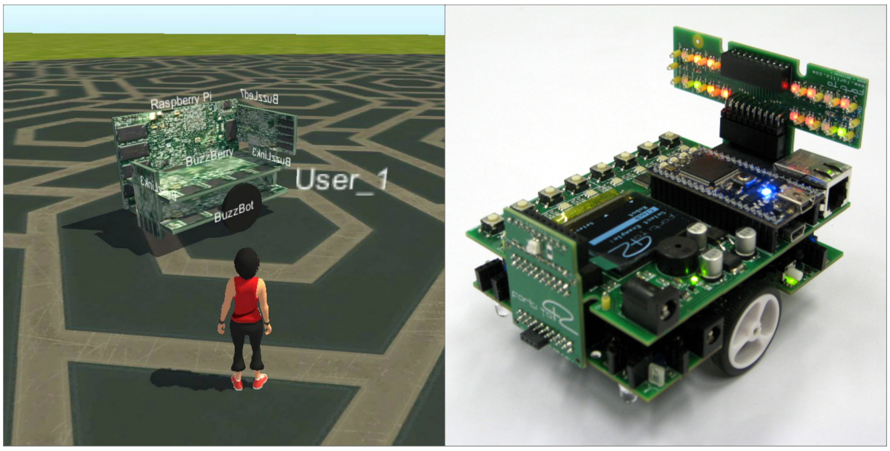
[1] Immersive Display Group - www.immersivedisplay.co.uk

[2] Unity3D Game Engine – www.unity3d.com

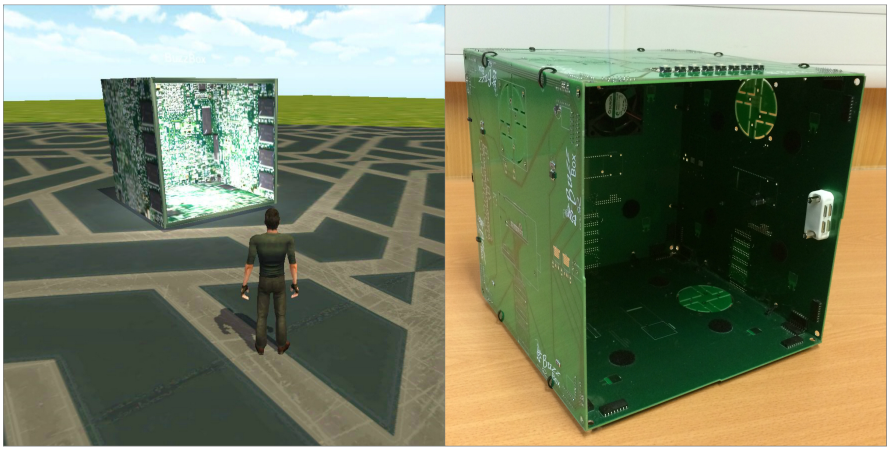
platforms, such as SecondLife[3] or OpenWonderland[4], because of the flexibility that it provided to create and adapt a virtual world.

5.1.2 xReality objects implementation

As defined previously, an xReality object is a networked smart object able to keep and maintain a virtual representation of itself in real time (fig. 5.6).



(a) Desktop-size robot



(b) Desktop-size Smart Room

Figure 5.6: xReality object implementation

The physical implementation is formed by two parts (fig. 5.7):

- The main module, which detects other components and works as a hub to

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[3] SecondLife - www.secondlife.com

[4] OpenWonderland - www.openwonderland.com

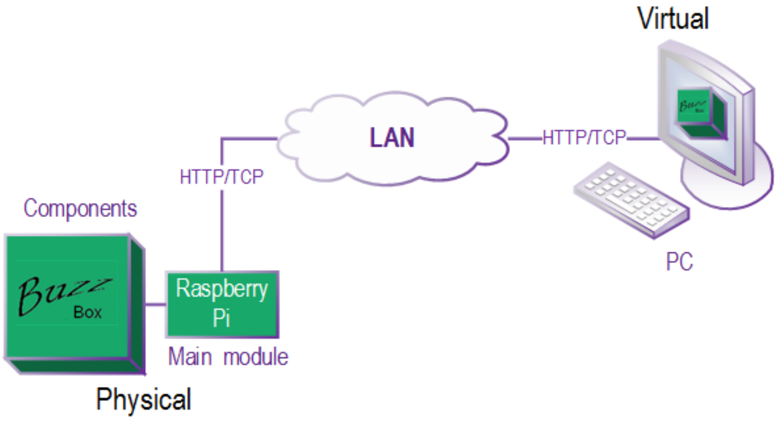

Figure 5.7: xReality Object. Architecture

connect them to the virtual object within the interreality system;

- A group of interchangeable pluggable components which comprises different actuators and sensor capabilities to allow bi-directional communication between both worlds and, the creation of diverse physical mashups.

The main component was implemented using a Raspberry Pi[5] (RPi), a small low-cost computer which uses a linux-based operating system. The Raspberry Pi (fig. 5.8) is an open-source single board computer created for educational purposes; however, due to its cost, size and low power requirements, it has been used as a component in embedded systems and implementations by hobbyist and creative makers worldwide (Brock et al., 2013; Halfacree and Upton, 2012).

The interchangeable pluggable components were implemented using Fortito's BuzzBoard Educational Toolkit[6] range (fig. 5.9), a set of diverse pluggable network-aware hardware boards which can be interconnected allowing the creation of quick Internet-of-Things (IoT) prototypes by using combinations of modules plugged together (Callaghan, 2012; Wang et al., 2011a).

A key feature, and reason for choosing BuzzBoards, was that they used I2C as their intercomponent connect scheme. This made it ideal for mixed reality, as it

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[5] Raspberry Pi Foundation - http://www.raspberrypi.org

[6] Fortito - http://www.fortito.com

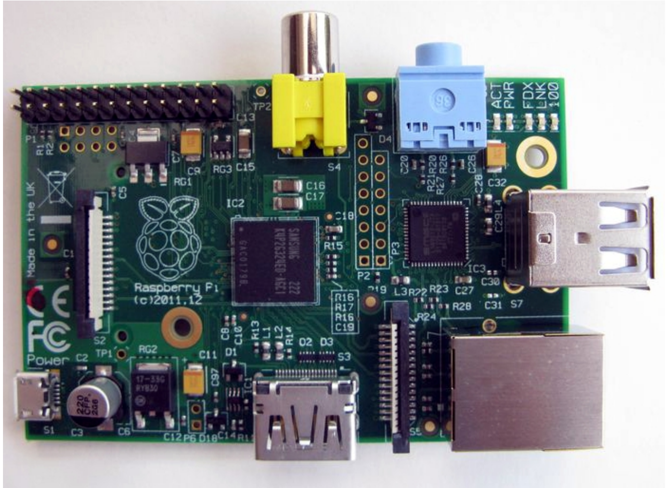

Figure 5.8: Raspberry Pi 1 model B revision 2

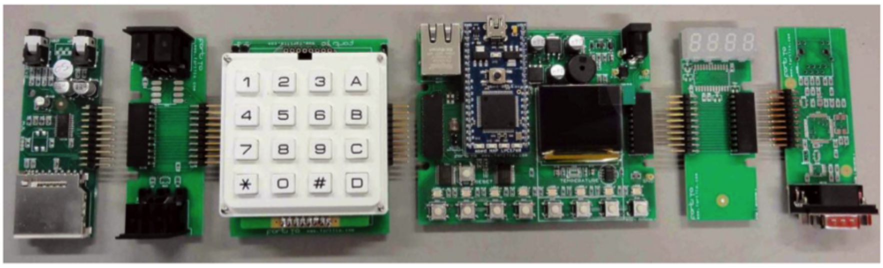

Figure 5.9: FortiTo Buzz Boards

was possible to implement discovery and communication between the components (i.e. BuzzBoards) and the main module (i.e. RPi)), reporting on connection topology and status. However, in order to do that, it was necessary to develop and implement an API[7] based on the *python-smbus* module, which allows SMBus access through the Inter-Integrated Circuit bus (I^2C) /dev interface on Linux hosts (The Linux Kernel Archives, 2009). Python is an open-source general-purpose multi-paradigm programming language which promotes simplicity and code readability (Python Software Foundation, 2001). I^2C is a multi-master serial single-ended computer bus created by Philips in 1982 for attaching low-speed peripherals (NXP Semiconductors, 2014). The System Management Bus (SMBus) is a subset of I^2C defined by Intel in 1995 (The System Management Interface Forum (SMIF) Inc., 2009). Figure 5.10 shows an exemplar implementation of the

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[7] API available at: www.github.com/prlosana/BuzzBoards under the GNU AFFERO General Public License

physical part of an xReality object.

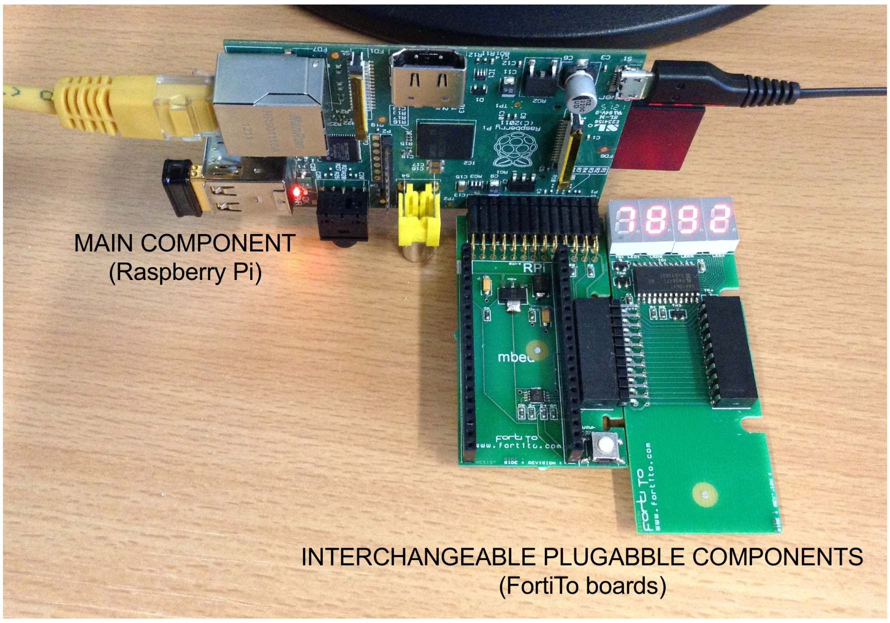

Figure 5.10: Example of xReality object (physical component)

Figure 5.7 illustrates the architecture of a xReality object. Communication between the InterReality portal and the xReality object is based on the Transmission Control Protocol / Internet Protocol Communication (TPC/IP), following ideas of the Web-of-Things (WoT), which propose the use of web standards to integrate real-world things into the existing Web (Guinard and Trifa, 2009; Guinard et al., 2011). Following this approach, RESTful web services were implemented for the pluggable components (i.e. BuzzBoards). Each BuzzBoard was decomposed into controllable services using Uniform Resource Identifiers (URI) and HTTP's main operations (GET, POST, PUT, DELETE) sending and retrieving information as a JSON object. This was implemented on the RPi using Bottle[8], a Python-based Web Server Gateway Interface (WSGI) distributed as a single file module with no dependencies other than the Python Standard Library which makes it simple and lightweight. However, preliminary communication tests showed a slow performance generally imperceptible in other applications, but vital in the implementation of a blended-reality space, as it depends on a high level of synchro-

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[8] Bottle: Python Web Framework - http://bottlepy.org/docs/dev/index.html

nisation between physical and virtual worlds. Overheads in the use of RESTful communications for the WoT were caused as a result of two factors: a) the constant opening/closing of TCP connections, b) the need of sending/receiving HTTP headers on each of those requests (Bovet and Hennebert, 2013; Gupta, 2014). Due to this, a second implementation using persistent TCP connections (also known as WebSockets) was done. WebSockets are used for managing event-based communications where the channel is kept open on both sides as long as possible (Fette and Melnikov, 2011; Bovet and Hennebert, 2013). This was achieved using Twisted[9] an open-source event-driven networking engine written in Python used to implement custom network applications. Socket implementation in the InterReality Portal was done inside the 3D GUI creating the correspondent c# libraries in Unity3D.

5.1.3 xReality objects' End-User Programming

Finally, functionality of the xReality object is depicted as a list of available services for the BuzzBoards (e.g. lights on and off, fan on and off, alarm sound on and off, etc.) on the left menu at the GUI main screen (fig. 5.11a). By combining different modularised components in an xReality object, a number of functionalities (services) become available on the menu. These services represent atomic functions which can be combined into a nuclear function (program) to create behaviour for the xReality object(s).

Additionally, the Services menu lists a series of conditional instructions (IF, THEN, ELSE), logical operators (AND, OR), and mathematical operators (GREATER THAN, LESS THAN, EQUAL THAN) which can be added to create a program. Figure 5.11b shows the programming tool, designed on the principles of programming via analogy (i.e. using graphical icons or physical representations), to allow

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[9] Twisted Matrix Labs - https://twistedmatrix.com/trac/

(a) Services Menu (atomic functions)

(b) Programming Board (nuclear function)

Figure 5.11: InterReality Portal. End-user programming environment

the construction of behavioural rules. As an example, figure 5.11b illustrates an IF-THEN-ELSE behavioural rule written in the "Programming Board" which can be interpreted as:

```
IF TEMPERATURE is greater than 10
THEN turn LIGHT_1 and LIGHT_2 on,
ELSE turn LIGHT_1 and LIGHT_2 off
```

Similarly to the relationship between services (atomic functions) and programs (nuclear functions), the physical modules (i.e. the sets of autonomous networked resources) represent atomic functions on the physical world, as they can be reconstruct into different combinations creating new physical mashups (nuclear functions). Is the combination between hardware and software components (programs) what creates a complete functional xReality object.

5.2 A distributed blended-reality architecture

Figure 5.12 illustrates the proposed architecture for the implementation of the distributed blended-reality system. It is based on a client-server model where, once the physical and virtual objects of one local environment are synchronised, the information of the current status is sent to an authoritative server which broadcasts the information to all the environments/objects subscribed to that particular shared mixed reality session; replicating the synchronisation mechanism in each local environment, interconnecting xReality objects, and creating multiple dual-reality states.

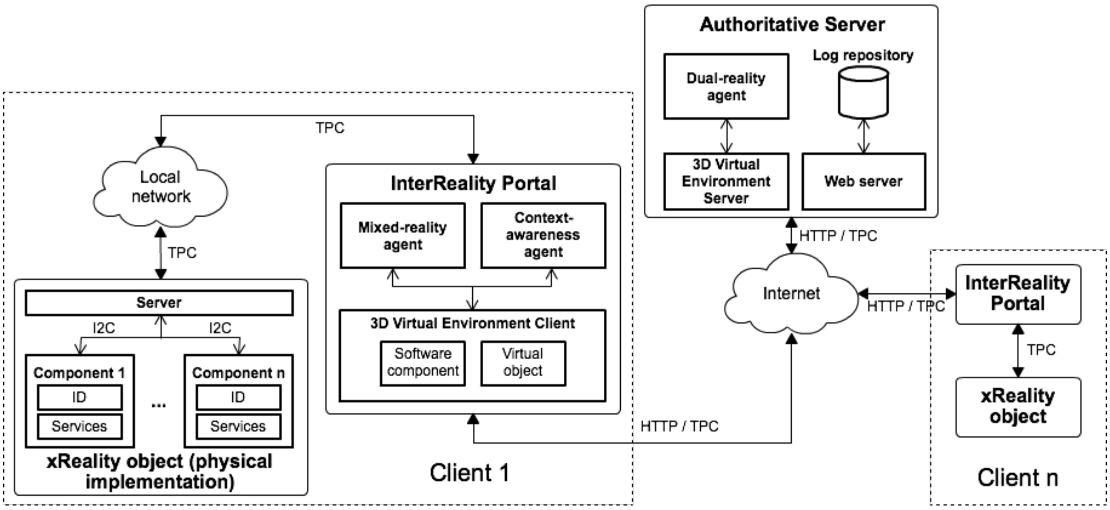

Figure 5.12: Blended Reality Distributed System architecture (Pena-Rios et al., 2013)

Figure 5.13 shows the implementation of the distributed architecture. The server implementation was done using SmartFoxServer X2 (SFS2X)[10], a middleware platform optimized for real-time large scale multiplayer games, massively multiplayer online games (MMO) and virtual communities. SFS2X provides an API able to connect multiple clients to the server via a persistent connection (us-

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[10] SmartFoxServer - http://www.smartfoxserver.com

ing the TCP protocol). Using this connection, the server was able to maintain mirroring and communication between xReality objects, sending back synchronisation messages to every client.

The server implementation also includes a MySQL database[11] to keep a log of the actions performed by users within the system. MySQL is an open-source relational database management system (RDBMS) popular on web applications. As creating direct connections between the Unity3D client (which needs to be installed on user's computers) and the database is not a recommended practice, because it would create a security hole, it was necessary to include PHP[12] scripts hosted on a web server in the server machine. PHP is an open-source server-side scripting language created in 1995 that can be embedded into web pages. Requests to the web server were triggered via HTTP requests inside Unity's WWW class.

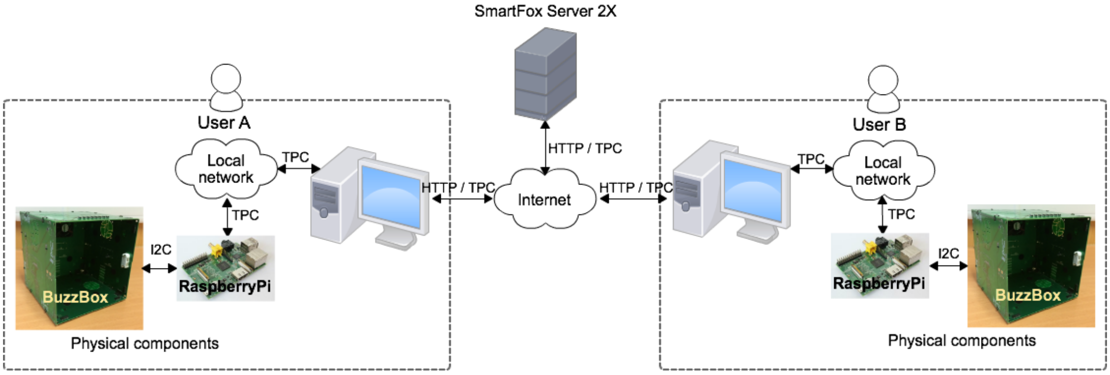

Figure 5.13: Distributed blended-reality implementation

5.2.1 Multiple xReality objects implementation

Figure 5.14 describes the synchronisation between the physical components of an xReality object and the InterReality Portal. To use the BReal Lab, users need to login to the InterReality Portal (fig. 5.16a), which after creating a session on the server, attempts to start a connection to the xReality object(s) using its IP address

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[11] MySQL - www.mysql.com
[12] PHP - www.php.net

and port previously configured in the 3D GUI (fig. 5.16b). The InterReality Portal establishes a connection with the main module of xReality object's physical implementation (i.e. Raspberry Pi), which verifies the status of any connected physical component (i.e. BuzzBoards). Once the connection with the xReality object is established, the InterReality Portal creates a virtual representation of the object (as showed on figure 5.6). At this point, both objects are connected, thus, when an action is triggered either in the virtual or physical world, the InterReality portal parses the information retrieved and sends an update to its mirrored object, triggering a similar action, creating a dual-reality state (fig. 5.15).

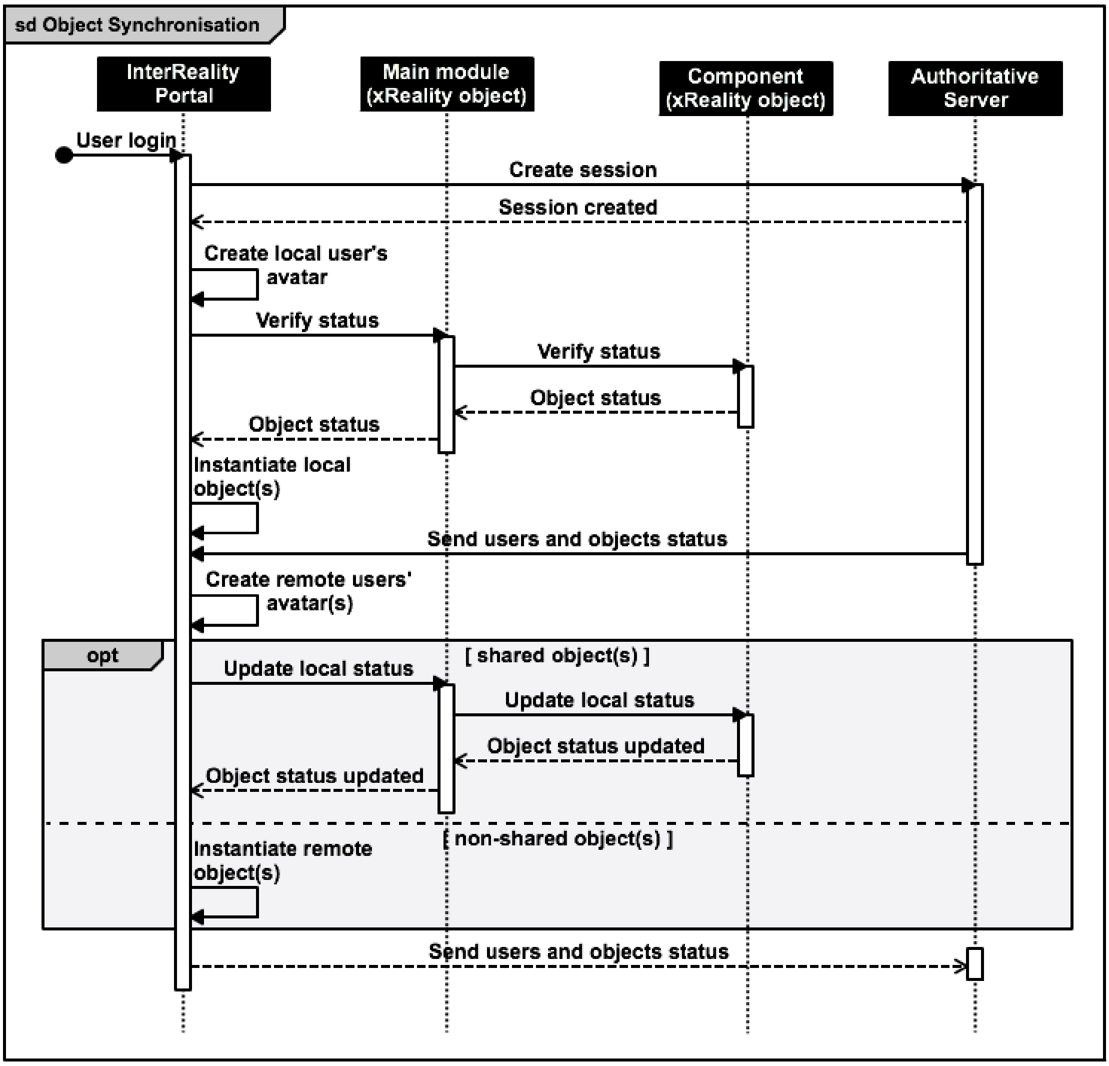

Figure 5.14: BReal Lab. Interaction Diagram

After creating the local xReality object, the InterReality Portal receives information sent by the server about current users and objects within the session. Based on that, the InterReality portal a) creates users' avatars; b) if there is a remote xReality object with the same ID, it updates the local xReality object with the status information sent by the server; otherwise it creates the virtual instances of the distant xReality objects. When interconnecting a specific local xReality object with a remote one that shares the same ID, the object leading the changes is the one that was created first in the session. For example, in a session where environment "A" connected first a temperature sensor component with the same ID as a temperature sensor component in environment "B", the value that the InterReality portal will use is the value of the sensor "A" because it was connected first to the virtual environment, ignoring "B" sensor values.

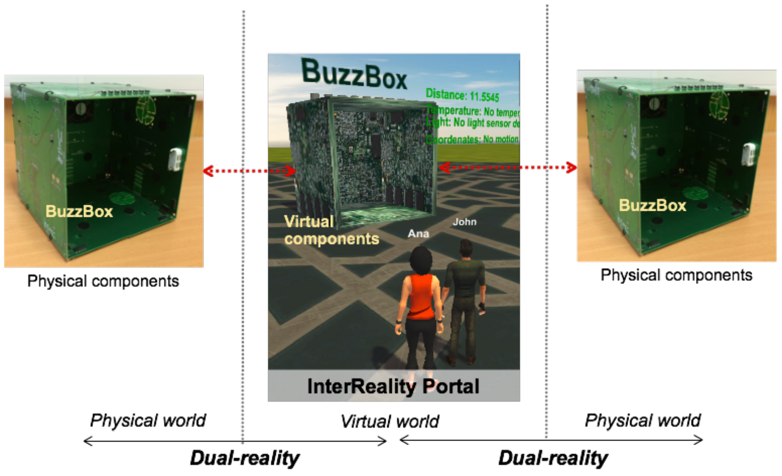

Figure 5.15: Multiple xReality objects implementation

5.3 Collaborative mixed-reality learning activities implementation

As stated on previous sections, the design of learning activities in the proposed model was oriented to the creation of co-creative learning activities, where collaboration is a key point in the creative process, and students should be able to create their own deliverables, following constructivists ideas. In this scenario, the

SmartFoxServer IP: 155.245.92.172
SmartFoxServer Port: 9933
Database IP: 155.245.92.172
Database Port: 8888
Bot IP: 155.245.23.150
Bot Port: 50000
Bot Port2 (buttons): 50001
Box IP: 192.168.5.38
Box Port: 50000
Box Port2 (buttons): 50001
Kinect Server IP: 127.0.0.1
Kinect Server Port: 2000
CWW Server IP: 155.245.23.49
CWW Port: 2500
iClassroom WS IP: 192.168.5.67
iClassroom WS Port: 8080
Max users in a session: 5

(a) Login screen (b) Configuration screen

Figure 5.16: GUI screens

figure of the teacher or instructor becomes a guide to help students when they have doubts about the activity in general or the technology used.

Elliott et al. (2012) argue that “technical components are part of the learning environment, and as such should not be treated as separate, but interconnected constructs”. Following a similar point of view, the classification presented in the previous chapter (fig. 4.18) explored learning activities from a technological point of view, based on the nature and complexity of the task. However, it is necessary to also consider pedagogical challenges in the implementation of these activities, evaluating the learning benefits.

In 2012, Time magazine (Wagstaff, 2012) reported (based on a study by US’ IES National Center for Education Statistics (2009)) that Computer Science was the only one of the STEM (science, technology, engineering and mathematics) fields that decreased in student participation over the last 20 years in the US at a high-school level (from 25% to 19%). One of the possible causes was an outdated too broad curriculum for Computing, which either it focuses on the use of tools such as word-processors, spreadsheets and presentation software only or introduces object-oriented programming to students with no previous background in Boolean logic, algorithms, data structures, etc. Similarly, a report by The Royal Society (2012), found that the delivery of Computing education in many UK schools was unsatisfactory as many pupils gained only basic digital literacy skills such as how to use a word-processor or a database. Due to this, the US and the UK currently face a critical skills shortage in the technology sector. The 2011 IDC Microsoft Economic Impact study found over 110,000 IT vacancies in the UK, and expected the IT workforce to grow by a further 113,000 by 2015 as reported by Computing at School Working Group (2012b).

Many initiatives that address these issues are at the process of being implemented, for example, UK Department for Education (2013) updated the National Curriculum defining the following computing aims:

- Understanding and application of the fundamental principles and concepts of computer science, including abstraction, logic, algorithms and data representation.
- The ability to analyse problems in computational terms, and have repeated practical experience of writing computer programs in order to solve such problems.
- The ability to evaluate and apply familiar and unfamiliar technologies to solve problems analytically.
- The creation of responsible, competent, confident and creative users of information and communication technology.

Organisations such as the Computing at School Working Group (CAS) (Computing at School Working Group, 2012a) has produced a Curriculum for Computing focusing in Key Stage 3 (ages 11-14) and 4 (ages 14-16). In like manner, The Joint Task Force on Computing Curricula (Association for Computing Machinery IEEE-Computer Society) (2013) presented a Curriculum Guidelines for Undergraduate Degree Programs in Computer Science.

In their report, The Royal Society (2012) pointed out that in the 1980s, the BBC Micro (a series of microcomputers and associated peripherals designed and built by the Acorn Computer company for the BBC Computer Literacy Project), introduced many children to computing for the first time, creating a generation of computing-skilled individuals able to pass on its knowledge to next generations. The BBC reported that from October 2015, the Make it Digital Initiative will build on the legacy of that project launching the BBC micro:bit[13], a pocket-sized programmable computer with motion detection, a built-in compass and Bluetooth technology, which is to be given free to every child in year 7 or equivalent across the UK (BBC, 2015). The micro:bit is BBC's most ambitious education initiative in 30 years, with the aim of inspiring young people to get creative with digital and develop core skills in science, technology and engineering. Previously, the Raspberry Pi Foundation in partnership with Google, gave away 15,000 Raspberry Pi with the same aim for schoolchildren around the UK (Upton, 2013). Other physical computing products, such as the BuzzBoards modular kit, have explored how they supported the changes proposed by the 2013 ACM-IEEE Computer Science Curricula (Callaghan et al., 2013).

From a different perspective, initiatives that involve physical computing, such as the BBC micro:bit, Raspberry Pi or Fortito BuzzBoards, pose a big challenge for distance education, as options for hands-on activities in Computer Science and Engineering are limited, particularly in group-oriented tasks. It is necessary for distance learners being integrated as seamlessly as possible to these curricula changes and initiatives, in a manner that recreate as similar as possible meaningful hands-on real-life tasks.

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[13] BBC micro:bit - www.microbit.co.uk

The learning objective of the proposed BReal Lab is to facilitate computer science hands-on activities for distance learners, based on the deconstructed model and combining creatively hardware and software modules (xReality objects) to implement Internet-of-Things (IoT) applications emphasising computing fundamentals such as the ones proposed by the curricula and initiatives previously mentioned. Implementation of collaborative mixed-reality learning activities is possible due to the distributed architecture of BReal Labs proposed. In this matter, the BReal Lab does not focus on implementing a specific learning activity; instead it creates a dynamic learning environment where instructors and students can explore and experiment different combinations of xReality objects, focusing on particular bits of the Computing curricula according to their necessities; and working in an environment with group dynamics similar to a physical laboratory setting.

5.4 Summary

This chapter introduced the design of the Blended-reality Lab (BReal Lab) platform, which acted as the proof-of-concept demonstrator by implementing the conceptual InterReality system described in chapter 4. The BReal Lab is a mixed-reality learning environment formed by an implementation of: a) the InterReality Portal, based on massively multiplayer online games (MMO) technology and, b) xReality objects, based on a modularised set of hardware components with network capabilities, mirrored to its virtual representation. xReality objects also comprise software modules (i.e. user-programmed functionality) that allow the creation of mixed-reality mashups based on the disaggregation of physical/logical devices and services (deconstructed model).

Additionally, this section presented a blended-reality distributed architecture and implementation able to manage multiple shared xReality objects, addressing the problem of synchronising multiple dual-reality states. Is this synchronisation, the key mechanism that allows collaboration between distant students in a distributed configuration of BReal Labs, blending them into one large collaborative learning environment designed for hands-on activities.

Finally, the chapter presented a discussion on the learning goal of mixed-reality laboratory activities based on the proposed technology and within the context of current Computer Science curricula. The learning goal is to produce Internet-of-Things-based computer projects, emphasising computing fundamentals, and grounded on co-creative and collaborative interaction between learners using the deconstructed model.

The following section describes the evaluation undertaken by students of eight universities in six different countries which worked in collaboration using xReality objects in sessions of two or more remote students. In like manner, it presents results of a user and technical evaluation of a distributed configuration of BReal Labs implemented as described in this chapter.

Chapter 6

Evaluation

> *"Where my reason, imagination or interest were not engaged, I would not or I could not learn."*
>
> — Winston Churchill (1874 – 1965)

Previous sections presented the rationale, conceptual and architectural models, and implementation towards the creation of a distributed mixed-reality system. This chapter presents the experimental results that reveal to what extent the model and architecture proposed enables the connection between geographically dispersed locations into one unified continuous space, allowing collaboration between remote students in hands-on activities. In doing so, this section begins with an introduction of different user studies utilised for mixed-reality, then moves to the description of the evaluation strategy adopted for the proof-of-concept demonstrator (BReal Lab), describing the experimental design used to gather evidence of the value of the concepts proposed in this thesis. The chapter concludes by reporting the results from the technical and user evaluation, discussing the findings of the experiments and their wider consequences for the research area.

6.1 Evaluation techniques used in Mixed Reality studies

Despite the increasing use of diverse mixed-reality applications in different scenarios, there remains a lack of evaluation methods for the specific challenges that mixed-reality systems pose (Bach et al., 2004). However, researchers have adapted evaluation methods used in other domains. Bach et al. (2004) identified three categories of general methods used in MR systems evaluation: a) questionnaires and interviews to collect user preferences and views; b) inspection methods, which can be limited as there is still little knowledge about ergonomic issues and design guidelines for MR systems; and c) user testing, which is critical for identifying usability issues and driving designed activities (Gabbard and Swan, 2008).

Dix et al. (2003) identified three typical goals of user evaluations: a) testing the systems functionality, b) rating the users' experience of the system; c) and identifying usability problems. Dünser et al. (2008) classified user studies for mixed-reality systems as:

1. **Perception studies**: try to understand how human perception and cognition operate in Mixed Reality;
2. **User performance studies**: evaluate specific application domains to understand how MR technology could impact underlying tasks;
3. **Collaboration studies**: examine communication and interaction between multiple users doing a collaborative task.
4. **Usability studies**: examine issues with system usability without involving measurement of user task performances. Nilsson (2010) identified that a *formative* evaluation is used in iterative design processes, where the evaluation is an ongoing process that shapes and reshapes the system, whereas a

summative evaluation is often done in the form of end-user studies, where researchers measure how the system is actually used by end-users.

Blended-reality, as described in previous chapters, involves two important aspects: *a*) user's perception of continuity which heavily depends on technical performance of the architecture proposed (perception study); and *b*) completion of the pursued activity (user performance studies). As the intended use of the proposed distributed blended-reality system was to offer a platform able to allow geographically remote students to work on regular laboratory collaborative activities rather than substitute them with alternative educational activities; the evaluation described in the next section focused primarily on perception, collaboration and usability studies instead of focusing on user learning performance.

A particular aspect in usability studies is related to the way people perceive, accept, and adopt technology for the tasks it is designed to support (Dillon, 2001; Louho and Kallioja, 2006). Different technology acceptance models (e.g. *Innovation Diffusion Theory* (IDT) (Rogers, 2003), *Technology Acceptance Model* (TAM) (Davis, 1993), *Unified Theory of Acceptance and Use of Technology* (UTAUT) (Venkatesh et al., 2012), *System Usability Scale* (Brooke, 1996)) have been proposed to measure and explain user acceptance of technology.

According to the Technology Acceptance Model (TAM) (Davis, 1993) two important factors that influence the acceptance of new technology are "*the degree to which a person believes that using a particular system would enhance his or her job performance*" (perceived usefulness) and "*the degree to which a person believes that using a particular system would be free of effort*" (perceived ease of use). Whereas usability often focuses on the ease of use rather than the usefulness of a system, perceived usefulness is actually more important to users than the perceived ease of use (Davis, 1993). Applied to mixed-reality, this means that if applications are perceived as useful, then the users will accept them in spite of awkward design or bulky interfaces (e.g. head-mounted devices) (Yusoff et al., 2011). Equally, if a mixed-reality system is not perceived as useful, then the system will not be used, even though it may be easy to use or people enjoy using it (Nilsson and Johansson, 2008). One of the most widely used models in usability studies is the Technology Acceptance Model (TAM) (fig. 6.1), an adaptation of the Theory of Reasoned Action which predicts behavioural intention based on attitudes (Fishbein and Ajzen, 1975). However, many researchers usually merge the basic TAM model with other weighted factors (constructs) specific to the technology being tested in order to explain its acceptance and use (Legris et al., 2003; Yusoff et al., 2011). In like manner, it has been used in some mixed-reality studies (Nilsson and Johansson, 2008; Yusoff et al., 2011; Theng et al., 2007) to determine acceptance of their applications.

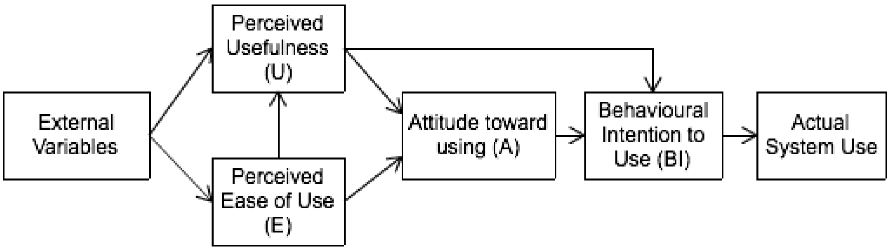


Figure 6.1: Technology Acceptance Model (TAM)(Davis, 1993)

For the evaluation described in the following sections, this thesis has adopted the strategy of using TAM's main constructs: perceived usefulness (PU), perceived ease of use (PEOU), and the intention to use (ITU). The evaluation also included participants' personal innovativeness (PI) (based on Innovation Diffusion Theory) as it suggests that *a*) users with higher levels of personal innovativeness are more likely to have a more favourable attitude towards new technologies; and *b*) highly innovative users are more willing to embrace new technologies into their daily routine by coping with the uncertainty of innovative technologies (Rogers, 2003). The reason for adopting this approach was to enable the evaluation to be able to differentiate collaboration and acceptance between innovators and non-innovators along with the level of enjoyment (PE) (Yusoff et al., 2011). Two more constructs related to the main aspects of this research, perceived blended-reality (PBR) and perceived collaboration (COL) were used to determine the level of perception of blended-reality, collaboration and general enjoyment of the mixed-reality laboratory activity. As the PBR construct has a heavy dependency with technical aspects of the distributed model such as network latency and particular aspects of the user's environments such as system lag, the user study is complemented with a technical report on performance of the BReal Lab demonstrator. Similarly, the COL construct is complemented with an analysis of the interactions and conversations captured by the BReal Lab prototype's log. Additionally, as the "Programming board" had an important role in the experiments, the evaluation included a construct to measure the perceived ease of use of the end-user programming tool (EUP) to determine if its use affected the general perceived ease of use of the BReal Lab demonstrator.

Code	Constructs
PEOU	Perceived ease of use
PE	Enjoyment
PU	Perceived usefulness
ITU	Intention to Use
PBR	Perceived blended reality
COL	Perceived collaboration
EUP	Perceived end-user programming tool's ease of use
PI	Personal innovativeness

Table 6.1: List of constructs

6.2 Experimental design

Chapter four presented the conceptual model proposed to enable distance learners to undertake collaborative activities in a distributed mixed-reality environment, and chapter five discussed architecture and implementation of the functional prototype (the BReal Lab). This prototype was used in the experimental evaluations to validate the hypotheses stated in chapter 1, which said that "*it is possible to* *devise a computational model and architecture able to connect locations, that are physically separated, into one unified continuous space by linking elements situated in those locations, using a mix of physical and virtual objects* (hypothesis 1 - main), *and enabling remote users (with no technical mixed-reality expertise* (hypothesis 3 - secondary)) *to perform collaborative creative teamwork based on hands-on-activities* (hypothesis 2 - main); *preferring the use of mixed physical and virtual objects over simulated (virtual) objects* (hypothesis 4 - secondary); *and fostering engagement and participation* (hypothesis 5 - secondary)".

For evaluation purposes the original hypothesis was re-worded into the following high-level premises:

1. Participants should be able to perceive the interaction between a mix of physical and virtual interconnected objects, sharing its functionality (hypothesis 1 - main).
2. Participants should be able to collaborate using hands-on mixed-reality learning activities (hypothesis 2 - main).
3. The use of the BReal Lab does not require any specialised technical mixed-reality expertise from participants (hypothesis 3 - secondary).
4. The use of xReality objects should be preferred over simulated virtual objects (hypothesis 4 - secondary).
5. The use of the BReal Lab should provide an enjoyable experience, fostering engagement and participation of team members (hypothesis 5 - secondary).

The experimental evaluation employs a collaborative activity based on a hypothetical scenario were students were able to create simple IF-THEN-ELSE behavioural rules to control a xReality object. IF-THEN rule programming was chosen because they are natural parts of everyday life and do not demand technical expertise to understand (as many participants came from non-technical backgrounds). Generally, the aim in using scenarios was to recreate a natural context for participants in a simulated or emulated situation (Klein, 1985), thereby providing a situation that is reflective of real life situation which has been shown to have positive associations with learning (Adobor and Daneshfar, 2006). Mixed-reality experiences offer the possibility of creating realistic, engaging, authentic and fun experiences (Kirkley and Kirkley, 2004), which, when designed properly, can foster millenial learning styles through physical and sensory immersion (Dede, 2005b) as discussed in chapter three; increasing students' motivation (Hanson and Shelton, 2008). Based on this, the hypothetical scenario was established as follows:

- First by giving the participants an environment that consisted of a simulated (virtual) (and for some, emulated (mixed-reality)) (fig. 6.2) domestic room (a bedroom) and asking the question "*If you lived in an intelligent house, how would you program your house to wake you up in the mornings?*".
- Second, by providing them with a special end-user programming tool, designed to follow the principles of programming via analogy (i.e. using graphical icons or physical representations), whereby participants were able to create these behavioural rules via a "Programming Board" inside the virtual world (fig. 6.3).

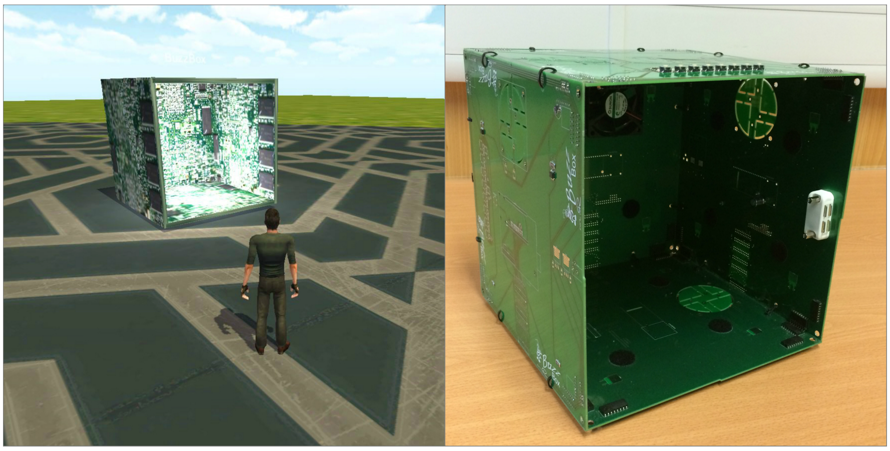


Figure 6.2: xReality object experimental implementation

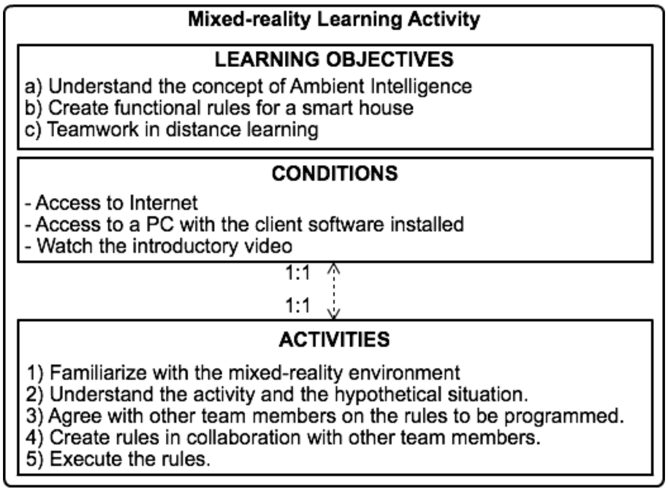
Current room: Anasol's session
Activity: 1 - Construct
Elapsed time: 1:25
Virtual object only.

Figure 6.3: Construction of a behavioural IF-THEN-ELSE rule

Figure 6.3 shows an example of a IF-THEN-ELSE behavioural rule written in the "Programming Board" which can be interpreted as:

```
IF TEMPERATURE is greater than 10
THEN turn LIGHT_1 and LIGHT_2 on,
ELSE turn LIGHT_1 and LIGHT_2 off
```

The objective of the learning activity was to illustrate concepts of ambient intelligence (AmI) using a co-creative approach to encourage evaluees to create as many behavioural rules as possible based on the hypothetical situation using basic programming logic principles. Ambient intelligence (AmI) is defined as a discipline that incorporates artificial intelligence to everyday environments making them sensitive and responsive to the presence of people (Cook et al., 2009). The learning activity was inspired by earlier pioneering work on the embedded-internet (the forerunner of the Internet-of-Things) (Chin and Callaghan, 2003) and internet-of-things appliances (Scott and Chin, 2013). Figure 6.4 describes the learning activity in the context of IMS Units of Learning.



Mixed-reality Learning Activity

LEARNING OBJECTIVES

a) Understand the concept of Ambient Intelligence
b) Create functional rules for a smart house
c) Teamwork in distance learning

CONDITIONS

- Access to Internet
- Access to a PC with the client software installed
- Watch the introductory video

ACTIVITIES

1) Familiarize with the mixed-reality environment
2) Understand the activity and the hypothetical situation.
3) Agree with other team members on the rules to be programmed.
4) Create rules in collaboration with other team members.
5) Execute the rules.

Figure 6.4: Unit of Learning - activity used in proof-of concept trials

Implementation of the physical part of an xReality object was undertaken using a Raspberry Pi (RPi) [1] and Fortito's BuzzBox[2], a desktop-size emulation of a smart-room (fig. 6.5) constructed by plugging together six 25x25cm (10×10

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[1] Raspberry Pi - www.raspberrypi.org
[2] Fortito Ltd. - www.fortito.mx

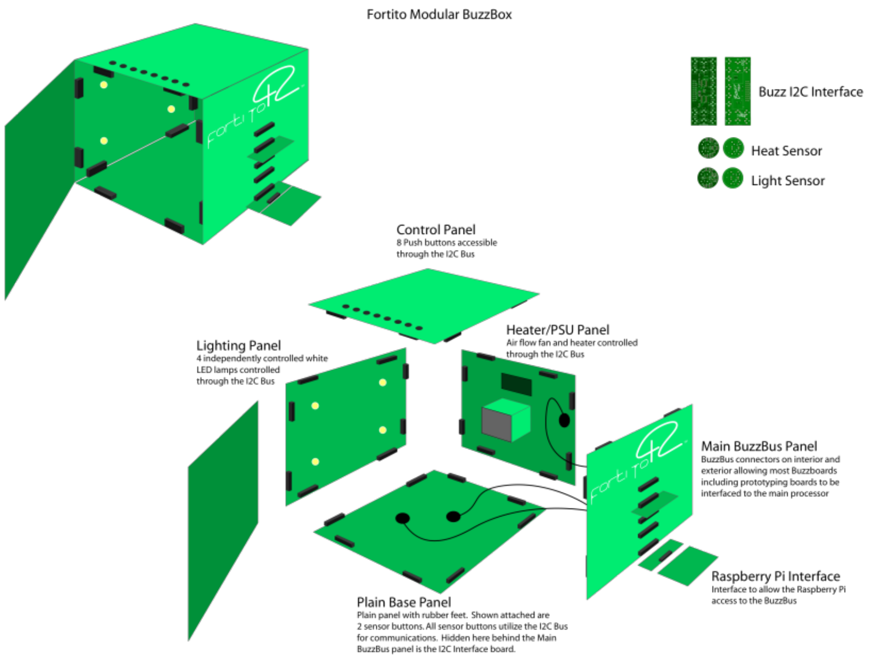
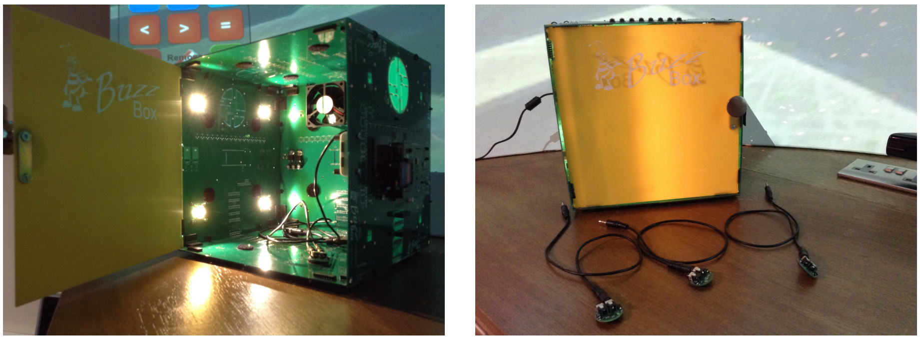


Figure 6.5: Fortito's BuzzBox diagram, image courtesy Fortito Ltd. (2014)

inches) panels with diverse embedded actuators (a variable speed ventilator fan, a controllable heater, 4 dimmable 'warm white' LED lights, 8 push buttons, 8 tricolour LED's) (fig. 6.6a) and and two pluggable interchangeable sensors (temperature and light) (fig 6.6b). Audio functionality was added using RPi's embedded audio hardware and a pair of speakers. Additionally, a virtual proximity sensor was available in the 3D interface. This virtual sensor measures the distance between the avatar and the virtual box, and it was available for every participant regardless if they have the physical object.

When two BuzzBoxes were used together in the experiments, the InterReality portal detected both and linked them to the same virtual representation of the BuzzBox, creating a physical-virtual-physical connection between the two objects. Thus, when an actuator was triggered (e.g. a light), the action was replicated: first, in the BuzzBox in environment A; then, in the virtual BuzzBox shared for all the participants in the session; and finally in the environment B. In the case of the sensors, if a participant had a sensor plugged to the BuzzBox, it was shared across environments. However, if another participant had the same sensor connected, then the InterReality portal uses the one belonging to the participant who had joined the session first. Figure 6.7 shows the area in the 3D GUI screen that contains information about the three types of sensors: a) virtual sensors, which does not exist in the physical world but can be used to form the rules (e.g. virtual proximity sensor); b) remote shared sensors, which are tangible sensors that are physically located in a remote environment, but can be used to form the rules (e.g. a temperature sensor physically located in China can be shared and used for all the members of the session); and c) local sensors, which are those physical sensors available in the local environment and that are shared with other participants. Their values were updated in real-time for all the participant in the session.



(a) BuzzBox (b) Sensors

Figure 6.6: Fortito's BuzzBox

Trials with the proof-of-concept demonstrator were divided into three phases:

1. **Preparation** (before the experience). Participants were informed about the study and their phases by a facilitator, and as part of the preparation, they were provided with two links, the first one to watch a video explaining the use of the 3D GUI and the activity to be performed before the day of the experiment[3]. The second link was to an on-line survey to gather information about demographics and their familiarity with computing, gaming,

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[3] The video is available at `https://youtu.be/oTJRoRLae_8`

Figure 6.7: Types of sensors

virtual worlds, mixed reality and intelligent environments. A copy of the questionnaire is included in Appendix A.

2. **Trial** (during the experience). During the trial, facilitators in each location guided students to login into the 3D GUI and introduce to each other. Once all the participants were inside they started working collaboratively on the assigned programming task.

3. **Feedback** (after the experience). Participants were provided with a link to an online survey to gather information about perception of the overall experience (the technology used and the activity performed). A copy of the questionnaire is included in Appendix A.

Both, qualitative data and quantitative data were collected for the user studies. Qualitative data was analysed identifying relevant issues raised by students and facilitators when evaluating the BReal Lab demonstrator. Quantitative data was explored through descriptive statistics to find correlations with the research questions and premises. The data was studied, focusing on the interaction between the participants as they used the proof-of-concept BReal Lab demonstrator.

The research instruments consisted in two questionnaires for participants, a short questionnaire for facilitators, experiment annotations, video recordings and data gathered from the prototype's log. The first questionnaire collected general demographic information and preliminary knowledge on evaluated topics to establish participant's background. The second questionnaire measured participants' perception and acceptance of both, the prototype system and the collaborative task. The questionnaire for facilitators asked about their impressions of the experiments. The three questionnaires are included in Appendix A. Participant's questionnaires were designed using a combination of open and closed questions. Closed questions were employed to collect the participant's feedback using Likert scales, whilst open questions were used primarily to give users the opportunity to clarify or provide more detail on any feedback given. Likert items are commonly used to measure respondents' attitudes to a particular question or statement. In the user study, a 4-point Likert scale was used (removing the neutral option), as opposed to the standard 5-point, due to the fact that an even numbered scale is less likely to give neutral responses (i.e. value 3 in a 5-point scale) (Johns, 2010; Saris and Gallhofer, 2007). In this way, the questionnaires forced participants to avoid neutral responses that would not result in useful information to evaluate the BReal Lab demonstrator. Participants were observed while performing the activity and annotations were made with the goal of documenting any events of interest in relation to the research themes and clarify results from other data sources. The prototype recorded a log of events performed by the participants within the system, and a log of the conversations between participants. They were informed about this before starting the trial and they were instructed not to discuss unrelated topics. Information collected in this log was analysed statistically in combination with the *Perceived Collaboration* (COL) construct to measure collaboration and engagement. Data was anonymised and analysed using the statistical program SAS (Statistical Analysis System) University Edition[4].

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[4] SAS University Edition - http://www.sas.com

In order to get reliable data, it was important that the participants in the studies were prospective users, as new technologies can be integrated successfully into society when they are used by people they are intended for (Yusoff et al., 2011). Therefore, the BReal Lab demonstrator's evaluation took place with 52 students from Essex University (UK), Anglia Ruskin University (UK), Leon Institute of Technology (Mexico), San Diego State University (USA), Shijiazhuang University (China), Shanghai Open University (China), Khalifa University of Science, Technology and Research (UAE) and Monash University (Malaysia) between March and May 2015 (fig. 6.8). Requirements for running the 3D GUI were: a) a personal computer with Windows 7 onwards or MacOS Mavericks onwards, b) access to internet and c) TCP ports 9933 and 8888 open (bidirectional communications) to enable communication between the client software and the server. In some cases, students participated in the learning activity using only the virtual object (simulation), and in other cases they used the xReality object (the BuzzBox). In any case, the absence of a physical box did not interfere with the execution of the trial. Table 6.2 summarises the number of participants using xReality or virtual objects.

	Virtual object	xReality object	Total
Participants	28	24	52

Table 6.2: Number of participants with xReality and Virtual objects

Each session lasted 30 minutes and the activity was designed to have one student seated in front of one computer connected to the 3D virtual world. Thus each one of the students needed to work with their own equipment. The first session was between students in Essex University (UK) and Anglia Ruskin University (UK). The second session connected students in Essex University (UK) with students at Leon Institute of Technology (Mexico). The third test was between students at Essex University (UK), Anglia Ruskin University (UK) and Leon Institute of Technology (Mexico), creating a three-way connection. Fourth session was between on-line students of San Diego State University in different locations within the United States. The fifth session involved students at Essex University (UK) and students from Shijiazhuang University (China). The sixth session connected students from Shanghai Open University (China) with Essex University (UK) students. The final session connected students located at Shijiazhuang University (China), Khalifa University of Science, Technology and Research (UAE), Monash University (Malaysia), and students in two different labs at Essex University (UK) at the same time (the iClassroom and the iSpace). Table 6.3 summarises the undertaken sessions.

Institution	Session						
Essex University - iClassroom (UK)	X	X	X	X	X	X	X
Essex University - iSpace (UK)							X
Anglia Ruskin University (UK)	X		X				
Leon Institute of Technology (Mexico)		X	X				
San Diego State University (USA)				X			
Shijiazhuang University (China)					X		X
Shanghai Open University (China)						X	
Monash University (Malaysia)							X
Khalifa University of Science, Technology and Research (UAE)							X

Table 6.3: Trials summary

6.3 Evaluation

6.3.1 Demographics and preliminary data

The objective of the preliminary questionnaire was to get demographic information and explore participants' background knowledge. Table 6.4 presents the set of abstractions (constructs) investigated in the preliminary survey. A copy of the survey questions is available on Appendix A.

The sample of 52 participants was formed by 27 males and 25 females with

(a) Essex University (iClassroom), UK

(b) Instituto Tecnologico de Leon, Mexico

(c) Shijiazhuang University, China

(d) Shanghai Open University, China

(e) Essex University (iSpace), UK

(f) Monash University, Malaysia

(g) San Diego State University, USA

(h) Anglia Ruskin University, UK

(i) Khalifa University of Science, Technology and Research, UAE

Figure 6.8: Students working on MR collaborative activity

Construct	Code
General demographics	GD
Familiarity with the use of computers	PRE
Preliminary experience with educational technology	ET
Preliminary experience with Science and Engineering laboratory activities	LAB
Preliminary experience with programming	PR
Personal innovativeness	PI
Preliminary experience with video games	VG
Preliminary experience with virtual worlds	VW
Preliminary knowledge on Mixed Reality	MR
Preliminary knowledge on Ambient Intelligence	IE

Table 6.4: Constructs in preliminary survey

ages ranging from 19 to 55 years old, a mean value of 30 years old in both genders (mode = 28) (fig. 6.9). In terms of cultural background, participants identified themselves as nationals of 14 different countries, where 69.23% had a good level of English understanding, ranging from native to professional working proficiency, and 30.77% had limited or elementary proficiency (fig. 6.10). The level of studies participants were doing at the time of the experiment varied, with 23.08% pursuing a PhD, 50.0% studying for a postgraduate degree and 26.92% doing an undergraduate course. Their courses ranged from Computer Science (61.54%), and related subjects such as Electronic and Electrical Engineering (3.85%) and Computer Engineering (3.85%) to Learning Design and Technology (21.15%) and a broader range of topics (9.61%) (i.e. Economics, Linguistics, Politics, Graphic Design, etc.).

All the participants had familiarity with the use of computers, with 80.77% assessing their computer expertise as good or very good and 19.23% qualifying themselves as average users. 96.15% of participants owned a personal computer (PC) against 3.85% that said they did not have a PC. Primarily uses of the PC were: studies (75%), leisure (55.77%), social interactions (46.15%) and paid work (40.38%) with a mode of between 7 to 9 hours of daily use (fig. 6.11).

86.54% stated that they use technology in their classes or modules and 75.00%

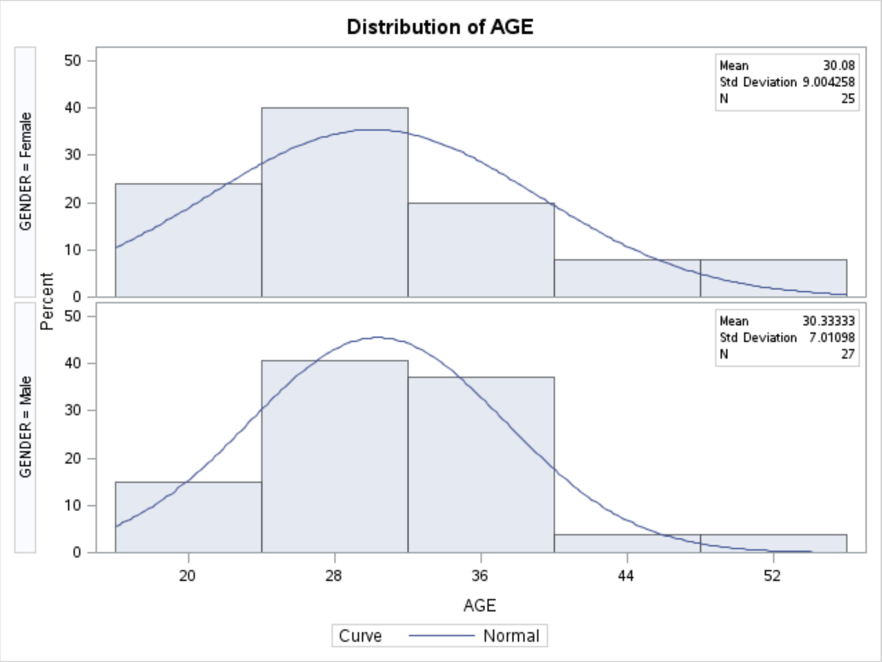

Figure 6.9: Participant's age distribution

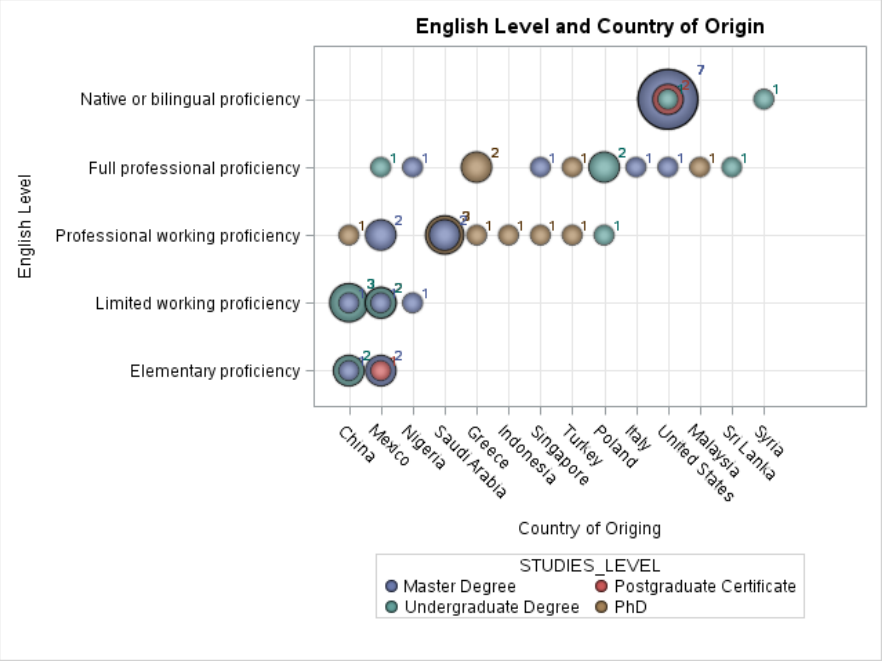

Figure 6.10: Cultural background of the sample

have used educational software outside the classroom to clarify or practice a particular subject (fig. 6.12). The most common educational tools reported as used by participants were learning management systems such as Moodle[5] and Black-

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[5] Moodle - www.moodle.org

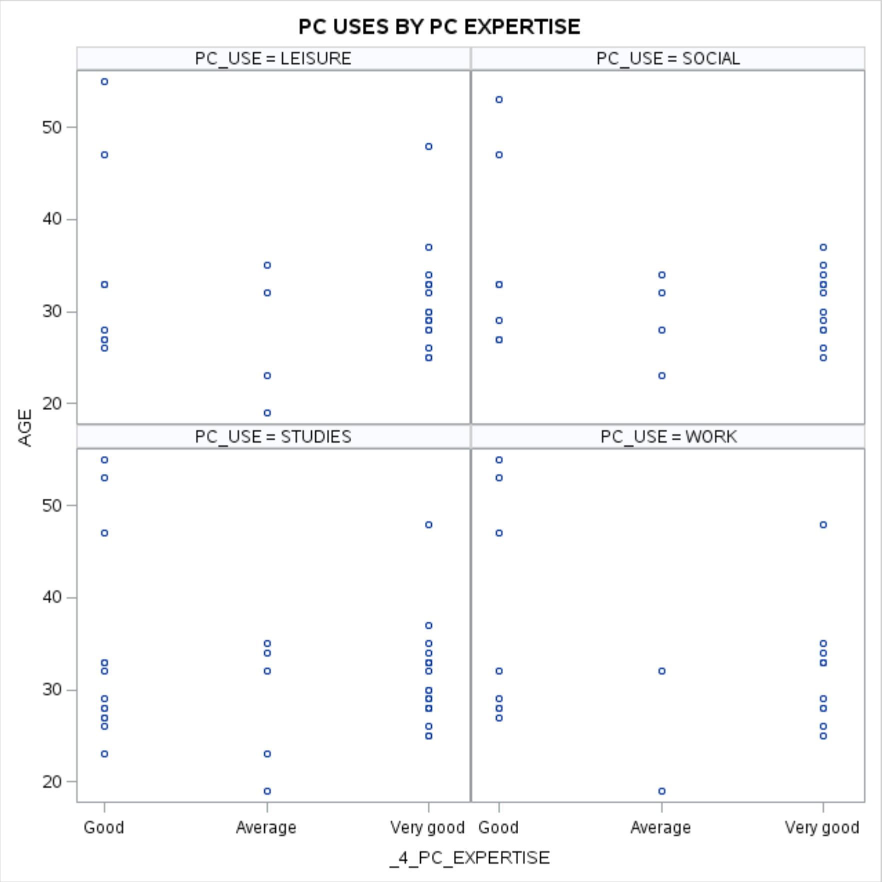

Figure 6.11: Uses of PC based on computer expertise

board [6], followed by diverse MOOC providers such as Coursera [7], Udacity [8], Khan Academy [9], UniMOOC [10], UDEMY [11], emagister [12]. The third option reported was the use of video tutorials in YouTube[13]. Other educational software tools were provided by the participants, but as they are very specific to their subject of studies they have not been included in this report.

In relation to their previous experience in Science and Engineering laboratory assignments, 28.85% answered that they did not have any experience (fig 6.13 (a)). From the remaining 71.15% that have experience, is possible to observe that lab-

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[6] Blackboard - www.blackboard.com/
[7] Coursera - www.coursera.org
[8] Udacity - www.udacity.com
[9] Khan Academy - www.khanacademy.org
[10] UniMOOC - www.unimooc.com
[11] UDEMY - www.udemy.com
[12] emagister - www.emagister.co.uk
[13] YouTube - www.youtube.com

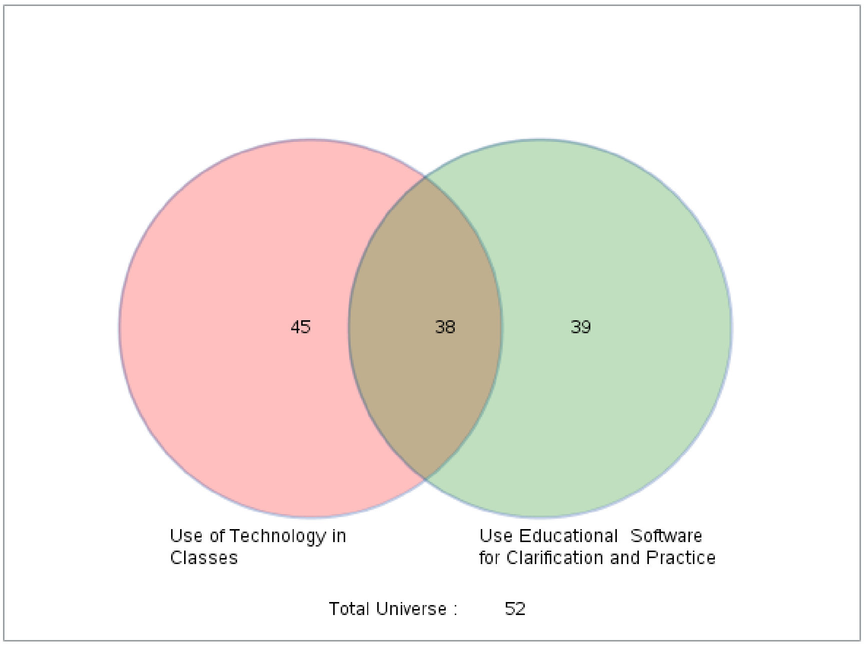
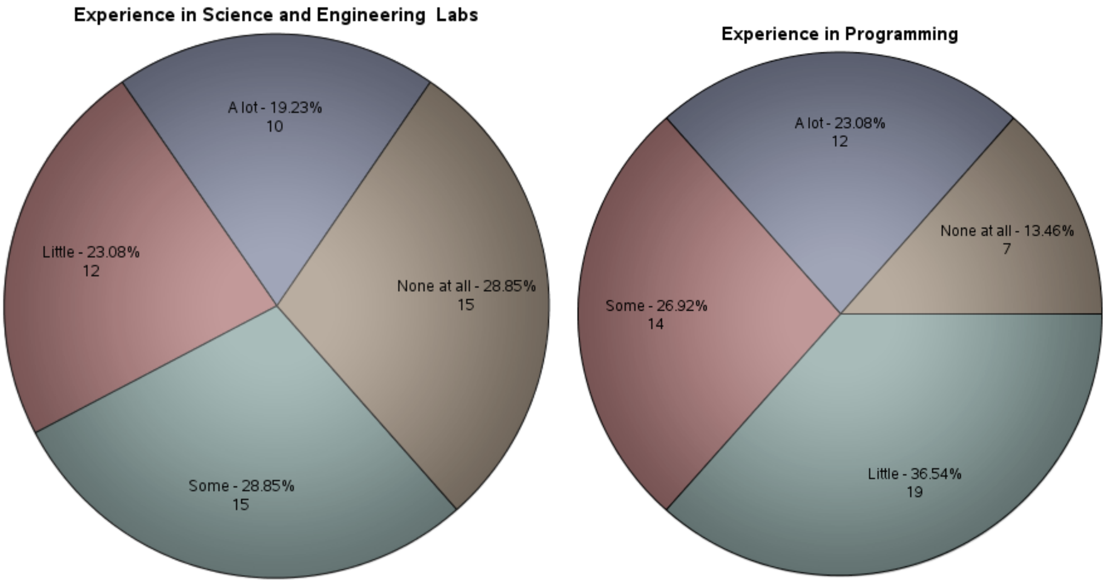


Figure 6.12: Use of educational tools

oratory activities are more commonly done in collaboration, where 40.54% stated having worked individually and in groups equally, 35.14% having predominantly worked in groups and 24.32% having worked individually most of the time (LAB-2 in table 6.5). About their experience in programming, only 13.46% said that had no experience at all (fig 6.13 (b)). From the remaining 86.54% that have experience, 62.22% declare having worked individually most of the times, 24.44% having equally worked individually and in groups, and 13.33% having predominantly worked in groups. From this data it is possible to observe that participants' experience in programming is predominately as an individual activity with more restricted collaboration (PR-2 in table 6.5) whereas laboratory activities are more commonly done in groups.

Questions from the construct *Personal Innovativeness* (PI-1 to PI-3) were used to understand how open the participants were to use and accept new technologies. 94.23% liked to try new technologies, and the same percentage (94.23%) stated that can use and understand new technologies quite easily. However, in spite of their confidence in understanding and using new technologies, 78.85% said that



(a) Experience in labs [LAB-1] (b) Experience in programming [PR-1]

Figure 6.13: Participant's previous experience

	LAB-2		PR-2	
	Freq	Percent	Freq	Percent
I have worked equally, individually and in groups	15	40.54%	11	24.44%
Most of the times I have worked in groups	13	35.14%	6	13.33%
Most of the times I have worked individually	9	24.32%	28	62.22%
	37	100%	45	100%

Table 6.5: Group vs. individual activities previous experience

sometimes they have found difficulties in their use, with 11.54% stating that these difficulties happen very often to them.

In relation to their experience in virtual interfaces, half of the participants (50.0%) were familiar with virtual worlds but only 23.08% used them regularly, the best known being Second Life[14]. Similarly, only 28.85% used video games on a regular basis with first-person shooters being the most popular option followed by action-adventure and strategy games.

From the sample, 55.77% were familiar with augmented reality or mixed re-

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[14] Second Life - www.secondlife.com

ality applications, the AR HDM device Google glass[15] and the AR mobile app Aurasma[16] were the best known. About their knowledge of intelligent environments, 73.08% said they were familiar with the concepts of *smart houses* and *intelligent spaces* with 78.85% having used or heard about technology to make their homes *smart*.

6.3.2 Analysis procedure

This section describes the results obtained from two sources: a) questionnaires answered by the users after the trials, and b) data taken from the proof-of-concept BReal Lab demonstrator log. Similarly to the preliminary survey, questions were grouped using a series of constructs. A copy of the survey questions is available in Appendix A.

Cronbach's alpha of each of the constructs was used to determine the reliability of the questionnaire. Technically speaking, Cronbach's alpha is not a statistical test, however it is used as a measure of internal consistency and scale reliability, that shows how closely related a set of items are, as a group. A reliability coefficient of .70 or higher is considered *acceptable* in most social-science research situations (UCLA: Statistical Consulting Group).

$$\alpha = \frac{N \cdot \bar{c}}{\bar{v} + (N - 1) \cdot \bar{c}} \tag{6.1}$$

Here N is equal to the number of items, $\bar{c}$ is the average inter-item covariance among the items and $\bar{v}$ equals the average variance. Values in table 6.6 suggests that the items have relatively high internal consistency. The method is not applicable to open ended questions (e.g. the construct Intention to use (ITU) is formed

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[15] Google glass - www.google.com/glass/start

[16] Aurasma - www.aurasma.com

by open ended questions only, the construct PU has more open ended than closed questions) which are marked N/A.

Code	Constructs	No. items	Cronbach's alpha
PEOU	Perceived ease of use	9	0.81598
PE	Enjoyment	4	0.72491
PU	Perceived usefulness	5	N/A
ITU	Intention to Use	3	N/A
PBR	Perceived blended reality	5	0.79624
COL	Perceived collaboration	7	0.76807
EUP	Perceived end-user programming tool's ease of use	8	0.86679

Table 6.6: Post-survey constructs reliability

Closed questions were designed based on a 4-point Likert scale using different semantic labels, (e.g. 1=Strongly agree / 2=Agree / 3=Disagree / 4=Strongly disagree; 1=Very easy/ 2=Easy/ 3=Difficult / 4=Very difficult; 1=Very useful / 2=Somewhat useful / 3=Not very useful / 4=Not useful at all; 1=Very likely / 2=Likely / 3=Unlikely / 4=Very unlikely). When constructs were composed by positively and negatively loaded items in the questionnaire, scores in negative items were transformed in order to make the result easier to interpret. This means that a lower value represents a positive score on participants' view and a higher value represents a negative score.

Before doing the statistical analysis it was necessary to test if the data followed a normal distribution. To do so, the one-sample Kolmogorov-Smirnov Goodness-of-Fit test was used as following:

H_0: The data is normally distributed (Null hypothesis)

H_a: The data is not normally distributed (Alternative hypothesis)

$\alpha = 0.05$ (Significance level)

Critical value = 0.04301

$$D = \max_{l \leq i \leq N} (F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_1)) \tag{6.2}$$

Where F is the theoretical cumulative distribution of the distribution being tested (National Institute of Standards and Technology, 2015).

Question	D
GD-4	0.15138
GD-6	0.1641
LAB-1	0.19192
PR-1	0.22541
PE-1	0.42122
PE-2	0.35635
PE-3	0.45876
PE-4	0.42347
PEOU-1	0.26153
PEOU-2	0.29245
PEOU-3	0.25317
PEOU-4	0.224
PEOU-5	0.25583
PEOU-6	0.33724
PEOU-7	0.30901
PEOU-8	0.32568
PEOU-9	0.29695
EUP-1	0.25082
EUP-2	0.32914
EUP-3	0.30028
EUP-4	0.38088
EUP-5	0.24578
EUP-6	0.2956
EUP-7	0.34522

Table 6.7: One-sample Kolmogorov-Smirnov Goodness-of-Fit

The test showed that the data sample cannot be considered as following a normal distribution because D is greater than the critical value (0.04301), thus the null hypothesis (H_0) is rejected 6.7.

Based on this result, quantitative data analysis was performed using non-parametric techniques. Another reason for using non-parametric techniques was the constant use of Likert scales in the questionnaires. Traditionally, Likert-type data is considered as ordinal data, where each point means that one score is higher than another, but it does not measure the distance between the points, thus the distance cannot be presumed equal (Boone and Boone, 2012). In cases like this, the median instead of the mean should be used to characterize distributions of ordinal data. As the sample did not follow a normal distribution, Kruskal-Wallis tests were used to compare medians and detect attributes that influenced the results.

6.3.3 User evaluation

Perceived ease of use

The *perceived ease of use* (PEOU) construct, was employed to define how easy was for participants to learn how to use the technology and complete the learning activity. Table 6.8 lists the questions used.

Code	Question
PEOU-1	It was difficult to use the equipment (software/hardware)
PEOU-2	It was easy to use the equipment (software/hardware)
PEOU-3	It was demanding to use the equipment (software/hardware)
PEOU-4	It was difficult to understand the principles of operation of the system
PEOU-5	It took a lot of effort to learn how to use the system
PEOU-6	How easy or difficult you found communication through chat?
PEOU-7	How easy or difficult you found to complete the activity assigned?
PEOU-8	How easy or difficult you found to move yourself inside the virtual environment?
PEOU-9	How easy or difficult you found to interact with the Programming Board?

Table 6.8: Perceived ease of use (PEOU)

Some items in this section were designed as a set of randomly alternating positive and negative worded questions, to diminish probability of response bias induced by simply agreeing with the scale items regardless of the item content (Guo-Qingke et al., 2006). To calculate the results of this questions pairs (one

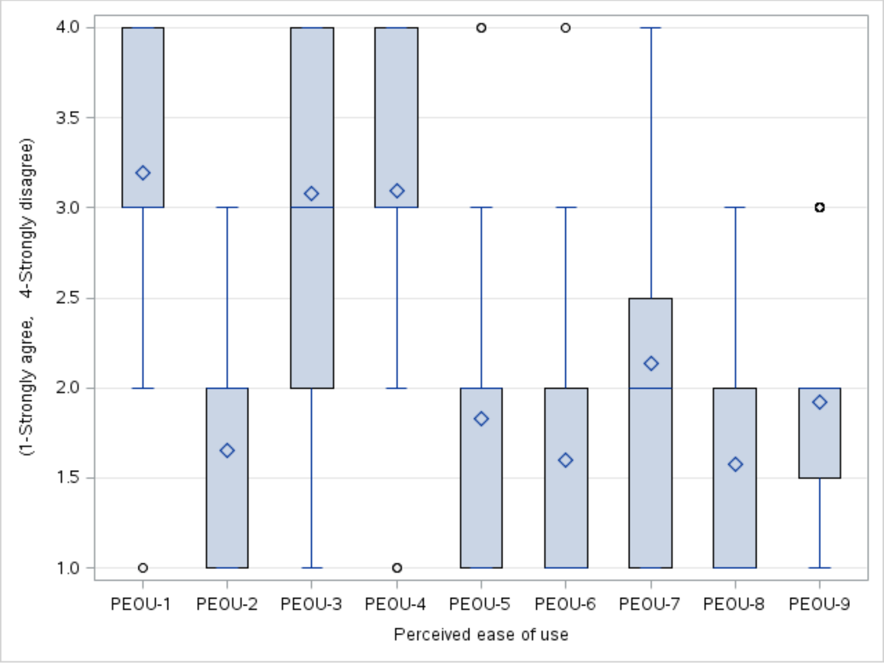


Figure 6.14: Evaluation Perceived ease of use (PEOU)

positive loaded and one negative loaded) were used, transforming the negative loaded item to calculate composite values.

	Easy (PEOU-1)		**Difficult (-1) (PEOU-2)**			
	Freq	**%**	**Freq**	**%**	**Freq Cml**	**% Cml**
Strongly agree	24	46.15	22	42.31	46	44.23
Agree	22	42.31	19	36.54	41	39.42
Disagree	6	11.54	10	19.23	16	15.38
Strongly disagree	0	0.00	1	1.92	1	0.96
	52	100	52	100	104	100

Table 6.9: PEOU-1/PEOU-2 composite EASY-DIFFICULT values

In general, 83.65% of participants found the BReal Lab easy to use against 16.35% (PEOU-1/PEOU-2 composite, median = 1.00, “Strongly agree”). Figure 6.14 shows that other aspects of the prototype application such as communication using a chat window (PEOU-6), interaction with the Programming Board (PEOU-9) and navigating inside the virtual reality space (PEOU-8) did not required much effort form the participants, and were considered as easy to understand.

Results from a Kruskal-Wallis test (table 6.10) revealed that the type of object used (virtual or xReality object) did not have a significant influence in the perceived easiness of using the equipment (PEOU-1: H (1) = 0.0469, p .05), (PEOU-2: H (1) = 0.0801, p .05), thus participants found easy to interact with the BReal Lab regardless the object used. In like manner, preliminary experience or knowledge on programming (preliminary survey PR-1), virtual worlds (preliminary survey VW-1), intelligent environments (preliminary survey IE-1) or the level of computing expertise (preliminary survey PRE-4) demonstrated no significant effect on the perceived easiness of the activity undertaken in the experiment.

However, these results could be related to the fairly simple mechanisms adopted to facilitate interaction with the virtual world (e.g. avatar movement using a keyboard, programming board using a mouse device) and between participants (i.e. chat window).

Dependent variable	Independent variable	Chi-square	DF	P_value
Easy (PEOU-1)	Type of object (PBR-1)	0.0469	1	0.8285
Difficult (PEOU-2)	Type of object (PBR-1)	0.0801	1	0.7772
Activity Easiness (PEOU-7)	Programming knowledge (PR-1)	1.8693	3	0.6000
Activity Easiness (PEOU-7)	VW knowledge (VW-1)	2.1487	1	0.1427
Activity Easiness (PEOU-7)	IE knowledge (IE-1)	0.2717	1	0.6022
Activity Easiness (PEOU-7)	Computing expertise (PRE-4)	4.7274	2	0.0941

Table 6.10: PEOU Kruskal-Wallis results

The research was particularly interested in discovering if the multiple dual-reality principles were easy or difficult to understand to which 76.92% participants answered that they were not difficult (question PEOU-4, median = 2.00, “Disagree”), and 78.85% thought that it did not require a lot of effort to learn how to use the system (question PEOU-5, median = 2.00, “Disagree”).

As it can be seen, these results support premise 3 which states that “*The use* *of the BReal Lab does not require any specialised technical mixed-reality expertise from participants*" (hypothesis 3 - secondary).

Perceived enjoyment

To determine participant's *perceived enjoyment* (PE), users were asked about how much do they enjoyed using the proposed technology when doing the learning activity (table 6.11).

Code	**Question**
PE-1	It was fun to use the equipment (software/hardware)
PE-2	It was annoying to use the equipment (software/hardware)
PE-3	It was interesting to use the equipment (software/hardware)
PE-4	It was boring to use the equipment (software/hardware)

Table 6.11: Perceived enjoyment (PE)

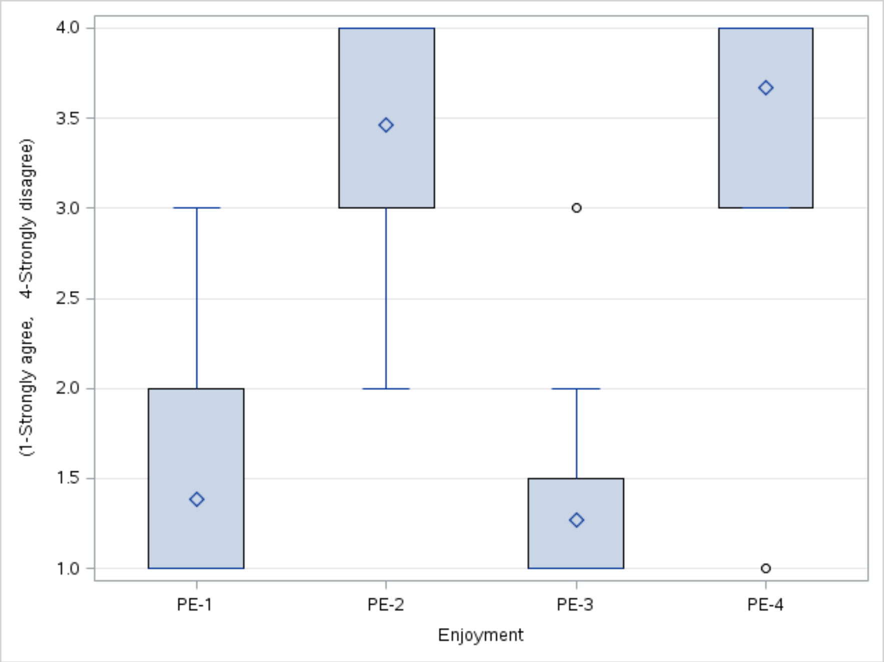


Figure 6.15: Evaluation Perceived enjoyment (PE)

Similarly to previous constructs, composite values were used on items PE-1/PE-2 (table 6.12), and PE-3/PE-4 (table 6.13) to determine results. Based on this, 90.38% participants found the activity amusing (median = 1, "Strongly agree") and 98.08% interesting (median = 1, "Strongly agree") against 9.62% that thought the activity was annoying and 1.92% thought it was boring. In general, these results support premise 5, *"The use of the BReal Lab should provide an enjoyable experience, fostering engagement and participation of team members"* (hypothesis 5 - secondary).

	Fun (PE-1)		**Annoying (-1) (PE-2)**			
	Freq	**%**	**Freq**	**%**	**Aggregate Freq**	**Aggregate %**
Strongly agree	36	69.23	30	57.69	66	63.46
Agree	12	23.08	16	30.77	28	26.92
Disagree	4	7.69	6	11.54	10	9.62
Strongly disagree	0	0.00	0	0.00	0	0.00
	52	100	52	100	104	100

Table 6.12: PE-1/PE-2 composite FUN-ANNOYING values

	Interesting (PE-3)		**Boring (-1) (PE-4)**			
	Freq	**%**	**Freq**	**%**	**Aggregate Freq**	**Aggregate %**
Strongly agree	39	75.00	37	71.15	76	73.08
Agree	12	23.08	14	26.92	26	25.00
Disagree	1	1.92	0	0.00	1	0.96
Strongly disagree	0	0.00	1	1.92	1	0.96
	52	100	52	100	104	100

Table 6.13: PE-3/PE-4 composite INTERESTING-BORING values

Looking more in detail, Kruskal-Wallis tests (table 6.14) suggest that the perceived amount of amusement and interest depends on the type of object used (virtual or xReality) (PE-1: H (1) = 3.9793, p .05), (PE-2: H (1) = 3.7621, p .05). Inspection of the group medians suggests that participants considered that using the xReality object (i.e. BuzzBox) was more amusing and interesting, supporting premise 4 "*The use of xReality objects should be preferred over simulated virtual objects*" (hypothesis 4 - secondary).

Dependent variable	Independent variable	Chi-square	DF	P_value
Fun (PE-1)	Type of object (PBR-1)	3.9793	1	0.0461
Annoying (PE-2)	Type of object (PBR-1)	0.9168	1	0.3383
Interesting (PE-3)	Type of object (PBR-1)	3.7621	1	0.0524
Boring (PE-4)	Type of object (PBR-1)	1.4967	1	0.2212

Table 6.14: PE Kruskal-Wallis results

Perceived usefulness

After the experiment, participants were asked once more about their experience in Science and Engineering laboratory activities (question PU-2), where 46.15% answered they had previous experience. Here is useful to remark that this question was previously asked in the preliminary test (question LAB-1), where 71.15% answered that they had experience in labs. This difference of 25% shows the adjustment of users' concept of science and engineering laboratory activities after the trial. From the 46.15% that answered positively in the second time, 63% thought that the BReal Lab has significant advantages over traditional laboratories and 29% thought that it brings some advantages (question PU-3), giving a total of 92% positive responses against 4% that answered that the BReal Lab does not make any difference and 4% who thought the BReal Lab have very poor capabilities for laboratory activities (median = 4, "I think a Mixed-Reality lab has significant advantages over a traditional Science and Engineering laboratory") (fig 6.16).

When asked about if having the physical component in the MR lab activity was necessary for doing laboratory activities in distance education (question PU-1) (fig 6.17a), 50% considered it was necessary, 37% said it was not required and 13% said it depends on the activity itself. Some of the comments were:

> *"I don't think it was necessary as I could see the result of my actions on the screen but it was more interesting to see the results on the box*

Code	Question
PU-1	In this exercise you used a physical device connected to a virtual device. Do you think it was necessary in your exercises to have the physical object? Please explain
PU-2	Have you ever participated in a traditional Science and Engineering laboratory?
PU-3	[IF PU-2 answer = YES] Which of these statements is closer to your opinion? I think that a Mixed-Reality lab: a Has a very poor capability for doing Science and Engineering lab work b Is marginally worst than traditional labs for Science and Engineering c I don't see that it makes any difference d Brings some advantages over a traditional Science and Engineering laboratory e Has significant advantages over a traditional Science and Engineering laboratory
PU-4	How useful is the capacity of the system to allow participants in different locations to work together
PU-5	In this case, we developed the system as a means of doing a programming exercise between students in different locations. Can you think in other application that you consider would be useful in your studies?

Table 6.15: Perceived usefulness (PU)

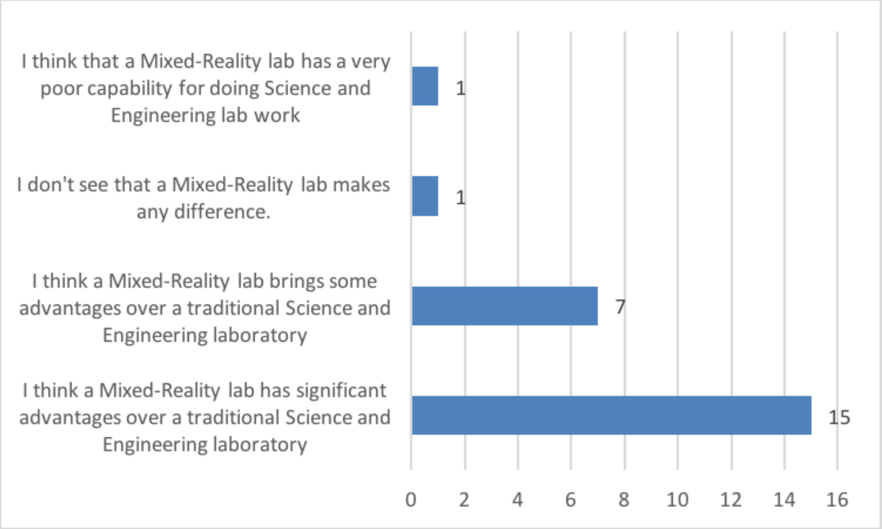


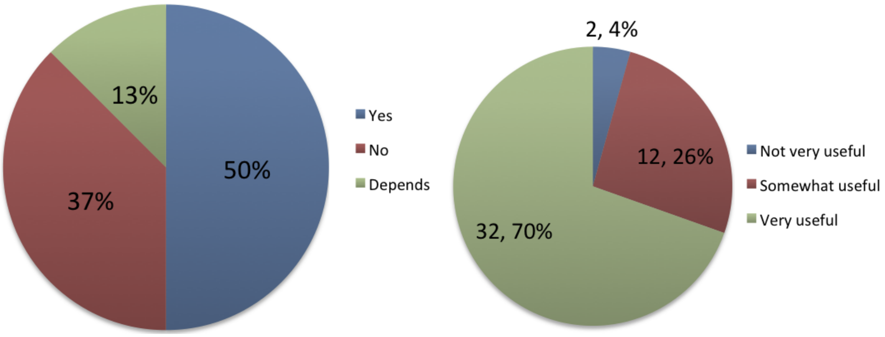
Figure 6.16: Perceived usefulness (PU-3)

> *itself.”* (Participant 10).

> *“I guess it depends on the activity, in this particular one there is only one room so the physical box felt not required necessarily but if it was a more complex problem with multiple spaces then the physical object would be more useful.”* (Participant 44).

> *“Not strongly necessary, due to the fact that I could see on the screen whether my rules were well programmed. In the other hand, it is a great experience when as a student you can see how the theory goes beyond to real applications and you can change the physical object itself.”* (Participant 17).

From these comments it is possible to see that although some participants did not think of the physical component as necessary, they clearly think it gave extra value to the activity, helping them to feel more interested in the activity and giving them a feeling of accomplishment when the physical object got updated. This supported premise 5 which states that “*The use of the BReal Lab should provide an enjoyable experience, fostering engagement and participation of team members*” (hypothesis 5 - secondary).



(a) Do you think it was necessary in your exercises to have the physical object?

(b) How useful is the capacity of the system to allow participants in different locations to work together

Figure 6.17: Evaluation Perceived usefulness (PU)

Students were also asked about their opinion on the capacity of the system to allow remote participants to work together (question PU-4), where 69.57% answered that it was very useful, 26.09% thought it was somehow useful and 4.35% saw it as not very useful (median = 1, “Very useful”)(fig 6.17b). Finally, although participants were generally positive about the BReal Lab, most of them could not think about any other specific scenario where this technology could be applied; and when they did, it was closely similar to the activity that they performed (i.e. changing the BuzzBox for other electronic devices). This perception could be due to the very specific scenario given to students in the trial.

Intention to use

Finally, participants were asked about how likely they were to use an educational system similar to the one used in the trial if it were available in their universities (question ITU-3). Response was positive, where 80.77% answered they were likely to use it (median = 1, “Very likely”), against 19.24% that answered they were unlikely to use it (fig. 6.18).

Code	Question
ITU-1	The system you tested was created as a pilot programme for educational purposes. Please list the reasons why you would use it
ITU-2	What are the reasons not to use the system you tested today?
ITU-3	How likely is that you would use a system like this if it was available in your University?

Table 6.16: Intention to use (ITU)

A Kruskal-Wallis test (table 6.17) showed that the level of personal innovativeness has no influence in how likely were participants to use the BReal Lab (PE-1: H (2) = 1.0175, p .05), reinforcing the positive response given by users of the BReal Lab.

In general, the main reasons given for not using the tool (question ITU-2) were related to user interface design issues (e.g. not showing which user is up-

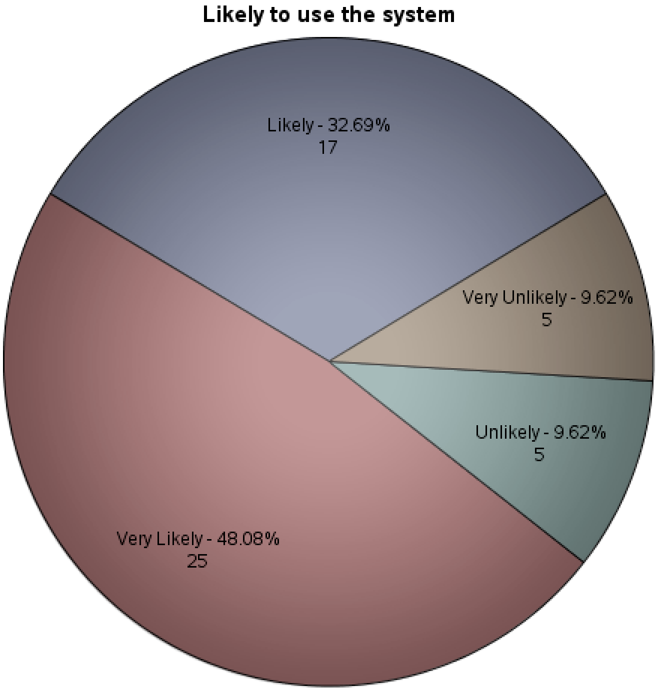


Figure 6.18: Intention to use (ITU)

Dependent variable	Independent variable	Chi-square	DF	P_value
Likeliness of usage (ITU-3)	Level of Personal Innovativeness (PI-1)	1.0175	2	0.6012

Table 6.17: ITU Kruskal-Wallis results

dating/controlling the programming board, the size of the chat window, limited end-user programming capabilities), user's worries about network issues (e.g. Internet speed, connection problems), and communication and collaboration issues (e.g. coordination with other users, responsiveness of their partners, a similar skills level between users), as can be seen from some of the comments:

> *"It needs to organize the task more clearly, no place to show who is programming and there is no chat history if lost connection."* (Participant 54).

> *"The UI is a little bit clunky, rigid and cumbersome."* (Participant 18).

> *"Because we need Internet to connect with the other team."* (Partici-

> pant 13).
>
> *"The only reasons [for not using it] are: a) if I fail to find good friend(s) to study collaboratively and, b) if there will be network issues (Internet)."*(Participant 4).

Comments related to the reliability of the network connection reflect a bias in the answers due to existing previous knowledge, which could be related to the background of the participants as 69.24% were Computer Science and Engineering students, and 21.15% were students in Learning Design and Technology; which make them aware about the possible issues when dealing with Internet-based technology. An interesting comment by Participant 4 reflected the social nature of the task, as one of his/her reasons for not using the BReal Lab would be the difficulty of finding suitable partners for the activity. This is a problem reported by Stiles (2000) when designing learning activities, as the learner could be considered as operating individually, instead of being working in a team; leading to a sense of isolation, and thus by ignoring the social aspects of learning leading to less effective learning situations.

When users were asked about their reasons for using the BReal Lab (question ITU-1), they said that they found the possibility of working with other students located in different parts of the world attractive. Participant 10's comment (below) describes part of his/her experience in the trials when doing the activity in collaboration with other remote participant, supporting premise 2 "*Participants should be able to collaborate using hands-on mixed-reality learning activities*" (hypothesis 2 - main):

> *"It is a fun way to learn because you can learn by playing around with technology as well, which I personally like. It makes the class more interesting as you can communicate and learn together with another person and share experiences during the process. One can learn from*

> *the mistakes of the other or even from their success; for example[,] by communicating with my partner, we explored what happens if you use the board multiple times and what is the outcome on each side."* (Participant 10).

Additionally, participants reported that they would use the BReal Lab because the experience was enjoyable, supporting premise 5 which states that "*the use of the BReal Lab should provide an enjoyable experience, fostering engagement and participation of team members*" (hypothesis 5 - secondary), as it can be seen from the comments below:

> *"I would use it to learn because is an interactive, its non-conventional, is visual and graphical, its easy, and above all because its like playing a videogame. I would really like to see the physical box, I guess that's way more exciting, and it makes you feel useful and intelligent, because you see results right away."* (Participant 23).

> *"I think the idea is really interesting as I have thought about the issue of labs for online students before. I also like the way it allowed you to immediately test what you were practising and get 'real' feedback. Often even if testing in an IDE isn't cumbersome, it can be difficult to determine if something worked as expected."* (Participant 42).

In like manner, they expressed in these comments the importance of having the physical component available for the learning activities, as can be seen in the two previous comments, showing the benefit of using xReality objects and supporting premise 4 "*The use of xReality objects should be preferred over simulated virtual objects*" (hypothesis 4 - secondary).

6.3.4 Perceived blended-reality

The concept of blended-reality, as defined in previous chapters, could be considered dependent upon user's perception of how synchronised are the events happening in the virtual and physical worlds. Particularly this research focused more on visual synchronisation of the distributed model of xReality objects, which was easier to identify by participants as upon each action a visual effect was triggered in both virtual and physical worlds. To determine the perceived blended-reality, participants were presented with the questions in table 6.18.

Code	Question
PBR-1	Which equipment you used in this session?
PBR-2	[IF PBR-1 answer = physical box] Did you feel that the physical box was synchronised with the object on the screen?
PBR-3	[IF PBR-1 answer = physical box] Do you think it make a difference to have the physical box? Please explain why.
PBR-4	[IF PBR-1 answer = physical box] Which output were you more focused on: the physical box or the box on the screen?
PBR-5	[IF PBR-1 answer = physical box] Is there any extra feedback you would like to add about the question above? (optional)

Table 6.18: Perceived blended-reality (PBR)

	Frequency	%	Cumulative Freq	Cumulative %
Virtual object	28	53.85	28	53.85
xReality object	24	46.15	52	100

Table 6.19: xReality and Virtual objects used in the sessions

Perceived user's blended-reality was assessed only on participants who worked with an xReality object in the experiments (PBR-1) (table 6.19). They were asked about their perception on how synchronised the physical component was in relation with its virtual representation (*"PBR-2: Did you feel that the physical object was synchronised with the object on the screen?"*). In general, participants perceived the xReality object as being synchronised when using it in the learning activity. Table 6.20 shows the detail of perceived blended-reality for each device used, with an aggregate value of 61.11% of participants that said the physical and the virtual objects were always synchronised. Thus, the level of blended-reality on the proposed proof-of-concept BReal Lab demonstrator and architecture was regarded as high by the participants, supporting premise 1 "*Participants should be able to perceive the interaction between a mix of physical and virtual interconnected objects, sharing its functionality*" (hypothesis 1 - main).

	Lights		**Heater**		**Fan**		**Sound**		**Light & Temp sensor**		**Proximity sensor**			
	Freq	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Aggr Freq**	**Aggr %**
Always	18	75.00	15	62.50	18	75.00	13	54.17	12	50.00	12	50.00	88	61.11
Most of the time	4	16.67	4	16.67	4	16.67	3	12.50	4	16.67	4	16.67	23	15.97
Only sometimes	0	0	0	0	0	0	1	4.17	1	4.17	0	0	2	1.39
Never	0	0	0	0	0	0	2	8.33	0	0	1	4.17	3	2.08
I didn't use it	2	8.33	5	20.83	2	8.33	5	20.83	7	29.17	7	29.17	28	19.44
	24	100	24	100	24	100	24	100	24	100	24	100	144	100

Table 6.20: Perceived blended reality (PBR) by device

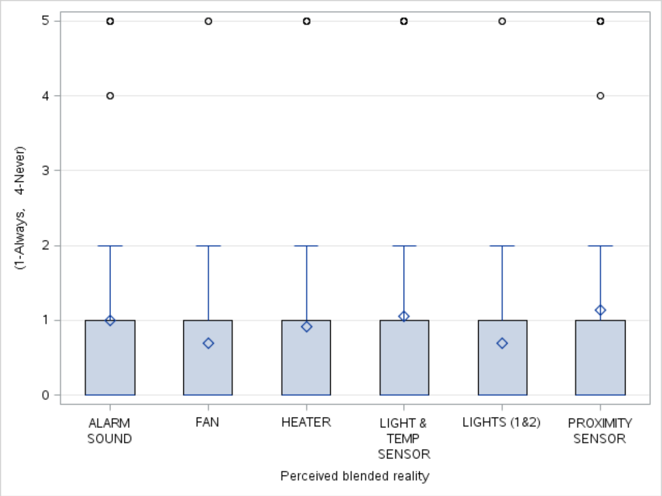


Figure 6.19: Evaluation Perceived blended reality (PBR) by device

When participants were asked about in which object during the activity they concentrated their attention the most, 75% of participants responded that in the physical component of the xReality object (i.e. BuzzBox), against 25% which said that they were more focused on the virtual component (PBR-4) (fig 6.20). However, when asked for extra (optional) feedback on their answer (PBR-5), participants reported some issues:

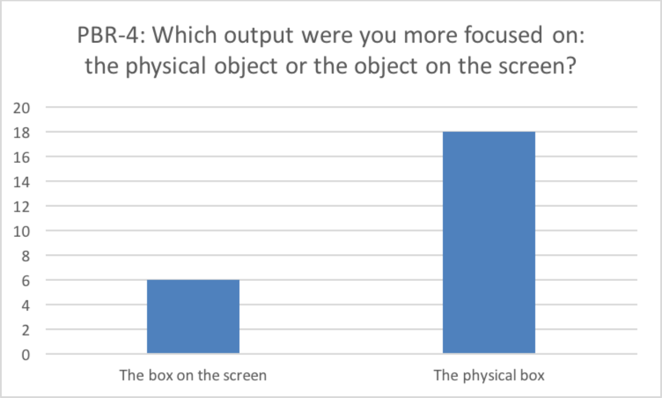


Figure 6.20: Participant's attention

> *"I think that the physical box may have even been a source of distraction for me. I would have preferred [to work] with the box on the screen and then see what happens with the physical box only when executing the commands."* (Participant 16).

> *"I tried to keep an eye on both. However, as the programming board is in the virtual world, it was easier to have a look in the virtual world. I guess having the physical box requires more attention in general given that we had a time constraint."* (Participant 9).

A particular comment made by participant 16 revealed a very interesting pattern, which was observed constantly during the trials:

> *"Honestly, I was paying more attention to the other users and our discussions in the chat room as we were trying to coordinate our actions and much less attention to the box."* (Participant 16).

From these comments and observations annotated during the experiments it was possible to identify two reasons why participants could focus their attention towards the virtual box more than the real one: a) time constraint introduced due to practical management of the multiple sessions; and b) user interface design, as the programming tool and the chat window were located inside the 3D GUI, forcing participants to focus on the screen to keep the collaboration and communication with their peers going.

When asked if having a physical component made a difference for them when performing the activity (question PBR-3), 83.33% pointed out that it made a difference. Some of the comments were:

> *"It does, because we use more of our senses and I think working with physical objects need less cognitive load rather than imagining to work with virtual ones."* (Participant 29).
>
> *"It makes a difference because it gives a better view of the reality, however, I did not find the particular box interesting, if the physical object interested [me] more I would focus on it more than the virtual object/world."* (Participant 44).

The results and comments above show that although participants thought it makes a difference to have a mixed-reality object during the activities, supporting premise 4 "*The use of xReality objects should be preferred over simulated virtual objects*" (hypothesis 4 - secondary), two important aspects arose during the activity: a) the importance of communication between participants and b) the design of mixed-reality interfaces able to provide different resources to facilitate those communications, as these enable better possibilities for users to enjoy and engage on activities such as the one proposed for the experimental BReal Lab demonstrator.

Technical Evaluation

In addition to the user evaluation described in this section, a technical evaluation was performed to measure the level of synchronisation between physical/virtual objects and remote/local objects, which as defined previously is directly related to user's perceived blended-reality and perception of a unified extended environment. As reported by Miller and Bishop (2002), some of the problems related to immersive environments are due to the time interval between when a user acts and when the virtual environment reflects an action, this effect is known as latency. Latency is the cause that can break the sense of immersion in the user, becoming him/her aware of being in an artificial environment. Additionally, in distributed systems (such as the one proposed for this research) the time between nodes when communicating within the network (network latency) needs to be considered. Thus, technical evaluation was divided in two: network and system latency (fig. 6.21).

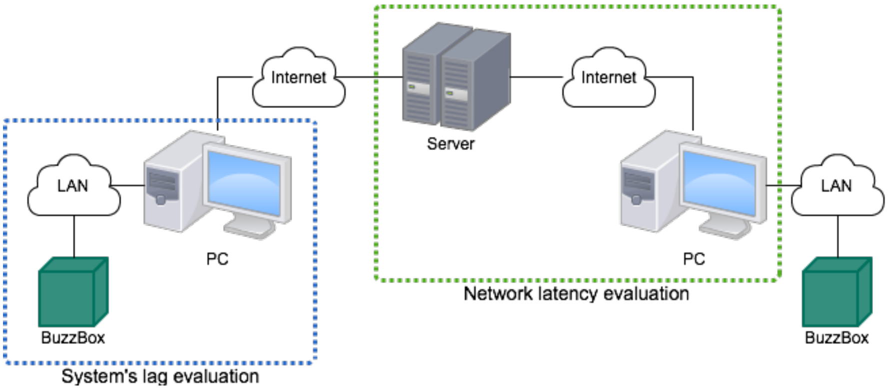


Figure 6.21: Technical evaluation

Network latency involves many factors: transmission and reception time, propagation time (distance), time spent waiting during network congestion, encryption and fragmentation time, etc. (Claypool and Claypool, 2006).

To measure network latency, facilitators at the eight hosting universities provided information obtained by executing the *traceroute* network diagnostic tool, used for measuring transit delays of packets across a network. Table 6.21 shows an estimation of network latency between the institutions and the authoritative server, controlling all the synchronisation requests, located at Essex University.

System latency in mixed-reality implementations can be generated due to a number of factors such as low frame rate display, rendering issues, environmental conditions among others (Haniff and Baber, 2003). Rendering is the process of generating an image from a 2D/3D model, and have a direct cost to the user's

	USA GMT-8	Mexico GMT-6	UK GMT	UAE GMT+3	China GMT+8	Malaysia GMT+8
San Diego State University	148	–	–	–	–	–
Leon Institute of Technology	–	153	–	–	–	–
Essex University (iClassroom/iSpace)	–	–	49	–	–	–
Anglia Ruskin University	–	–	87	–	–	–
Khalifa University of Science, Technology and Research	–	–	–	277	–	–
Shanghai Open University	–	–	–	–	354	–
Shijiazhuang University	–	–	–	–	269	–
Monash University	–	–	–	–	–	209

Table 6.21: Participant institutions' network latency (in milliseconds)

PC Graphical Processing Unit (GPU) and Central Processing Unit (CPU). If the computational intensity of the processing is high, mixed-reality systems present a slower performance when displaying what is happening in the real world (Low frame rate display). Usually the frame rate for high-end mixed-reality systems is approximately 30 frames per second (fps) (Haniff and Baber, 2003).

To estimate how system latency could affect perceived blended reality, a number of tests were performed to measure how long it took for the proof-of-concept demonstrator to react to an event performed on the xReality object. Installation of the 3D GUI was done in a regular PC (Intel(R) Core(TM) i3-2100 CPU @ 3.10GHz, RAM 4GB, Windows 7 64-bit) and the evaluation measured the time between the triggering and representation of an event in the GUI, and the reception and reaction to the event on the xReality object, in this case Fortito's BuzzBox. To have a better estimation of the time, these evaluations were performed connecting the 3D GUI's PC host and the BuzzBox to a LAN using both, a wired and a wireless connection. They both were located at Essex University iClassroom laboratory and connected to the internal network for these experiments. A sample of 60 measurements formed by 10 response time records of three BuzzBox's components (light 1, light 2 and fan) in a wired and a wireless connection were registered for the evaluation. Figures 6.22a, 6.22b, 6.22c show the response times of each component.

BReal Lab demonstrator's latency was calculated using the elapsed time interval (Δt) between virtual ($\bar{x}\ v_t$) and physical ($\bar{x}\ p_t$) component's mean response time (table 6.22).

BReal Lab demonstrator's latency

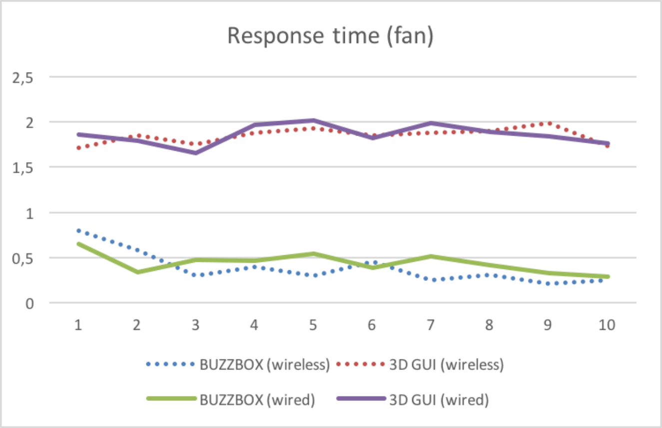
$$\Delta t = \bar{x}\ v_t - \bar{x}\ p_t \tag{6.3}$$

	Wireless			Wired		
	BuzzBox ($\bar{x}$)	**3D GUI** ($\bar{x}$)	**Elapsed time**	**BuzzBox** ($\bar{x}$)	**3D GUI** ($\bar{x}$)	**Elapsed time**
LIGHT 1	0.464	1.613	1.149	0.404	1.674	1.27
LIGHT 2	0.424	1.72	1.296	0.403	1.752	1.349
FAN	0.386	1.846	1.46	0.442	1.857	1.415
$\bar{x}$			1.30167			1.34467

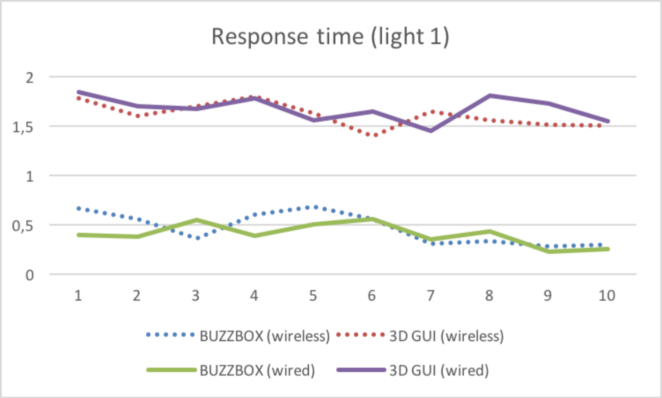
Table 6.22: BReal Lab demonstrator - Latency

Results showed a mean $\bar{x} = 1.30$ seconds wait between the execution of an action in the virtual world to be replicated in the physical world when using a wireless connection, and a mean $\bar{x} = 1.34$ seconds when using a wired connection. These results are estimated times because a great deal of the proposed mixed-reality distributed system's performance relays on participant's particular conditions such as their own network latency and their PC's computing power.

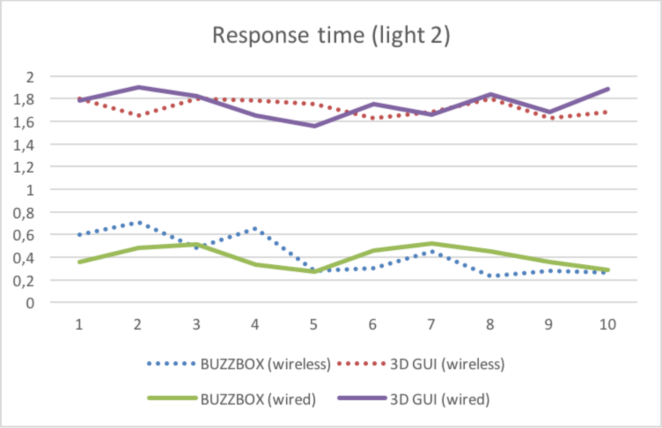
To measure response time between synchronised objects, it is necessary to consider the wider environment, as xReality objects' statuses are sent to all in-



(a) Fan

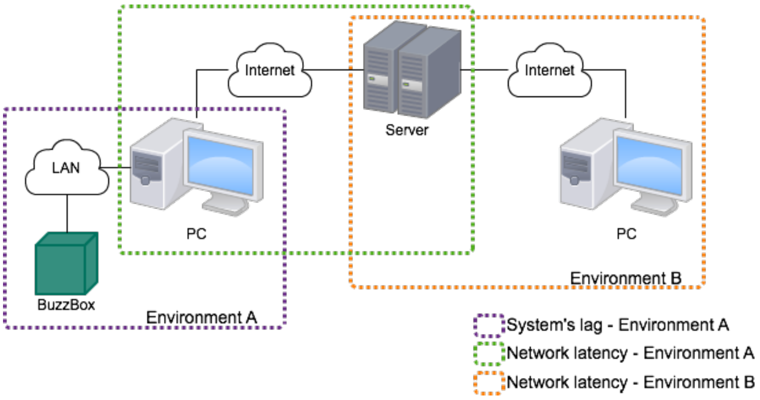


(b) Light 1

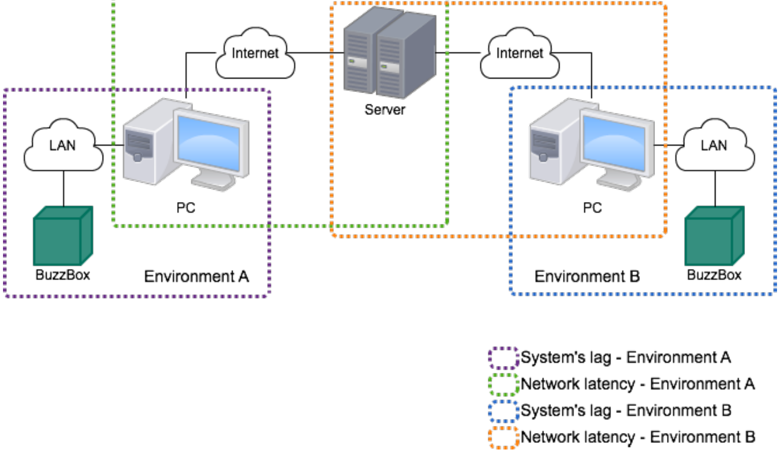


(c) Light 2

Figure 6.22: BReal Lab demonstrator - Response time



(a) One xReality object (one dual-reality state)



(b) Multiple xReality objects (multiple dual-reality states)

Figure 6.23: Blended-reality distributed system - Response time

terconnected environments, and thus replicated in a remote environment. Taking as a base the estimated times presented, response time of the wider distributed blended-reality system could be calculated using BReal Lab demonstrator's latency (Δt) plus the network latency between the local computer and the authoritative server in each environment as follows:

Synchronisation latency for one xReality object (one dual-reality state, fig. 6.23a)

$$ReponseTime = \Delta t_A + t_{networkLatency_A} + t_{networkLatency_B} \tag{6.4}$$

Synchronisation latency for multiple xReality objects (multiple dual-reality states, fig. 6.23b)

$$ReponseTime = \Delta t_A + t_{networkLatency_A} + t_{networkLatency_B} + \Delta t_B \qquad (6.5)$$

By way of an illustration, and based on the values reported previously in this section (a mean $\bar{x} = 1.34$ for system latency on a wired connection, and network latency reported in table 6.21), tables 6.23 and 6.24 presents estimated xReality objects' synchronisation latency for the eight universities involved in the trials when working with the BReal Lab demonstrator at Essex University:

	USA GMT-8	Mexico GMT-6	UK GMT	UAE GMT+3	China GMT+8	Malaysia GMT+8
San Diego State University	1.54167	–	–	–	–	–
Leon Institute of Technology	–	1.54667	–	–	–	–
Anglia Ruskin University	–	–	1.48067	–	–	–
Khalifa University of Science, Technology and Research	–	–	–	1.67067	–	–
Shanghai Open University	–	–	–	–	1.74767	–
Shijiazhuang University	–	–	–	–	1.66267	–
Monash University	–	–	–	–	–	1.60267

Table 6.23: Estimated synchronisation latency with one xReality object (one dual-reality state) in a wired connection (in seconds)

To situate the estimations presented in a context, Nielsen (1994, 1993) identified three time limits related to system's usability.

- About 0.1 second as the limit for user's perception of instantaneous reaction to an event in a system.
- A 1.0 second limit for the user to notice the delay. During delays of more than 0.1 but less than 1.0 second, users lose the feeling of an event being

	USA GMT-8	Mexico GMT-6	UK GMT	UAE GMT+3	China GMT+8	Malaysia GMT+8
San Diego State University	2.88634	–	–	–	–	–
Leon Institute of Technology	–	2.89134	–	–	–	–
Anglia Ruskin University	–	–	2.82534	–	–	–
Khalifa University of Science, Technology and Research	–	–	–	3.01534	–	–
Shanghai Open University	–	–	–	–	3.09234	–
Shijiazhuang University	–	–	–	–	3.00734	–
Monash University	–	–	–	–	–	2.94734

Table 6.24: Estimated synchronisation latency with multiple xReality objects (multiple dual-reality states) in a wired connection (in seconds)

instantaneous, but its flow of thought stays uninterrupted.

- Finally, 10 seconds limit for keeping the user's attention focused. At longer delays, users will move from the system to do other activities while they wait for the computer to finish.

Estimations of synchronisations presented in this section cannot be considered as instantaneous; however, the values are less than 10 seconds, hence, following Nielsen's classification, they are between the range where user's attention is still focused on the activity. The results presented in this section are consistent with users' reported perceptions on the synchronisation of the xReality object, where 61% said that they felt that the physical component was always synchronised with the object on the screen (table 6.20), supporting premise 1 "*Participants should be able to perceive the interaction between a mix of physical and virtual interconnected objects, sharing its functionality*" (hypothesis 1 - main).

6.3.5 Collaboration

Sessions between students were organised to test the possibilities of collaboration using the BReal Lab distributed learning environment between at least two students working in geographically separated locations (table 6.25).

No. of Participants	No. of Sessions
With 2	22
Between 3-6	4
Between 7-10	1
More than 10	2
Total	29

Table 6.25: Number of participants per session

After these sessions, when students were asked about if they enjoyed the collaboration with other students during the activity, 95.65% answered positively (median=1 “Strongly agree”, question COL-2).

Code	**Question**
COL-1	Did you worked on the assigned exercise with other student?
COL-2	I enjoyed collaborating with other student(s) inside the virtual world
COL-3	It was comfortable to communicate with the other student(s) through the virtual interface (i.e. using the chat window only)
COL-4	Explain the reasons why it was comfortable (or not) to work with other student(s) through the virtual interface
COL-5	I found difficult to communicate with the other student(s)
COL-6	How would you rate your experience of collaborating with students in other locations?
COL-7	Please provide any extra comment you have on your experience working with other students in the experiment (optional)

Table 6.26: Perceived collaboration (COL)

In like manner to previous constructs, composite values were used on items COL-3/COL-5 (table 6.27) to determine how comfortable was communication between users via the BReal Lab prototype. Based on this, 82.61% said they were comfortable establishing communication using the virtual interface (median=1 “Strongly agree”, question COL-2). As the result was more positive than ex-

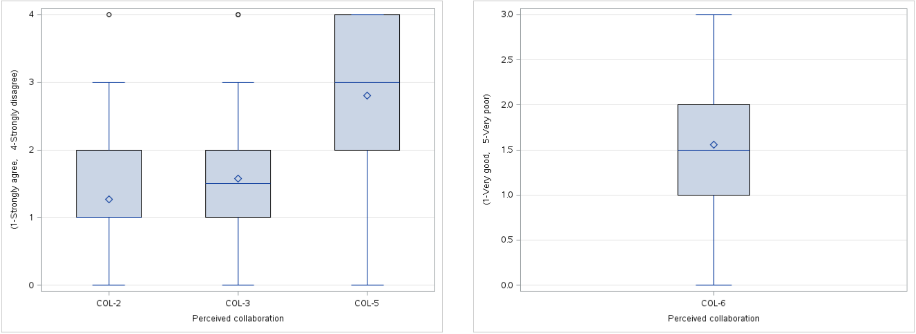


Figure 6.24: Evaluation perceived collaboration (COL)

	Comfortable (COL-3)		**Difficult (-1) (COL-5)**			
	Freq	**%**	**Freq**	**%**	**Aggr Freq**	**Aggr %**
Strongly agree	20	43.48	20	43.48	40	43.48
Agree	15	39.13	15	32.61	33	35.87
Disagree	10	13.04	10	21.74	16	17.39
Strongly disagree	1	4.35	1	2.17	3	3.26
	46	100	46	100	92	100

Table 6.27: COL composite COMFORTABLE-DIFFICULT

pected from observations during the experiment and previous comments on other questions, it was complemented with comments captured on the reasons why it was or was not comfortable.

Particularly, comments in table 6.28 illustrate the following findings:

a The use of well-known mechanisms for interacting with the platform allowed users to feel more comfortable with the BReal Lab in general (statement 1), as presented by construct *perceived ease of use* (PEOU) results in previous sections;

b Participants reported social anxiety that comes from collaborative activities (statements 2 and 3), supporting reports by Dede (2005a) which states that shy students are often reluctant to participate in face-to-face dialogue, and they engage more easily in intellectual interchanges when their physical characteristics are masked by the medium. Their familiarity with written

1	“Because the chat interface is very common nowadays, I think everyone is familiar using this tool.”	Participant 17
2	“It was comfortable because I do not really know them and probably will never meet them so I do not have to worry about them liking me.”	Participant 55
3	‘It was comfortable to work with the other student through chat because it is a more impersonal means of communication. Having a telephone conversation, for example, or a Skype meeting for the first time with another person would be more intimidating. However, it does slow down communication as you need to wait for the other person’s response. Talking to him/her would speed things up.”	Participant 10
4	“The chat window was very easy to use, but it would be even more useful to have audio conversations to be efficient with time. In addition, it would allow for easier problem-solving.”	Participant 41
5	“I personally find communication via microphones faster but using the chat overcome the issue of not understanding others’ pronunciation.”	Participant 4
6	“It wasn’t comfortable because it is limited. We couldn’t see each other or hear his/her voice intonation.”	Participant 29
7	“The chat is limiting, but the cooperation and encouragement of my playmate was very nice. The phrases in chat not cut into a new line when reach the size of window´s chat, causing it to shift the chat bar to the left to read the entire message.”	Participant 22
8	‘The chat window was too small, and the comments went by too quickly. I think it would be better on the side and longer, so you can see more chat history. Voice chat capabilities would be helpful as well.”	Participant 36
9	“Chat was difficult and there was no communication. It would have been better to do [it] individually.”	Participant 35
10	“Group work online always feels awkward to me. Particularly when limited to chat, it can be difficult to build a rapport that allows for collaboration.”	Participant 42

Table 6.28: Example Statements (COL-4)

communication tools (i.e. chat window) made them more comfortable and gave them control over the situation, as interacting with strangers was considered a stressful situation for some of them;

c Even though participants reported that it was easy to use a written communication mechanism; they considered that using text-chat communication slowed down the collaboration and interactivity between users (statements 3,4,5), supporting findings from Salinäs (2002) which stated that communication through text-chat in collaborative virtual environments (CVE) makes the interaction in the environment less social compared with video or voice conferences in CVE;

d Another aspect to consider in users' preferences of spoken over written communication could be related to language proficiency (statement 5). Experiments used English as a *de facto* language for communication, but, as showed previously in the demographics data, participants came from fourteen different countries with more than half of the sample (69.23%) reporting a high level of proficiency. This factor could have influenced their preferences on spoken over written communication, as they felt secure enough to start verbal interchanges (Horwitz et al., 1986; Woodrow, 2006; Cheng et al., 1999);

e Some participants found communication uncomfortable due to user interface design issues such as size and position of the chat window (statements 7 and 8).

f Finally, a reduced number of participants expressed their general personal unwillingness towards online teamwork (statements 9 and 10).

From all these comments it is possible to see that collaboration between students was challenging as they were only able to see each other using avatar representations of each other, and did not know each other on beforehand. Some of them were happy about the anonymity that working from a 3D virtual environment provides, but participants with a more dominant personality preferred a more personal communication via voice conversations. In general, GUI design issues, although noted by the participants, did not pose a barrier for completing the activity. All these are factors needed to be considered when designing collaborative learning experiences for distance learners. The general mark given by participants on the collaboration with other colleagues was positive (question COL-6) with 78.26% saying that their experience was good (median = 1, "Very good") (fig 6.25).

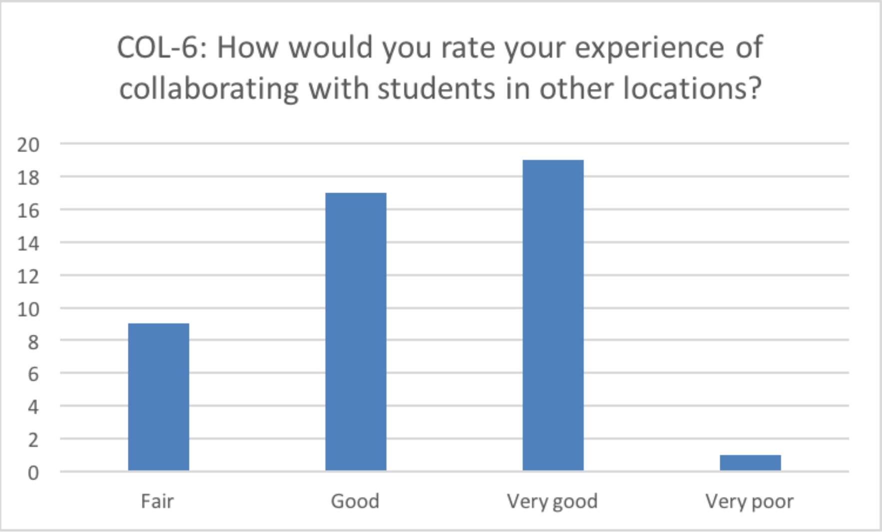


Figure 6.25: User's collaboration experience

Participants' final optional comments about their general experience working with other students using the BReal Lab (question COL-7) expressed some of the challenges to which participants were exposed when working with other online students:

> *"I found coordination with other end users challenging. If we faced difficulties to coordinate when only three people, how would coordination problems be solved out in a class of 20? I strongly believe that the teacher/instructor should also have their own avatar in the virtual space so as to help out with coordination issues."*(Participant 16).

> *"Due to the number (10 or more) of avatars in the experience, it was somewhat disorganized. Although, working with a smaller, more focused group would have been much easier."*(Participant 41).

> *"I guess it would matter if I was not certain that I will learn something from the other person. It would be helpful if I collaborated with a person that had something to teach me on a particular difficult task."*(Participant 44).

From these comments, it can be observed that participants noticed the need for a team leader to give the group direction that a teacher or instructor generally gives in a traditional class. This was something very noticeable particularly on sessions with a large numbers of students with different cultural backgrounds, where coordination and negotiation was difficult, and it took a noticeable period for participants to start working on the assigned activity. Although at least one facilitator was at each location to help them use the BReal Lab, they did not participate in the discussions between students inside the virtual world.

To gain a deeper understanding of the team dynamics and collaboration during the experiments, the activity logs, recorded by the prototype during the experiments, were analysed. This consisted of:

- A chat log with all written conversations between students classified by sessions.
- An activity log containing all the instructions executed from the "Programming Board" during the sessions.

Chat log

As reported by Garrison et al. (1999), computer-mediated communication (CMC) is becoming increasingly common in higher education due to the proliferation of technology-enhanced learning models. Whilst oral communication tends to be spontaneous and less structured than text-based communication, providing multiple non-verbal information such as facial expression and tone of voice. In contrast, research suggests that written communication is closely connected with careful and critical thinking (Applebee, 1984; Fulwiler, 1987; White, 1993), however much of the information that creates and sustains group dynamics is not transmitted.

To find more results about collaboration and group dynamics, data in the chat log was analysed to find collaboration patterns, based on a series of linguistic classifiers (table 6.29). The method to determine the frequency of these classifiers on the conversations consisted in identifying particular phrases that belonged to a classifier (e.g. "*hello*" or "*hi*" belong to the classifier GREETINGS), and then finding and counting those strings within the log of conversations, using as a model the 40 tags associated with different dialogue acts developed by Stolcke et al. (2000) for its use in discourse analysis. The full list of phrases and classifiers used is included in Appendix B.

Linguistic classifiers
EMOTICON
GREETINGS
AGREEMENT / CONFIRMATION
INQUIRY
TRANSITIVE / IMPERATIVE
PERSONAL OPINION / BELIEF
BUILDING RULE EXPLICITLY
STATEMENT
EXPRESSING POSITIVE FEEDBACK
FEEDBACK ABOUT EXECUTION

Table 6.29: Linguistic classifiers

Results from the chat analysis (fig. 6.26) revealed the high use of *emoticons* to transmit emotions over the use of written positive feedback (EMOTICON 5.85% versus EXPRESSING POSITIVE FEEDBACK 1.01%). Emoticons are symbols representing facial expressions, used as a way to express non-verbal cues in written communication (Walther and D'Addario, 2001). This results supported user's feedback stating that the use of written text for communication was not enough for the interaction needed. An interesting thing to notice is that the dynamics between participants never included negative feedback. Available data is not enough to determine why there was an absence of negative feedback, as this could have been related to the controlled conditions of the experiment, where participants knew the feedback was being recorded. Additionally, the high use of the classifiers INQUIRY (16.4%) and AGREEMENT/CONFIRMATION (16.87%) over the classifier TRANSITIVE/IMPERATIVE (6.78%) in the sessions suggests the general disposition of students to collaborate in the learning activity.

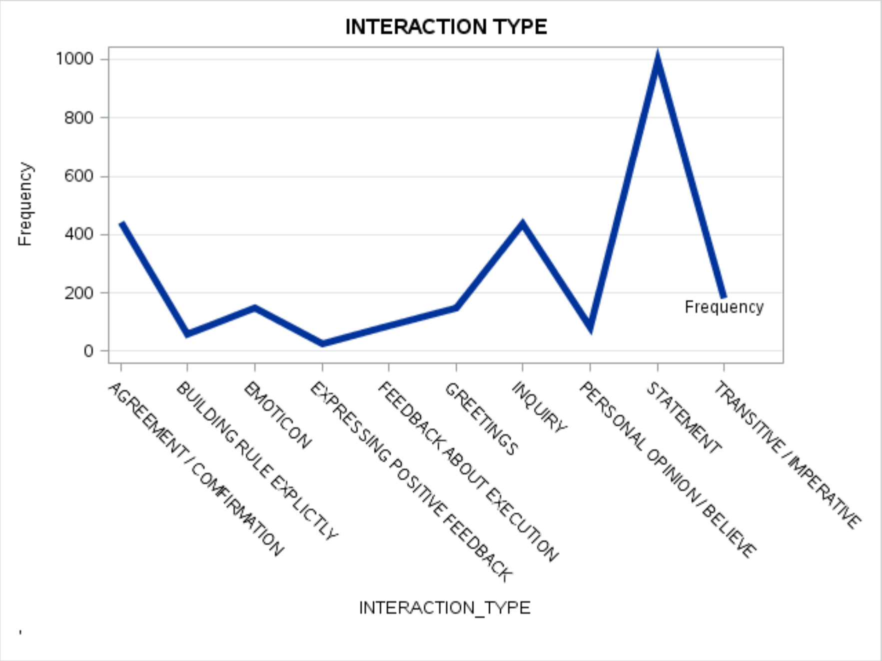


Figure 6.26: Interaction type

To calculate the amount of participation, the number of interactions were analysed, based on the number of participants that collaborated in a session (table

6.30). A detailed analysis on the sessions with more than 10 participants showed that 6 users logged in those sessions did not interact at all with their peers. This phenomenon is known as *social loafing*, and refers to the tendency to reduce individual effort when working in groups compared to the individual effort expended when working alone (Williams and Karau, 1991) and is commonly seen in large teams as cooperation tends to decline as groups grow (Kerr and Bruun, 1983; Komorita et al., 1992). According to Chidambaram and Tung (2005) study, the smaller the group, the more likely each member participates, regardless if its a face-to-face or online group. For online teams Piezon and Donaldson (2005) suggest groups no larger than six, unless the activity to be performed by the group is brainstorming (e.g. not delivering a physical outcome but conceptual). Hare (1981) suggests that an optimal small group size may be five; indicating that group satisfaction becomes an issue for even numbered groups due to the development of subgroups. For groups larger than five, group members may have fewer opportunities to contribute. Thus, groups should be no larger than required to accomplish the group goals (Hare, 1981).

Results from the number of interactions made by each participant (fig. 6.27) supported literature findings, and showed that the highest level of interaction occurred in sessions with 3 participants, suggesting that BReal Lab sessions with up to 3 participants would lead to more equitable participation and involvement of the users.

No. of Users	**Sessions**	**Total Interactions**	**Interaction By User ($barx$)**
2	22	1596	36.27
3	3	371	41.22
5	1	151	30.2
8	1	182	22.75
11	1	191	17.36
21	1	116	5.52

Table 6.30: Number of sessions based on the number of participants

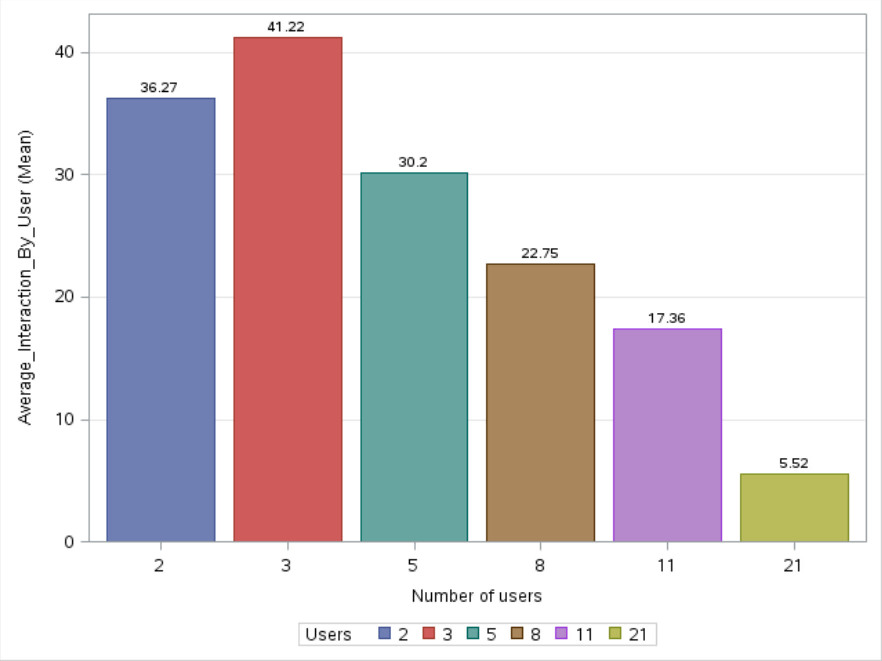


Figure 6.27: Session interaction by user

Activity log

The activity log was analysed to measure participants' productivity by identifying the number of behavioural rules successfully tested. This does not involve the final result of the rule (i.e. if the logic implemented was executed successfully or not according to participants' goal), instead the analysis was focused on how many rules participants were able to construct and test in their sessions regardless their result (table 6.31). Results in figure 6.28 show that collaboration between participants produced 98.55% of well-constructed rules, against 1.45% with wrong syntax, supporting BReal Lab's easiness of use indicated in previous sections of this chapter. Literature in online teams productivity suggests that, with the exception of brainstorming, computer-based groups are equally productive than face-to-face groups (Parks and Sanna, 1999; Piezon and Donaldson, 2005); which could give an estimated comparative against real world collaborative tasks.

Moreover, Locke and Latham (2006) have suggested that there is a positive linear relationship between goal difficulty and task performance, thus the assign-

Result	Instruction type			
	IF	IF-ELSE	SEQUENTIAL	Total
Condition-false	76 15.7%	152 31.4%	0 0	228 47.11%
Condition-true	61 12.6%	96 19.83%	0 0	157 32.44%
Sequential-instruction	0 0	0 0	92 19.01%	92 19.01%
Wrong Syntax	0 0	0 0	7 1.45%	7 1.45%
Total	137 28.31%	248 51.24%	99 20.45%	484 100%

Table 6.31: Participants' productivity

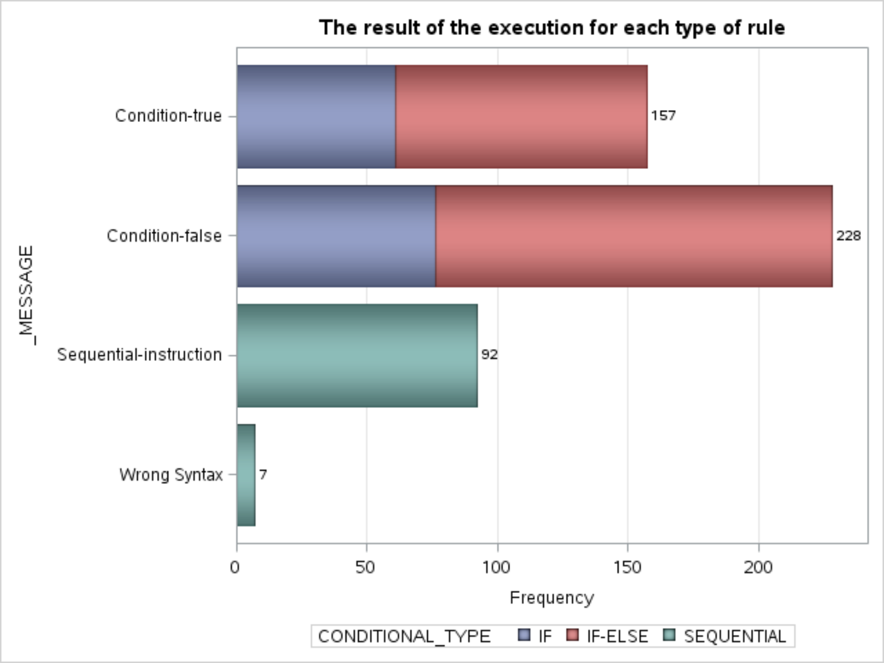


Figure 6.28: Result after execution

ment of specific and ambitious goals lead to more performance improvement than easy or general goals. To assess this, rules were classified by complexity according to three options: a) construction of a sequential instruction (low) (i.e. no logical conditions involved), b) construction of an *IF* instruction (medium) and, c) construction of an *IF-ELSE* instruction (high). Figure 6.29 shows that instructions with a higher level of complexity were more used in comparison with less complex

Object type	**Instruction type**			
	IF	IF-ELSE	SEQUENTIAL	Total
Virtual	62 12.81%	155 32.02%	91 18.80%	308 63.64%
xReality	75 15.50%	93 19.21%	8 1.65%	176 36.36%
Total	137 28.31%	248 51.24%	99 20.45%	484 100%

Table 6.32: Instructions' complexity per object type

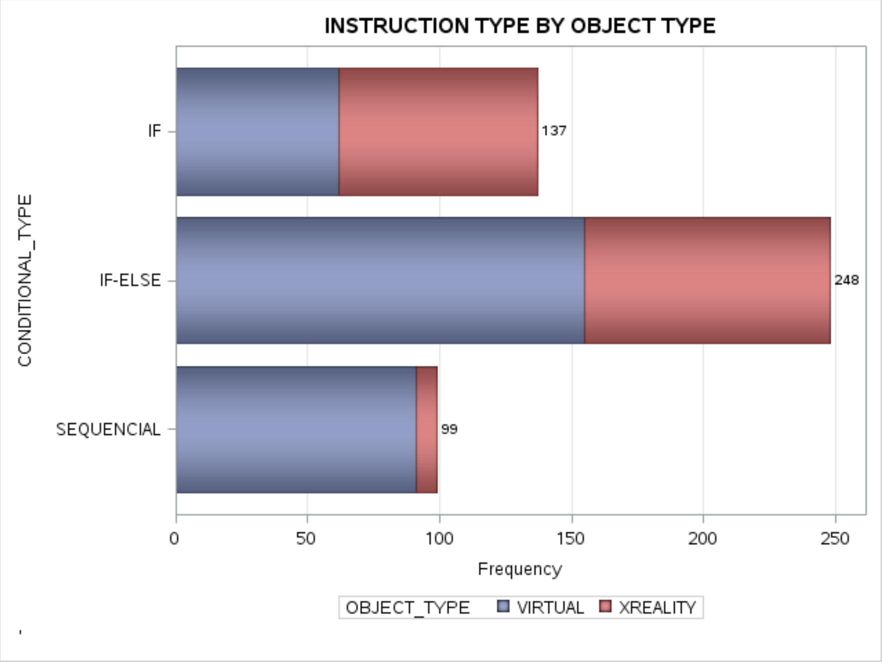


Figure 6.29: Instruction type by object type

rules, suggesting that the difficulty of the task encouraged participants to interact more with the BReal Lab. These results also show that users working with a virtual object created more rules regardless the complexity level. This could be due to two reasons: a) user's familiarity with virtual environments, as 50% of the participants were familiar with virtual worlds according to the demographics data, and b) the proportion of participants that worked in the experiments with a virtual object (53.85%) was marginally larger that those with a xReality object (46.15%). However, when using instructions with a medium-complexity level (*IF* instructions), participants working with a xReality object created more instructions than those with virtual objects (xReality 15.50% versus Virtual 12.81%), suggesting that the higher level of complexity implied in the use of xReality objects compensates the use of medium-complexity level tasks, in a similar way that the use of a less complex object (in this case the virtual object) is compensated by users' preference of a higher complex task (IF-ELSE - xReality 19.21% versus Virtual 32.02%).

Perceived end-user programming ease of use (EUP)

Finally, to complement findings from activity log's analysis in relation with collaboration and the task assigned, participants were asked about their views on the programming tool which was the mechanism that allowed them to finish the assigned task (fig. 6.30). Table 6.33 lists the questions asked to participants. As the items on this construct were positive and negatively worded, composite values were used, as in previous constructs. Tables 6.34, 6.36, 6.35 show the calculus of these composite values.

Current room: John's session
Activity: 1 - Construct
Elapsed time: 1:07
Virtual object only.

Figure 6.30: 3D GUI Programming Board

Results showed that 81.73% of participants considered the *Programming Board* as easy to use, against 18.27% that found it difficult (median = 2, "Agree"). Similarly, 97.12% found it interesting (median = 1, "Strongly agree"), 93.27%

Code	**Question**
EUP-1	Using the Programming Board (wall) was easy
EUP-2	Using the Programming Board (wall) was useful
EUP-3	Using the Programming Board (wall) was fun
EUP-4	Using the Programming Board (wall) was interesting
EUP-5	Using the Programming Board (wall) was difficult
EUP-6	Using the Programming Board (wall) was annoying
EUP-7	Using the Programming Board (wall) was boring

Table 6.33: Perceived end-user programming ease of use (EUP)

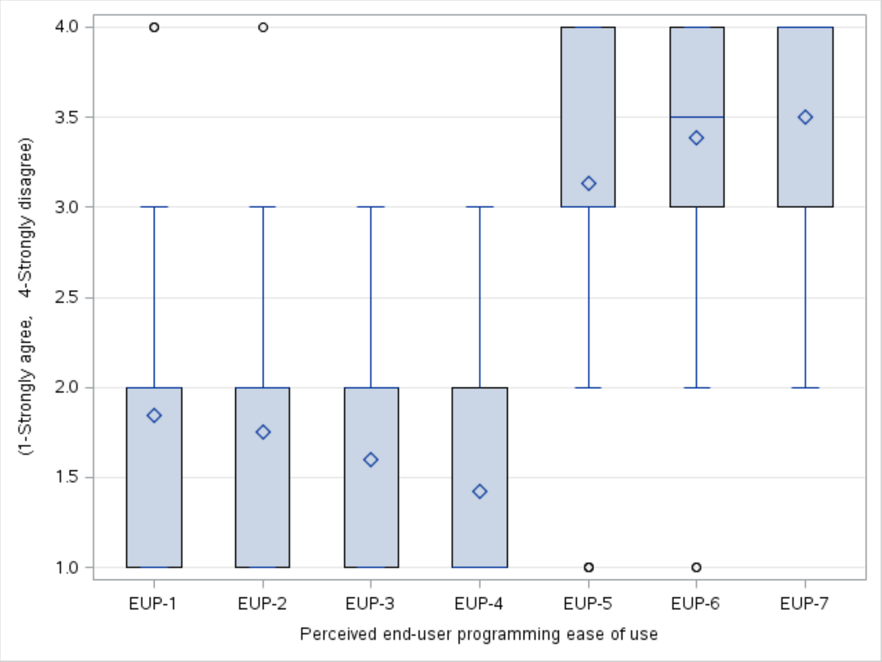


Figure 6.31: Evaluation end-user programming ease of use (EUP)

thought it was fun to use it (median = 2, "Strongly agree"), and 94.23% found it useful, which shows participants' positive acceptance in general.

	Easy (EUP-1)		**Difficult (-1) (EUP-5)**			
	Freq	**%**	**Freq**	**%**	**Aggregate Freq**	**Aggregate %**
Strongly agree	19	36.54	20	38.46	39	37.50
Agree	24	46.15	22	42.31	46	44.23
Disagree	7	13.46	7	13.46	14	13.46
Strongly disagree	2	3.85	3	5.77	5	4.81
	52	100	52	100	104	100

Table 6.34: EUP composite EASY-DIFFICULT

	Interesting (EUP-4)		**Boring (-1) (EUP-7)**			
	Freq	**%**	**Freq**	**%**	**Aggregate Freq**	**Aggregate %**
Strongly agree	31	59.62	28	53.85	59	56.73
Agree	20	38.46	22	42.31	42	40.38
Disagree	1	1.92	2	3.85	3	2.88
Strongly disagree	0	0.00	0	0.00	0	0
	52	100	52	100	104	100

Table 6.35: EUP composite INTERESTING-BORING

	Fun (EUP-3)		**Annoying (-1) (EUP-6)**			
	Freq	**%**	**Freq**	**%**	**Aggregate Freq**	**Aggregate %**
Strongly agree	24	46.15	26	50.00	50	48.08
Agree	25	48.08	22	42.31	47	45.19
Disagree	3	5.77	2	3.85	5	4.81
Strongly disagree	0	0.00	2	3.85	2	1.92
	52	100	52	100	104	100

Table 6.36: EUP composite FUN-ANNOYING

Dependent variable	Independent variable	Chi-square	DF	P_value
Easy (EUP-1)	Preliminary knowledge in programming (PR-1)	2.8944	3	0.4082
Useful (EUP-2)	Preliminary knowledge in programming (PR-1)	1.6587	3	0.6462
Fun (EUP-3)	Preliminary knowledge in programming (PR-1)	4.0129	3	0.2601
Interesting (EUP-4)	Preliminary knowledge in programming (PR-1)	2.4066	3	0.4924
Difficult (EUP-5)	Preliminary knowledge in programming (PR-1)	0.6158	3	0.8928
Annoying (EUP-6)	Preliminary knowledge in programming (PR-1)	0.4890	3	0.9213
Boring (EUP-7)	Preliminary knowledge in programming (PR-1)	1.9141	3	0.5904

Table 6.37: EUP Kruskal-Wallis results

A Kruskal-Wallis test showed that the level of previous knowledge/experience in programming had no influence in how participants rated the programming tool (table 6.37). A possible reason for this was the fairly simple mechanism used to implement the programming tool. During the collaborative sessions there was no ownership of the elements on the board, making an equitable environment where all participants have the same rights. Therefore, any of the students on the session could add or remove freely any element on the "Programming Board". This, was something that users noticed and commented as affecting the dynamics of the group:

> *"We proposed a solution, but was a little difficult when we used the programming board, because all of us tried to put the same sensor or sentence in the same time, but was fun."*(Participant 14).
>
> *"[It] would be better if [we] could differentiate the members with colours, [to know] who is working on [the] programming board, who is talking, etc."*(Participant 54).

In summary, the analysis of participants' collaboration showed that in spite of reported issues in the user interface design and preference towards spoken communication, participants enjoyed working with other remote students in the mixed-reality activity. A particular factor that affected collaboration was the number of participants per session, as sessions with larger number of participants were reported as unsatisfactory and chaotic. This observation was confirmed when analysing productivity in the BReal Lab via its activity log. Participants' attitudes towards online collaboration were predominantly open and cooperative, with an absence of negative feedback for team mates when doing the activity, which could be due to the fact that they knew they were being observed by the instructors that facilitate the activity. Finally, the analysis on tasks' complexity showing that participants had a good performance regardless the object used. These results support premises 2 "*Participants should be able to collaborate using hands-on mixed-reality learning activities*" (hypothesis 2 - main) and 3 "*The use of the BReal Lab does not require any specialised technical mixed-reality expertise* *from participants*" (hypothesis 3 - secondary), showing team-dynamics similar to the ones observed in laboratory activities in schools and universities.

6.3.6 Instructors' evaluation

After the sessions a link to an online survey with open questions was sent to instructors and facilitators that participated in the sessions to gather their views on the activity performed and the prototype (table 6.38). It was important for this evaluation to include them in this evaluation as they experienced the trials from a different perspective.

Code	**Question**
INS-1	Could you give us your views on the overall session?
INS-2	Considering the way the system stands at the moment (without any extra enhancement), What aspects of the system you think that could help teachers to deliver laboratory activities/sessions to remote students?
INS-3	If we were able to make any changes, what would be your suggestions for improving the technology we used in this trials?

Table 6.38: Instructors' evaluation

In general, views on the overall session were positive, with instructors reporting that students who participated were enthusiastic and interested in understanding the functioning of the prototype. According to the instructors, students did not want to abandon their sessions until finishing the specific rules they had imagined, even when the time allocated for the experiment had expired and team-mates had left the virtual room. Some of the comments were:

> *"It is impressive, with people from different continents connecting real-time onto the system. The feedbacks received from the participants was also excellent, welcoming global smart education (remote laboratory) in line with the education in smart cities."* (Instructor 3).

> *"The system is quite interesting, every one of the parts of the system*

> *(hardware and software) can be very helpful for teachers and students, I think the only thing teachers need is imagination to make the most of this technology. Devising a set of activities considering the benefits and limitations that the system offers, students would show certainly interested and active in the sessions."* (Instructor 2).

Suggestions for improving the prototype included some of the issues already reported by the students, such as improvements to the 3D GUI design (e.g. improving size and position of the chat window), inclusion of more communication tools (e.g. voice communication capabilities), team management tools (e.g. informing which avatar is modifying the xReality object to avoid frustrating other team members). From the pedagogical side they suggested the possibility of personalising the environment, ranging from customising users' avatars to the design of different complexity levels for the activities (e.g. more programming statements, adding different objects), giving students the opportunity to do activities that match with their appropriate level. Of course, while many of these comments might inform future design, in the case of this evaluation, the learning gain was not part of the BReal Lab examination. Instead, the assigned task was simply a means to allow the students to experiment with collaboration inside the prototype BReal Lab environment.

6.4 Discussion

The aim of this research, as explained in Chapter 1, was to propose an alternative to hands-on activities for teams of geographically dispersed learners. In doing so, the thesis explored the use of mirrored virtual/physical objects (xReality objects) (presented in chapter 4) in a distributed architecture implemented using a proof-of-concept demonstrator (the BReal Lab). This chapter presented user and technical evaluations of the BReal Lab, undertaken to support the core hypothesis that "*it is possible to devise a computational model and architecture able to connect locations, that are physically separated, into one unified continuous space by linking elements situated in those locations, using a mix of physical and virtual objects* (hypothesis 1 - main), *and enabling remote users (with no technical mixed-reality expertise* (hypothesis 3 - secondary)) *to perform collaborative creative teamwork based on hands-on-activities* (hypothesis 2 - main); *preferring the use of mixed physical and virtual objects over simulated (virtual) objects* (hypothesis 4 - secondary); *and fostering engagement and participation* (hypothesis 5 - secondary)". The strategy to validate it was to deconstruct it in a number of high-level premises which were evaluated in user studies against a number of constructs (abstractions), and validated with the data obtained from technical evaluations and from the proof-of-concept demonstrator's log. Table 6.39 presents a relation between the hypothesis, premises and constructs used.

Results from the evaluation showed in general a positive acceptance towards the use of the BReal Lab demonstrator. A fundamental concept underneath of this research was blended-reality, which, as explained in section 2.2.1, seeks to create "*interactive mixed-reality environments where the physical and the virtual are seamlessly combined (blended not merely mixed) and affect each other, in the service of interaction goals and communication aims*". This concept could be considered dependent upon user's perception of how synchronised are the events happening between the interrelated virtual and physical worlds, which in turn, depends directly on technology performance. In addition, the aim of the research was to connect not just virtual and physical objects, but to enable distant environments to be connected into one large environment able to share physical objects. Thus, hypothesis 1 posed the question of the possibility of creating such computational model. To evaluate this hypothesis, the user study obtained participants' perception on objects' synchronisation; which was complemented with a techni-

Hypothesis	Premise	Associated constructs	Additional evaluation
1 - main	"Participants should be able to perceive the interaction between a mix of physical and virtual interconnected objects, sharing its functionality."	Perceived Blended Reality (PBR)	Technical evaluation
2 - main	"Participants should be able to collaborate using hands-on mixed-reality learning activities."	Intention to Use (ITU), Perceived Blended Reality (PBR), Collaboration (COL), Perceived end-user programming ease of use (EUP)	Chat log
3 - secondary	"The use of the BReal Lab does not require any specialised technical mixed-reality expertise from participants."	Perceived Ease of Use (PEOU), Perceived end-user programming ease of use (EUP)	Activity log
4 - secondary	"The use of xReality objects should be preferred over simulated virtual objects."	Perceived Enjoyment (PE), Intention to Use (ITU), Perceived Blended Reality (PBR)	
5 - secondary	"The use of the BReal Lab should provide an enjoyable experience, fostering engagement and participation of team members."	Perceived Enjoyment (PE), Perceived Usefulness (PU), Intention to Use (ITU)	

Table 6.39: Hypothesis, premises and constructs

cal evaluation to calculate an estimated synchronisation latency between one or more interconnected xReality objects, based on two factors: network and system latency. Results from this evaluation showed that although response times were higher than those reported by the literature (Nielsen, 1994, 1993) to be considered as instantaneous by users (with estimated values ranging from 1.48 to 3.02 seconds, against a 1 second limit before a user notices the delay), latency was within the limit of less than 10 seconds before losing users' attention. These results were confirmed by 61% of users who worked with a xReality object; reporting the objects as being synchronised when using them during the activity and supporting the proposed hypothesis. Reasons for the delays are varied and mostly depend on particular settings for each user, for example: users were connected to different university networks with security firewalls, which could have added waiting times to the general latency. Another factor could be due to Internet speed variation within countries, with average connection speeds of 3.4 Mb/s in China, 5.0 Mb/s in Malaysia, 5.5 Mb/s in Mexico, and 7.0 Mb/s in UAE, against 11.7 Mb/s in the USA and 11.8 Mb/s in the UK (Akamai Technologies, 2015). Additionally, response times between the xReality object and the server could also vary based on the local network configuration and the specifications of the computer used to run the 3D virtual world.

Another fundamental aspect in this research was collaboration. Hypothesis 2 posed the question of the use of the proposed computational model and architecture to allow collaboration between students in hands-on activities. This aspect was assessed in two different ways: by obtaining participants' perception about collaboration when using the BReal Lab, and by analysing the log of conversations to determine how much does participants interacted during the activity. 78.26% responded that their experience of collaborating with students in other locations was good, however, collaboration in general was challenging, as the tools for interaction were limited to: a chat window in the user interface, avatar representation of participants, the "programming board", and the xReality object (BuzzBox). Additionally, a number of factors influenced the results of this evaluation, for example, sessions were organised from a minimum of two students up to a maximum of twenty-one students, working in geographically separated locations, and who did not know each other on beforehand. This created a mix of participants with different sociocultural backgrounds, and with different personal preferences, which were reflected in their feedback. Participants' views about the BReal Lab demonstrator's capacity to allow remote participants working together was considered useful by 69.57% of participants, and the possibility of working with other students located in different parts of the world was regarded as attractive by users, and it was mentioned as one of the reasons for using the proposed technology. A recurrent comment was regarding communication tool preferences. Participants reported familiarity with the use of written communication tools (i.e. text-based chat tool), however interface design issues, such as position and size of the screen, were regarded as uncomfortable. In general, these design issues, although noted by the participants, did not pose a barrier for completing the activity. Some participants reported that the anonymity provided by the BReal Lab's interaction tools (i.e. text-based chat and avatars) make them feel comfortable reducing anxiety of social interactions, giving them control over the situation. However, a majority of participants reported preference on personal communication using voice conversations, as they considered that using text-based communication slowed down the collaboration and interactivity between users. This divide between spoken and written communication preferences could have been influenced by the fact that experiments used English as a *de facto* language for communication. Demographics data showed that participants came from fourteen different countries, with more than half of the sample (69.23%) reporting a high level of proficiency, thus, those participants with high English proficiency could have been more inclined to starting a spoken conversation with strangers than those with lower levels of English proficiency.

Results from the chat log analysis revealed an absence of negative feedback between participants. However, this could have been related to experiments' controlled conditions, where participants were informed on beforehand about the recording of chat conversations. Participants' written interactions were mainly divided in agreements (16.87%), inquiries (16.4%), and transitive/imperative sentences (6.78%), which reflected the general disposition to collaboration between participants. Another interesting finding was the highest use of *emoticons* to transmit positive feedback over the use of written positive comments, which supported users' feedback about the need for more personal communication tools, as *emoticons* usually express non-verbal cues in written communication (Walther and D'Addario, 2001).

The amount of participation was calculated based on the number of interactions per participant per session, suggesting that BReal Lab sessions with up to 3 participants would lead to more equitable participation and involvement of the users, and supporting literature findings which pointed that numbers for online teams should be no higher than five, and preferable on even numbers to avoid the creation of subgroups (Chidambaram and Tung, 2005; Piezon and Donaldson, 2005; Hare, 1981). In sessions with a large number of participants the number of interactions per user decreased, finding that within larger sessions of more than 10 participants, 11.53% were only spectators and did not engaged in any communication/activity with other participants. In these sessions with large numbers of students with different cultural backgrounds, participants noticed and reported the need for a team leader, able to give the direction to the group (a task usually embodied by a teacher or instructor), as coordination and negotiation was more complex. All these results supported hypothesis 2, however, as noted by different researchers (Gilbert and Moore, 1998; Gunawardena et al., 1997; Liaw and Huang, 2000; Northrup, 2001), social interaction is the factor that influence the effectiveness of collaborative learning; and most of the times is taken for granted by educators and researchers (Kreijns et al., 2003). Thus, multiple aspects of human communication and social interaction need to be taken into account when designing mixed-reality learning activities.

An important angle for the computational model proposed was the requirement of making it accessible to any user, without the need of having technical background on mixed-reality, as proposed in hypothesis 3. The strategy to validate this was via the user study, by obtaining users' views on the ease of use, and by analysing results from the activity log, to identify the number of behavioural rules successfully constructed and tested, regardless if the logic implemented was executed successfully or not according to participants' goal. Demographic data showed a broad range of topics studied by the participants; mostly dominated by students with Computer Science or Computer/Electrical Engineering background (69.24%), and a percentage of 30.76% of participants that had various backgrounds (e.g. Learning Design and Technology, Economics, Linguistics, Politics, Graphic Design, etc.). A high number of participants considered the BReal Lab as easy to use (83.65%) regardless the object used (virtual or xReality) or the preliminary experience or knowledge on topics encompassed in the experiments (i.e. virtual worlds, programming, mixed-reality, etc.). This could be due to the fairly simple mechanisms adopted within the user interface (e.g. the use of keyboard to navigate within the virtual environment, control of the programming board using a mouse, etc.). An important finding in this evaluation was that the multiple dual-reality principles were regarded as not difficult to understand and the lack of experience on some of the topics involved in the activity (i.e. ambient intelligence and programming knowledge, videogames and laboratory experience) had no influence on the completion of the activity. Results from the activity log showed that collaboration between participants produced a high number of well-constructed rules (98.55%) which was used as an indicator of the ease of use of the proof-of-concept demonstrator. In the same way, results showed that participants considered the Programming Board as easy to use (81.73%), supporting the hypothesis of enabling users to interact with the BReal Lab regardless their technical mixed-reality expertise.

In a more in-depth activity log analysis, results showed that, in general, instructions with a higher level of complexity were more used in comparison with less complex rules, suggesting that the difficulty of the task encouraged participants to interact more with the BReal Lab (Locke and Latham, 2006). Additionally, users working with a virtual object created more rules, regardless the complexity level, which could be due to users' background (demographic data showed that 50% of the participants were familiar with virtual worlds), and due to the fact that users working with a xReality object (46.15%) were less than users working with a virtual object only (53.85%). An interesting observation was that participants working with a xReality object created more medium-complexity instructions than those with virtual objects (xReality 15.50% versus Virtual 12.81%), and the use of virtual objects created more high-complexity instructions (xReality 19.21% versus Virtual 32.02%), showing a level where participants with a xReality object felt comfortable to work and suggesting that the higher level of complexity implied in the use of xReality objects compensates the use of medium-complexity level instructions.

Hypothesis 4 specified that in order to obtain a benefit from the model proposed, users should prefer the use of the mirrored virtual/physical object over the virtual-only object. Based on users' feedback, the analysis showed that participants considered using the xReality object (i.e. BuzzBox) as more amusing and interesting than using just a virtual object; giving them a feeling of accomplishment when the physical object got updated, and thus, helping them to feel more engaged in the activity; supporting hypothesis 4. However, even though a high number of participants (83.33%) thought it made a difference to use a xReality object during the activity; the physical component was regarded as not necessary for doing laboratory activities in distance education by half of the participants (50%), and 13% said it depended on the activity itself. When participants were asked about in which object during the activity they concentrated their attention the most, 75% of participants responded that in the physical component. Nevertheless, users' comments reported activity's time constraint (introduced for the management of the multiple trial sessions), and user interface design (because communication and interaction tools, located inside the 3D GUI, forced participants to focus on the screen to keep the collaboration and communication with their peers going) as the two issues that forced them to pay more attention to the virtual environment, and thus to the virtual box. This feedback suggests the need for additional multi-modal mechanisms for users to perceive and engage in interaction with users and objects within the blended-reality environment.

Finally, hypothesis 5 pointed the importance of providing enjoyable experiences for participants using the model. Even though the activity did not include elements of gamification, a high number of participants enjoyed working with other students during the activity (95.65%), and perceived the BReal Lab as interesting (98.08%) and amusing (90.38%), which was one of the reasons students stated on why they would use the BReal Lab in their courses. Additionally, 92% participants regarded the BReal Lab as an option that present advantages over traditional laboratories, and 80.77% answered they were likely to use it if it were available for them in their universities, regardless the level of personal innovativeness; reinforcing the positive response given by users to the BReal Lab and supporting hypothesis 5. Similarly, instructors' views on the activity and the proof-of-concept demonstrator were positive and confirmed participants' feedback, reporting that students who participated were enthusiastic and interested in understanding the functioning of the prototype.

An aspect that was not addressed in this evaluation is related to the educational gain of using the proposed blended-reality distributed framework. Although, the ultimately goal of any learning environment is to improve learning effectiveness, the present study focused on the creation of a mixed-reality environment able to work as a platform for collaboration and creation between distant participants based on mixes of virtual (simulated) and mirrored physical/virtual objects (emulated). A study presented by Adobor and Daneshfar (2006), showed that scenarios which were perceived by users as reflective of real life situations, and with a high degree of exchange of ideas, were positively associated with learning.

Additionally, the aforementioned study reported that the ease of use of the tools positively affected learning. Stiles (2000) describes the implementation of "authentic" learning activities, supported by tools and artefacts (Brown et al., 1989; Kearsley and Shneiderman, 1998), as a condition required for effective learning. Moreover, 3D virtual worlds can improve students' self-efficacy beliefs in relation to a number of activities undertaken as part of collaborative team-based projects (Scullion et al., 2013). Johnson-Glenberg et al. (2014) presented two studies comparing an immersive, highly interactive mixed-reality learning platform with a quality classroom experience, where teacher and content were held constant. Results revealed that the use of the mixed-reality learning platform consistently led to greater learning gains, compared to regular instruction. Although, those studies were based on the embodied learning paradigm, presented in section 3.3.2, authors reported that learning gains could be due to the interactivity and enjoyment levels in their implementation, which is an aspect that was evaluated in the present study. These results in the literature are relevant as they address some of the affordances of the proposed model, suggesting that these affordances could have an impact on learning effectiveness.

6.5 Summary

This section presented the experimental design used to evaluate the conceptual and architectural models towards the creation of a distributed model of interconnected learning environments presented in previous sections. In doing so, it explained the methodology used to validate the hypothesis introduced in chapter 1, adopting the Technology Acceptance Model (TAM) and adapting it to evaluate important aspects such as collaboration and blended-reality perception, which are fundamental characteristics of the model presented. Likewise, this section described experimental settings and research instruments used in tests with the proof-of-concept demonstrator (BReal Lab) between students from eight different universities in six countries, namely China, Malaysia, Mexico, UAE, USA and UK.

The chapter presented user studies that evaluated a collaborative activity using the BReal Lab between a heterogeneous sample of 52 higher-education students from different fields, ranging from computer science, electronic engineering and learning technology to linguistics and government. This provided valuable feedback on usability, perceived blended-reality and collaboration, topics that are fundamental for this research. In addition, the section described a technical evaluation of latency between distributed mixed-reality objects to measure synchronisation, a key aspect to achieve blended-reality. Moreover, it included an analysis on the demonstrator log, used to evaluate collaboration and interaction between participants. Finally, the chapter presented a discussion on findings resulted from these experiments, in which the social aspect of human collaboration was an additional variable which should be considered when designing mixed-reality collaborative activities.

The next chapter presents a summary and final thoughts on this research, describing challenges for future work.

Chapter 7

Concluding Remarks

"The paradox of reality is that no image is as compelling as the one which exists only in the mind's eye."

— Shana Alexander, (1925-2005)

The motivation for this research was the vision to create a platform that would be able to improve interaction between geographically dispersed team members who have a need to collaborate together in creating mixed-reality embedded-computing prototypes. Examples of such activities include virtual laboratories that support students in online universities, or R&D staff in large international companies. In seeking a solution to this challenge, this thesis presented an in-depth literature review concerning mixed-reality (chapter 2) and educational concepts (chapter 3). Informed by the literature findings, the thesis proposed a number of novel conceptual and architectural models (chapter 4), that offered solutions to the challenge of creating an online collaborative computer laboratory. This was implemented as proof-of- concept prototype system (chapter 5) which was evaluated and reported on chapter 6. This final chapter (chapter 7) presents the conclusions from this work and suggests a number of topics for further research.

7.1 Summary of Achievements

This research posed the hypotheses that "*it is possible to devise a computational model and architecture able to connect locations, that are physically separated, into one unified continuous space by linking elements situated in those locations, using a mix of physical and virtual objects* (hypothesis 1 - main), *and enabling remote users (with no technical mixed-reality expertise* (hypothesis 3 - secondary)) *to perform collaborative creative teamwork based on hands-on-activities* (hypothesis 2 - main); *preferring the use of mixed physical and virtual objects over simulated (virtual) objects* (hypothesis 4 - secondary); *and fostering engagement and participation* (hypothesis 5 - secondary)".

To validate these hypotheses, this thesis presented user studies and a technical evaluation of a functional prototype (the BReal Lab) in a case study conducted with students from eight different universities in six countries (3 continents), namely China, Malaysia, Mexico, UAE, USA and UK. The BReal Lab prototype was built as a proof-of-concept implementation of the distributed blended-reality framework proposed in chapter 4, which describes the use of mixes of mirrored physical and virtual objects as a means of creating a platform to allow geographically dispersed team members to work together in collaborative hands-on activities. In doing so, it presented a mixed-reality learning environment (the InterReality Portal) able to work with such mirrored virtual/physical objects (xReality objects); marrying them to a pedagogical model of hands-on laboratories, based on constructionist learning paradigms.

Results of the user study and technical evaluation (presented in chapter 6), suggested a high degree of participants' engagement and satisfaction, indicating a positive acceptance of the blended-reality extended synchronised space and supporting hypothesis 5. Participants reported preference towards the use of physical/virtual mirrored objects (xReality) over simulated (virtual) objects in hands-on activities, which suggest that the dual-reality principles underlying the proposed models were not regarded as difficult to understand, supporting hypothesis 4. Moreover, participants and instructors stated they would use similar technology in their courses, recognising the added value of having physical/virtual mirrored objects in support of hands-on learning activities. Performance evaluation between the different experimental implementations of the BReal Lab in a global distributed architecture, reported an estimated latency between 1.48 and 3.09 seconds to reflect changes between interconnected objects. Although these results accurately depicted the expected network latencies, from a user perspective the delays were barely perceptible with users reporting satisfactory levels of synchronisation between objects, with 61% of participants perceiving the physical components as synchronised; enabling remote users' perception of their local environments as blended into one large common environment, and supporting hypothesis 1. Regarding collaboration, participants reported issues about communication, mainly due to three factors: a) issues on the user interface design, b) the use of written communication (i.e. chat tools) instead of spoken communication, and c) their own personal level of acceptance towards group activities; reinforcing previous literature findings stating that "the quality of communication channels impacts the effectiveness of interaction among distributed groups" (Slater and Wilbur, 1997). However, while this added an extra challenge to collaboration and team work between participants, the results showed that it did not interfere with the completion of the assigned activities, supporting hypothesis 2. Furthermore, analysis of the activity log suggested an optimal collaboration limit of three participants per session, to create equitable participation between users, and reported that participants produced a high number of well-constructed rules (98.55%), regardless the object used (virtual or xReality) or the preliminary experience or knowledge on topics encompassed in the experiments (i.e. virtual worlds, programming, mixed-reality, etc.), supporting hypothesis 3. Results presented in this document align well with the thesis' motivation for enabling distance learners to participate in laboratory activities, supporting the proposed hypotheses. Moreover, the proposed model could be used beyond education, in similar scenarios where collaboration between dispersed teams is needed, such as in tele-work or product research and development areas.

The research presented in this thesis, was motivated by the creation of better collaborative platforms for remote participants, where they could interact using physical objects, in a similar way to traditional team work spaces. To do so, it proposed the use of a linked virtual space, where users could share physical objects to be used by remote peers. An aspect that arose from experiments, primarily designed to test technology communication, was human communication and its social dimension. Communication and collaboration in distance environments can be more difficult than face-to-face interaction, as it was observed from experiments' results. For example, participants had the need to convey its emotions and experiences when communicating with other users, and they found in the use of *emoticons* a way to overcome the limitations of the interface. Other participants were curious about the virtual world and motivated to explore it rather than focusing on the activity. In general, participants found the BReal Lab demonstrator as an amusing easy to use tool, which could be due to the fairly simple mechanisms adopted within the user interface (e.g. the use of keyboard to navigate within the virtual environment, control of the programming board using a mouse, etc.). However, participants also reported a number of contradictory issues regarding the available communication mechanisms. For some, less secure about their proficiency in English (a *de facto* communication standard), the anonymity of written communication tools allowed them to participate in their own time. But for those more confident in the language, a chat window limited their options and slowed down their interaction with other users. Team dynamics, in larger multicultural groups without an established leader (a role that is usually embodied in teachers and instructors), were reflected in users working as spectators only and with participants leading the decisions over the activity. Social aspects inherent to human behaviour are constantly present, regardless the technology used, thus, it is necessary to design user interfaces that respect these natural characteristics.

7.2 Contributions

As part of the contributions of this work, this thesis proposed in chapter 4 the MiReSL model, a conceptual architectural model for technology-enhanced learning environments that encompasses personalisation, content creation, assessment and a mixed-reality learning environment. This model was complemented with a proposed classification of mixed-reality learning activities (MiReSL-LA classification).

This thesis also proposed a distributed blended-reality framework (chapter 4), formed by the InterReality Portal and the xReality objects, which extended the concept of dual-reality as proposed by Lifton (2007). The framework addressed limitations of current shared physical-virtual object implementations, allowing modification or regrouping of mixed-reality objects into new shapes/services collaboratively between remote end-users, extending their capabilities for collaboration and creation by allowing users to interact with remote objects and share the ones they have in their local environment, and addressing the challenge of synchronization of distributed objects.

Additionally, to link the proposed model of distributed mixed-reality objects with a pedagogical model of hands-on laboratories, this thesis presented The Deconstructed Model (chapter 3), a conceptual model based on constructionist learning paradigms.

To implement the proposed framework, this research presented a prototype software and hardware architecture in chapter 5, the BReal Lab, which scaled up learning environments by bridging between geographically distributed spaces using a series of shared mixed reality objects, thereby enabling remote users' perception of local environments as blended into one large common environment.

Finally, this thesis presented an evaluation of the BReal Lab prototype (chapter 6) through user studies in a case study between students of eight different universities in six countries, namely China, Malaysia, Mexico, UAE, USA and UK, including an analysis of collaboration; and a technical evaluation of the prototype performance in terms of latency, proposing methods to estimate synchronisation latency using one or more mixed-reality objects in a distributed architecture, adding this case-study to mixed-reality literature where, as Dünser et al. (2008) stated, studies evaluating collaboration are hardly represented in mixed-reality research.

Additionally, a number of secondary contributions were included as follows:

1. The presentation of the combined "Milgram's Reality-Virtually continuum vs Garrison's continue of e-learning" visualisation to situate mixed-reality paradigms in an educational context. (Chapter 3)
2. A definition of Immersive Learning in the context of learning technology. (Chapter 3)
3. Conceptual models to represent single and multiple dual-reality states and how they can be generated in interactions between mirrored virtual/physical objects (xReality objects). (Chapter 4)
4. A definition of adjustable mixed-reality based on the use of mixed-reality objects. (Chapter 4)
5. The creation of an open-source API middleware to connect physical components (BuzzBoards) with 3D virtual representations based on the Inter-

Integrated Circuit bus (I^2C) and the use of persistent TPC connections. (Chapter 4)

6. Implementation of a basic collaborative end-user programming tool which extends from single-user to multiple end-user programming, and is suitable for use in distributed mixed-reality learning environments. (Chapter 5)

7.3 Future work

The work presented in this thesis uncovered a number of additional research challenges which provide a general outline for future research. These can be listed as:

- Collaboration within the proposed distributed mixed-reality framework was focused on hands-on activities in formal education settings, where activities are specifically designed to achieve specific goals that complement previous existing knowledge. However, the integration of the proposed framework in product development departments in companies and makerspaces (all of which have elements of informal learning) would pose a different challenge that could usefully be investigated. Informal learning shares collaborative work and problem-solving strategies with the approach presented in this work, however, they "connote a philosophy of doing things with no particular preference to empirical or theoretical methods" (Altman, 2010), involving the challenge of orchestrate environments with a wider perception of collaboration.
- The proof-of-concept implementation (BReal Lab) utilised a particular set of smart objects in the creation of xReality objects (i.e. BuzzBoards), for which bespoke 3D virtual representations were created for each of them. An area for future work may be the definition of an ontology to classify objects

and identify different physical devices and diverse experimental equipment, adding a mechanism to automatically linking them to sets of standardised pre-designed virtual objects. The benefit of an ontological classification is that it opens up the use of AI and reasoning engines to provide automated support to the user of such environments. For example, there is no reason that all the participants need to be human, one (perhaps the instructor) could be a type of intelligent tutor. Also, an ontology underpins the semantic web, this may lead to a closer integration between the two. As was noted earlier in this work, apart from technology, this environment is critically depended on human communication which, to a large extent, is non-verbal. The inclusion of multi-modal interfaces, and paradigms, such as better vision analysis and/or affective computing, could, for example, add participants' emotions and gestures, leading to better and more natural interactions, and allowing an automated interaction between virtual/physical mirrored objects and users in a unified distributed blended-reality space.

- Another challenge comes when establishing limits to control and ownership of a shared mixed-reality objects/environments. In a scenario where there is only one physical object, the ownership privileges can be assigned automatically to the one in its possession. This case becomes more complex when there are two or more shared objects, especially in the case of identical objects. Theoretically, privilege assignment should work in the same way as the previous case, but when shared within blended-reality, both objects "become" the same and should maintain the same state, involving safety and privacy issues.

- In educational scenarios, the use of the proposed mixed-reality platform represents a challenge for teachers and instructors. From acceptance and inclusion into their everyday practice, to assessment and other pedagogical issues. As Gardner and Elliott (2014) stated "*learning within technology* *creates a pedagogical shift that requires teachers to think about measuring outcomes in non-traditional ways*". Thus, it is necessary to evaluate students' learning gains and propose adequate mechanisms for assessment.

- Finally, it is important to consider socio-cultural implications of collaborative work in distributed mixed-reality environments. As Stiles (2000) explained "*learning is a social process and development is linked to the specific culture in which learning activities are shared*".

7.4 Final thoughts

Chan (2014) stated that "the idea of technological transcendence from the physical body via immersion in virtual reality is problematic because it is based on a misleading dichotomy of mind versus body". This phrase illustrates clearly the fundamental problem between real and computer-generated environments, as they are conceptually exclusive. However, the design and use of mixed-reality interfaces could lead to a highly-technological environment where physical and virtual are intimately blended, as it has been constantly pictured in films and science fiction stories. Of course, technology has its limitations, as defined by Sutherland (1968) "*the ultimate display would, of course, be a room within which the computer can control the existence of matter*". Unfortunately, (or perhaps fortunately!) such technology does not exist yet, and even if it would exist, the human mind still has the ability to alter the degree of immersion in an activity, no matter if it is reading a book, watching a film, or interacting with people in an artificial virtual environment such as a video games, changing its perception of the world.

Finally, I would like to think that the ideas presented in this document would contribute somehow to the original vision presented in chapter one that argues for better learning platforms for remote students.

"*What makes humans special first and foremost is that we can model the world, and we can predict the future. Then we can imagine the future.*" — Bill Moggridge (1943–2012)

Appendix A

Research instruments

A.1 Preliminary Survey

Constructs

- General demographics (GD)
- Familiarity with the use of computers (PRE)
- Preliminary experience with educational technology (ET)
- Preliminary experience with Science and Engineering laboratory activities (LAB)
- Preliminary experience with programming (PR)
- Personal innovativeness (PI)
- Preliminary experience with video games (VG)
- Preliminary experience with virtual worlds (VW)
- Preliminary knowledge on Mixed Reality (MR)
- Preliminary knowledge on Intelligent Environments (IE)

Table A.1: Preliminary survey

Code	Question	Response scale
GD-1	Name	[open ended]
GD-2	Email	[open ended]
GD-3	Gender	Male\Female
GD-4	Age	[open ended]

Continued on next page

Table A.1 – *Continued from previous page*

Code	**Question**	**Response scale**
GD-5	Nationality	[open ended]
GD-6	Level of English proficiency	Elementary proficiency \Limited working proficiency \Professional working proficiency \Full professional proficiency \Native or bilingual proficiency
GD-7	Level of studies	PhD \Master Degree \Postgraduate Certificate \Undergraduate Degree \Other
GD-8	Subject of Studies	[open ended]
PRE-1	How many hours a day you spend on a computer in your everyday life?	0 hours \Between 1-3 hours \Between 4-6 hours \Between 7-9 hours \Between 10-12 hours \More than 12 hours
PRE-2	Do you own a personal computer? (laptop, desktop)	Yes\No
PRE-3	[If PRE-2 answer = YES] Which are the main uses you give to your personal computer?	Leisure (e.g. Internet, movies, music, etc.) \Studies (e.g. research subjects, help with assignments, etc.)\Social interactions (e.g. social networks, chats, etc.)\Paid work \Other
PRE-4	Do you consider your computing expertise as	Very good \Good \Average \Below average \Poor
ET-1	Technology is sometimes used in education to achieve educational targets, do you use technology (software or hardware) in your classes or modules?	Yes \No
ET-2	Have you ever used educational software that helped you to clarify or practice the subject of your studies?	Yes \No
ET-3	[IF ET-1 OR ET-2 answer = YES] Please write the name(s) of the software you have used?	[open ended]
LAB-1	How much experience do you have in doing assignments in a Science and Engineering lab?	A lot \Some \Little \None at all
LAB-2	If you have any experience in a Science and Engineering lab, have you worked individually or in groups?	Most of the times I have worked in groups \I have worked equally, individually and in groups \Most of the times I have worked individually
PR-1	How experienced are you in programming?	A lot \Some \Little \None at all

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Table A.1 – *Continued from previous page*

Code	**Question**	**Response scale**
PR-2	If you have any experience in programming, have you worked individually or in groups?	Most of the times I have worked in groups \I have worked equally, individually and in groups \Most of the times I have worked individually
PI-1	I like using new technologies?	Strongly agree \Agree \Disagree \Strongly Disagree
PI-2	I can use and understand new technologies quite easily	Strongly agree \Agree \Disagree \Strongly Disagree
PI-3	How often do you feel that new technologies may be difficult to use?	Always \Very often \Sometimes \Never
VG-1	How often do you play video games per week?	Not at all \once or twice per week \4-5 times per week \every day
VG-2	If you play video games, please name the ones you use	[open ended]
VW-1	Are you familiar with virtual worlds?	Yes \No
VW-2	[IF VW-1 answer = YES] How often do you use virtual worlds?	Not at all \once or twice per week \4-5 times per week \every day
VW-3	Please select the virtual worlds that you have used or heard of	Second Life \RealXtend \Meshmoon \Open Wonderland \OpenSim \IMVU \Habbo \Club Penguin \Other Option
MR-1	Are you familiar with augmented reality / mixed reality applications?	Yes\No
MR-2	Please select the applications that you have used or heard of	Google glass \AnkiDrive \Tiggly \Microsoft Hololens \Sphero/Ollie \Wikitude \Junaio \Aurasma \Disney Infinity \Other Option
IE-1	Are you familiar with smart houses/intelligent spaces?	Yes \No
IE-2	Have you used or heard of technology to make your house ”smart”?	Yes \No

A.2 Post Survey

Constructs

- General demographics (GD)

- Perceived ease of use (PEOU)
- Enjoyment (PE)
- Perceived usefulness (PU)
- Intention to use (ITU)
- Perceived blended reality (PBR)
- Perceived collaboration (COL)
- Perceived end-user programming ease of use (EUP)

Table A.2: Post survey

Code	**Question**	**Response scale**
GD-1	Name	[open ended]
GD-2	Email	[open ended]
PEOU-1	It was difficult to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PEOU-2	It was easy to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PE-1	It was fun to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PE-2	It was annoying to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PE-3	It was interesting to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PE-4	It was boring to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PEOU-3	It was demanding to use the equipment (software / hardware)	Strongly agree \Agree \Disagree \Strongly disagree
PEOU-4	It was difficult to understand the principles of operation of the system	Strongly agree \Agree \Disagree \Strongly disagree
PEOU-5	It took a lot of effort to learn how to use the system	Strongly agree \Agree \Disagree \Strongly disagree

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Table A.2 – *Continued from previous page*

Code	**Question**	**Response scale**
PEOU-6	How easy or difficult you found communication through chat	Very easy \Easy \Difficult \Very difficult
PEOU-7	How easy or difficult you found to complete the activity assigned	Very easy \Easy \Difficult \Very difficult
PEOU-8	How easy or difficult you found to move yourself inside the virtual environment	Very easy \Easy \Difficult \Very difficult
PEOU-9	How easy or difficult you found to interact with the Programming Board (the wall inside the virtual environment used to create behavioural rules)	Very easy \Easy \Difficult \Very difficult
ITU-1	The system you tested was created as a pilot programme for educational purposes. Please list the reasons why you would use it	[Open ended]
ITU-2	What are the reasons not to use the system you tested today?	[Open ended]
ITU-3	How likely is that you would use a system like this if it was available in your University?	Very likely \Likely \Unlikely \Very unlikely
PBR-1	Which equipment you used in this session?	The virtual box + the physical box \Just the virtual box
PBR-2	[IF PBR-1 answer = physical box] Did you feel that the physical box was synchronised with the box on the screen?	Always \Most of the time \Sometimes \Never
PBR-3	[IF PBR-1 answer = physical box] Do you think it make a difference to have the physical box? Please explain why.	[Open ended]
PBR-4	[IF PBR-1 answer = physical box] Which output were you more focused on: the physical box or the box on the screen?	The physical box \The box on the screen
PBR-5	[IF PBR-1 answer = physical box] Is there any extra feedback you would like to add about the question above? (optional)	[Open ended]
PU-1	In this exercise you used a physical device connected to a virtual device. Do you think it was necessary in your exercises to have the physical object? Please explain why	[Open ended]

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Table A.2 – *Continued from previous page*

Code	**Question**	**Response scale**
PU-2	Have you ever participated in a traditional Science and Engineering laboratory?	Yes \No
PU-3	[IF LAB-1 answer = YES] Which of these statements is closer to your opinion?	I think a Mixed-Reality lab has significant advantages over a traditional Science and Engineering laboratory \I think that a Mixed-Reality lab has a very poor capability for doing Science and Engineering lab work \I think a Mixed-Reality lab is marginally worst than traditional labs for Science and Engineering \I don't see that a Mixed-Reality lab makes any difference \I think a Mixed-Reality lab brings some advantages over a traditional Science and Engineering laboratory
COL-1	Did you worked on the assigned exercise with other student?	Yes \No
COL-2	[IF COL-1 answer = YES] I enjoyed collaborating with other student(s) inside the virtual world	Strongly agree \Agree \Disagree \Strongly disagree
COL-3	[IF COL-1 answer = YES] It was comfortable to communicate with the other student(s) through the virtual interface (i.e. using the chat window only)	Strongly agree \Agree \Disagree \Strongly disagree
COL-4	[IF COL-1 answer = YES] Explain the reasons why it was comfortable (or not) to work with other student(s) through the virtual interface	[Open ended]

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Table A.2 – *Continued from previous page*

Code	**Question**	**Response scale**
PU-4	How useful is the capacity of the system to allow participants in different locations to work together	Very useful \Somewhat useful \Not very useful \Not useful at all
COL-5	[IF COL-1 answer = YES] I found difficult to communicate with the other student(s)	Strongly agree \Agree \Disagree \Strongly disagree
COL-6	[IF COL-1 answer = YES] How would you rate your experience of collaborating with students in other locations?	Very good \Good \Fair \Poor \Very Poor
COL-7	[IF COL-1 answer = YES] Please provide any extra comment you have on your experience working with other students in the experiment	[Open ended]
PU-5	In this case, we developed the system as a means of doing a programming exercise between students in different locations. Can you think in other application that you consider would be useful in your studies?	[Open ended]
EUP-1	Using the Programming Board (wall) was EASY	Strongly agree \Agree \Disagree \Strongly disagree
EUP-2	Using the Programming Board (wall) was USEFUL	Strongly agree \Agree \Disagree \Strongly disagree
EUP-3	Using the Programming Board (wall) was FUN	Strongly agree \Agree \Disagree \Strongly disagree
EUP-4	Using the Programming Board (wall) was INTERESTING	Strongly agree \Agree \Disagree \Strongly disagree
EUP-5	Using the Programming Board (wall) was DIFFICULT	Strongly agree \Agree \Disagree \Strongly disagree
EUP-6	Using the Programming Board (wall) was ANNOYING	Strongly agree \Agree \Disagree \Strongly disagree
EUP-7	Using the Programming Board (wall) was BORING	Strongly agree \Agree \Disagree \Strongly disagree
EUP-8	Do you see any other application for this programming tool?	[Open ended]

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Table A.2 – *Continued from previous page*

Code	**Question**	**Response scale**
XX	Do you have any additional comments of the overall experience?	[Open ended]

A.3 Instructor's survey

Table A.3: Instructor's survey

Code	**Question**	**Response scale**
INS-1	Could you give us your views on the overall session?	[Open ended]
INS-2	Considering the way the system stands at the moment (without any extra enhancement), What aspects of the system you think that could help teachers to deliver laboratory activities/sessions to remote students?	[Open ended]
INS-3	If we were able to make any changes, what would be your suggestions for improving the technology we used in this trials?	[Open ended]

A.4 Information Sheet

University of Essex

Dear participant,

Nowadays, the use of the Internet has been extended to diverse areas such as entertainment, medicine or education. Particularly in education, the combination of Internet, computers and electronic media resources (known as online learning or eLearning) is widely extended and occurs in and out of the classroom. This has allowed more flexibility to provide education, mostly to students that, for many reasons, cannot be physically present in a classroom.

However, in the case of laboratory activities, where students learn from the experience of setting equipment, and solve problems by trial and error; the options are limited for distance learners. Usually they watch videos or simulate experiments using software tools that allow a restricted amount of creativity and freedom. Collaboration is often not considered in the use of these tools, whereas collaboration is a key element in laboratory assignments in schools and universities.

With this study, we want to investigate the use of Mixed Reality technology in collaborative activities for distance learners, to allow them to interact with physical objects in addition to the virtually simulated equipment. Mixed Reality refers to the merging of real and virtual worlds to produce new environments where physical and digital objects co-exist and interact in real time. In this study we will ask you to answer a preliminary survey to assess your familiarity with this type of technology (approx. duration 15 min). Afterwards, you will be asked to perform a specific task using our virtual platform only or in conjunction with an electronic networked device. This task could be individual or in cooperation with other student in a different location (approx. duration 30 min). Finally, we will give you a final survey to get your views about the experience (approx. duration 15 min).

While we intend to publish anonymised version of the data gathered we will not publish personal information that links you to the data. You can ask any question at any time (before, during or after the experience). You can withdraw from this study at any stage for any reason.

For more information, please contact Anasol Pena-Rios (acpena@essex.ac.uk).

A.5 Consent form

To be completed after reading the Information Sheet. Please read this page carefully.

Thank you for participate in this research trial, which intends to evaluate the uses of Mixed Reality in collaborative activities between geographically dispersed users. Throughout the session, you will be observed and an audio visual recording of your session will be made. The data collected throughout the trial will be kept confidential and the recordings will only be used by the researcher, for analysis purposes only. Further, it will not be possible to attribute information used in any test reports, whether verbal or written, to particular participants.

Participation is voluntary and you may withdraw from this evaluation at any time. If you do leave before the end of the session, and do not want any data collected from you to be kept, then these will be destroyed.

Please tick the appropriate boxes	Yes	No
I have been given the opportunity to ask questions about the project.	☐	☐
I agree to take part in the project.,Taking part in the project will include being interviewed and recorded (video).	☐	☐
I understand that my taking part is voluntary; I can withdraw from the study at any time and I do not have to give any reasons for why I no longer want to take part.	☐	☐
I understand that anonymised data drawn from my participation may be published, but any personal information linking me to the data will be treated in strict confidence and will be kept confidential to the researchers.	☐	☐
I understand that my words (anonymised) may be quoted in publications, reports, web pages, and other research outputs.	☐	☐
I have read and understood the information sheet and this consent form.	☐	☐
I agree to participate in this study.	☐	☐

Name of participant [printed]	Signature	Date
Anasol C. Pena Rios Researcher [printed]	Signature	Date

If you need further information please contact: Anasol Pena-Rios acpena@essex.ac.uk

Appendix B

Log analysis

B.1 Text analysis criteria

Table B.1: Text analysis criteria

String value in chat log	**Classification**
^-^	EMOTICON
^_^	EMOTICON
_D	EMOTICON
JAJA	EMOTICON
HAHA	EMOTICON
JEJE	EMOTICON
HEHE	EMOTICON
_P	EMOTICON
HI_	GREETINGS
HI_	GREETINGS
HI	GREETINGS
HELLO	GREETINGS
HOLA	GREETINGS
HEY	GREETINGS
HOW_ARE_YOU	GREETINGS
GOOD_MORNING	GREETINGS
FINE_	GREETINGS
GRACIAS	GREETINGS
SEE_YOU	GREETINGS
SEE_YOU	GREETINGS
THANKS	GREETINGS
THANK_YOU	GREETINGS
BYE	GREETINGS
NICE_TO_MEET	GREETINGS
YES	AGREEMENT / COMFIRMATION
YEAH	AGREEMENT / COMFIRMATION

Continued on next page

Table B.1 – *Continued from previous page*

String value in chat log	**Classification**
YEA_	AGREEMENT / COMFIRMATION
YEP	AGREEMENT / COMFIRMATION
YA	AGREEMENT / COMFIRMATION
OK	AGREEMENT / COMFIRMATION
I_AGREE	AGREEMENT / COMFIRMATION
TOTALLY_AGREE	AGREEMENT / COMFIRMATION
I_SEE	AGREEMENT / COMFIRMATION
AGREE	AGREEMENT / COMFIRMATION
GREAT	AGREEMENT / COMFIRMATION
SURE	AGREEMENT / COMFIRMATION
BRILLIANT	AGREEMENT / COMFIRMATION
ALRIGHT	AGREEMENT / COMFIRMATION
GOT_IT	AGREEMENT / COMFIRMATION
MAKES_SENSE	AGREEMENT / COMFIRMATION
I_CAN_	AGREEMENT / COMFIRMATION
SI_	AGREEMENT / COMFIRMATION
SI	AGREEMENT / COMFIRMATION
ARE_THE	INQUIRY
ARE_YOU	INQUIRY
WHAT	INQUIRY
DO_YOU	INQUIRY
DOES_	INQUIRY
YOU_AGREE	INQUIRY
WHICH	INQUIRY
SHALL	INQUIRY
WHY	INQUIRY
CAN_YOU	INQUIRY
CAN_WE	INQUIRY
CAN_SOMEONE	INQUIRY
COULD_YOU	INQUIRY
ANY	INQUIRY
HOW	INQUIRY
WHERE	INQUIRY
WHO	INQUIRY
DID_YOU	INQUIRY
WOULD_YOU	INQUIRY
HOW	INQUIRY
SHOULD_	INQUIRY
TRY_TO	INQUIRY
YOU_SEE	INQUIRY
IS_IT_	INQUIRY
IS_THAT	INQUIRY
IS_THE	INQUIRY
IS_THIS	INQUIRY
IS_T	INQUIRY

Continued on next page

Table B.1 – *Continued from previous page*

String value in chat log	**Classification**
CAN_I_	INQUIRY
CAN_	INQUIRY
TE_PARECE	INQUIRY
QUE	INQUIRY
QUIERES	INQUIRY
LET	TRANSITIVE / IMPERATIVE
GO_ON	TRANSITIVE / IMPERATIVE
GO_AHEAD	TRANSITIVE / IMPERATIVE
GO_FOR	TRANSITIVE / IMPERATIVE
TELL_ME	TRANSITIVE / IMPERATIVE
DO_IT	TRANSITIVE / IMPERATIVE
KEEP_GOING	TRANSITIVE / IMPERATIVE
MOVE	TRANSITIVE / IMPERATIVE
WAIT	TRANSITIVE / IMPERATIVE
YOU_CAN	TRANSITIVE / IMPERATIVE
HABER_	TRANSITIVE / IMPERATIVE
PODEMOS_	TRANSITIVE / IMPERATIVE
SO_YOU_CAN_	TRANSITIVE / IMPERATIVE
PLEASE	TRANSITIVE / IMPERATIVE
I_THINK	PERSONAL OPINION / BELIEVE
I_LIKE_	PERSONAL OPINION / BELIEVE
THINK_SO	PERSONAL OPINION / BELIEVE
I_SUGGEST	PERSONAL OPINION / BELIEVE
I_GUESS	PERSONAL OPINION / BELIEVE
I_ASSUME	PERSONAL OPINION / BELIEVE
I_MEAN	PERSONAL OPINION / BELIEVE
REALISED	PERSONAL OPINION / BELIEVE
MAYBE	PERSONAL OPINION / BELIEVE
I_BELIEVE	PERSONAL OPINION / BELIEVE
CREO	PERSONAL OPINION / BELIEVE
IF_	BUILDING RULE EXPLICTLY
ELSE	BUILDING RULE EXPLICTLY
IS_AMAZING	EXPRESSING POSITIVE FEEDBACK
IS_BRILLIANT	EXPRESSING POSITIVE FEEDBACK
_COOL	EXPRESSING POSITIVE FEEDBACK
IS_GREAT	EXPRESSING POSITIVE FEEDBACK
S_FUN	EXPRESSING POSITIVE FEEDBACK
S_GOOD	EXPRESSING POSITIVE FEEDBACK
AMAZED	EXPRESSING POSITIVE FEEDBACK
IT_WORKS_	FEEDBACK ABOUT EXECUTION
IS_WORKING	FEEDBACK ABOUT EXECUTION
HERE_	FEEDBACK ABOUT EXECUTION
WORK	FEEDBACK ABOUT EXECUTION
S_WORKING	FEEDBACK ABOUT EXECUTION
CONDITION_FALSE	FEEDBACK ABOUT EXECUTION

Continued on next page

Table B.1 – *Continued from previous page*

String value in chat log	**Classification**
SE_PREND	FEEDBACK ABOUT EXECUTION

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