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TAXONOMY OF LEARNING IN VIRTUAL REALITY

Doctoral Thesis

Submitted for the Ph.D. degree in Education Sciences
Subfield of General Education

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Abstract

The doctoral thesis by Lana Frančeska Dreimane titled "Taxonomy of Learning in Virtual Reality" was developed in the field of Education at the Faculty of Education, Psychology and Arts of the University of Latvia, under supervision of Dr. paed., professor Linda Daniela. The volume of the thesis is 147 pages, 30 figures and 16 tables in the main text, as well as list of bibliographic sources with 114 titles and 2 appendices.

There is a significant body of research available on both the technical solutions and the limitations of VR technology; however, in 2020 it has become very challenging for educators and instructional designers to find and to navigate the guidelines on how VR learning experiences should be designed in order to ensure that the set learning objectives would be achieved. Thus, a major problem of VR learning research seems to be the lack of understanding of the general principles that govern and facilitate learning in VR and how they are interconnected with the existing knowledge about learning, instructional design and virtual environments.

This research aims to inform educators and instructors, as well as VR technology developers and potential learners, about the alignment synergies and interconnections of VR learning principles by generating a substantive theory for the taxonomy of learning in Virtual Reality. The most important contribution of this inquiry is in systemising already existing but fragmented knowledge, and presenting evidence for theoretical basis for the taxonomy, as well as developing VR learning experience design and evaluation tools for practical applications.

Chapter I presents a Literature Review on a series of pedagogic and instructional design theories, as well as the application of VR for educational goals. Chapter II describes and unfolds the chosen methodology for this study and presents the devised Virtual Reality learning experience evaluation tool and the approbation analysis. Chapter III discusses the process underpinning the generation of theory for the proposed taxonomy. Chapter IV presents the findings of the research undertaken and outlines recommendations for its application as well as further research directions.

Kopsavilkums

Lanas Frančeskas Dreimanes promocijas darbs ar nosaukumu "Mācīšanās taksonomija virtuālajā realitātē" tika izstrādāts izglītības zinātņu nozarē, vispārīgās pedagoģijas apakšnozarē Latvijas Universitātes Izglītības, psiholoģijas un mākslas fakultātē, profesores, *Dr. paed.* Lindas Danielas vadībā. Darba apjoms ir 147 lpp., ieskaitot 30 attēlus un 16 tabulas, kā arī literatūras un avotu sarakstu ar 114 nosaukumiem. Darbam papildus pievienoti arī 2 pielikumi uz 21 lpp.

Zinātnisko publikāciju datubāzēs ir pieejams plašs pētījumu klāsts par virtuālās realitātes (VR) tehnoloģiju risinājumiem un ierobežojumiem, tomēr 2020. gadā pedagogiem un mācīšanās satura izstrādātājiem (mācīšanās dizaineriem) ir nepieciešamas skaidras vadlīnijas par to, kā būtu jāveido VR mācīšanās pieredze, lai nodrošinātu izvirzīto mācību mērķu sasniegšanu. Viens no nozīmīgākajiem VR mācīšanās pētījumu problēmjautājumiem ir saistīts ar izpratnes trūkumu par vispārīgiem principiem, kas nodrošina un veicina mācīšanos virtuālajā realitātē, tostarp, kā šie principi ir savstarpēji saistīti ar esošajām zināšanām par mācīšanos, tās dizainu un virtuālo vidi.

Pētījuma mērķis ir informēt pedagogus un mācīšanās dizainerus, kā arī VR tehnoloģiju izstrādātājus, un potenciālos izglītojamos par VR mācīšanās principiem, tostarp, to sinerģijām un mijsakarībām, piedāvājot pamatotu teoriju virtuālās realitātes mācīšanās taksonomijai. Šī pētījuma nozīmīgākais devums ietver esošo, bet sadrumstaloto zināšanu apkopošanu un sistematizēšanu, pierādījumos balstītas teorētiskās bāzes izstrādi virtuālās realitātes mācīšanās taksonomijai, kā arī praktisku VR mācīšanās pieredžu dizaina un izvērtēšanas rīku izstrādi.

Promocijas darba 1. nodaļa sniedz literatūras pārskatu par virkni pedagoģisko un mācīšanās dizaina teoriju, kā arī VR pielietojumu mācīšanās mērķiem. Darba 2. nodaļā ir aprakstīta izvēlētā pētījuma metodoloģija un tās posmi, kā arī aprakstīts izstrādātais virtuālās realitātes mācīšanās pieredžu izvērtēšanas rīks un izvērtēto 32 pieredžu analīzes rezultātā iegūto datu kvantitatīvā un kvalitatīvā analīze. 3. nodaļā ir izklāstīts taksonomijas teorētiskās bāzes izstrādes process, kā arī taksonomijas ietvara uzbūve. Pētījuma 4. nodaļā ir aprakstīti secinājumi un ieteikumi taksonomijas un mācīšanās pieredžu izvērtēšanas rīks pielietošanai praksē, kā arī definēti turpmākie pētījumu virzieni.

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Glossary

1. *3-dimensional virtual environment (3-D VE)* – "an environment that capitalises upon natural aspects of human perception by extending visual information in three spatial dimensions" (Dalgarno and Lee, 2010).

2. *3-dimensional virtual learning environment (3D VLE)* – a virtual environment which harnesses the educational potential of VR technology and is primarily distinguished by a combination of two unique VR space characteristics: 1) representational fidelity (dimensional authentic imagery, authentic object behaviour (as in a physical environment) including smooth temporal changes), 2) learner interaction (high interactivity and engagement possibilities including verbal and non-verbal, human and non-human avatars).

3. *3-dimensional learning experience* – a learning experience which leverages the affordances of a 3-dimensional learning environment in order to achieve the set learning objectives.

4. *Affordance* – "relates attributes of something in the environment to an interactive activity by an agent who has some ability" (Greeno, 1994, p.338). Alternatively it is a "relationship between the properties of an educational intervention (learning experience) and the characteristics of the learner that enable certain kinds of learning to occur." (Kirschner, 2002).

5. *Avatar* – a 3-dimensional virtual representation and extension of one's self. Alternatively it is "an online identity, a visual representation of his / her real or surrogate identity and appearance" (Dalgarno, Lee, 2010).

6. Desktop VR – a 3-dimensional visual environment displayed on a two-dimensional display – a personal computer desktop or simulator computers.

7. *Haptic VR technology* – tactile feedback technology which enables bilateral signal communication between computer and the user, and thus greatly enhances the immersion and interaction of VR systems (Dang-xiao, et. al., 2019). Alternatively it describes "devices that enable manual interaction with virtual environments (…) such as manual exploration and manipulation of objects" (National Research Council, Computer Science and Telecommunications Board, Committee on Virtual Reality Research and Development 1995, p.161). This includes haptic gloves, vests and haptic suits with hyper-fine feedback haptics including such technologies as HaptX and Teslasuit.

8. *Head mounted display (HMD)* – alternatively referred to as Virtual Reality headsets, VR headset, or VR glasses (googles) is a device worn on a user's head which transmits 3-dimensional images and audio, tracks user's position within virtual space and potentially tracks a user's eye movement.

9. *Immersive Virtual Worlds* – sometimes also referred to as Virtual Social Worlds, these are virtual platforms that enable social VR experiences. Immersive Virtual Worlds' users, sometimes referred to as residents, often actively engage in development of the environment, including investing time and resources in complex avatar creation, and build strong communities' around their common interests.

10. *Immersive VR* – Virtual reality technology involving head mounted displays (VR headsets) and VR controllers, alternatively 3D hand input for V (e.g. Leap Motion) or multi-wall CAVE automatic virtual environment projectors and google with built-in trackers.

11. *Massively multiplayer online games (MMOGs)* – sometimes also referred to as massively multiplayer online role play games (MMORPGs), and these are online games, which involve large number of players (transcending geographical borders). MMOGs allow

players to collaborate and compete in large groups, often forming strong communities or clans which interact verbally and non-verbally, to devise and execute strategies and achieve set objectives.

12. *Virtual immersive environment (VIE)* – a virtual technology environment which combines the affordances of both technologies - massively multiplayer online games (MMOGs) and Immersive Virtual Worlds which allow the creation of 3DLEs.

13. *Multi-wall CAVE automatic virtual environment system* – an immersive virtual reality environment which is achieved using projectors which are projected on three or six of the walls creating a room-sized cube of VR screens which are interconnected into one immersive environment.

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INTRODUCTION

This dissertation analyses and systemises the pedagogical principles and technological affordances that govern and facilitate learning in Virtual Reality (VR) and proposes a taxonomy of learning in the Virtual Reality environment. The research gathers previously fragmented knowledge and practical evidence and presents analytical evidence in order to establish a taxonomy mapping out the core principles which govern learning in VR. This study has applied, and built upon, existing research in the fields of educational psychology and instructional design, including established taxonomies and classifications of learning outcomes (Bloom, 1956; Biggs and Collis, 1982; Gagne, 1985; Anderson and Krathwohl, 2001; Churches, 2007) as well as Virtual Reality interfaces, learning environments, content and interaction modes (Winn,1993; Pantelidis, 2009, 1995; Salzman, 1999; Mclellan, 1996, 2003; Chee, 2001; Dalgarno, Hedberg, and Harper, 2002; Zacharia, 2003; Markaridian Selverian, 2004; Chen, 2006; Dalgarno, Lee, 2010, Kapp, O'Driscoll, 2010, Muhanna, 2014).

Background to the study

For centuries education has been entrusted with the responsibility of enabling individuals to access knowledge and practical learning experiences in order to become active and competitive members of society and through that to ensure the further sustainability of those societies. Questions such as how to better acquire, transfer, collect and structure knowledge, skills and competences were part of society much earlier than the first academic attempts to understand their conceptualisation or definition. Through the process of creating multi-layered synergies and continuous disruption of the status quo, increasingly fast-developing technology has had the power to transform learning and education in previously unimaginable ways but, even with an abundance of options, meeting the needs of learners has become something of a competition to provide meaningful and effective learning modes and designs. Currently, learning is thought of as an engaging process which provides learning experiences and allows learners to develop skills and competences of different cognitive, emotional and psycho-motor complexity. Indeed, analysing and understanding the diverse needs of learners as well as designing the most effective stimuli for desired learning outcomes – be that topical or contextual knowledge - have become ever so pivotal for educators, instructional designers, researchers and learning technology engineers. Thus, in order to design Virtual Reality (VR) learning experiences as well as to effectively learn, using VR technology, it is important to fully understand the educational rationale behind learning in VR and the affordances of VR space as a learning vehicle.

Since 1956, Bloom's Taxonomy of Educational Objectives: The Classification of Educational Goals (Bloom et al., 1956) has been the standard for the systematisation and classification of educational objectives. Later, a former student of Bloom's – Anderson together with Krathwohl - published a revised version of Bloom's Taxonomy in 2001, proposing the use of verbs over nouns to define the learning outcomes as competences or acquired skills and abilities. It must be noted that Anderson and Krathwohl considered creativity over evaluation within the cognitive domain (Anderson et al., 2001). Various taxonomies had been developed by Instructional Design practitioners and researchers, such as Gagne's Taxonomy which defined five levels of learning: verbal information, intellectual skills, cognitive strategies, motor skills and attitudes, and nine events of instruction which corresponded to learning processes (Gagne, 1985). Gagne's Taxonomy classified the learning process in terms of the degree of complexity of the mental processes involved. In 2007, Churches further developed the taxonomy proposed by Bloom, and Anderson and Krathwohl and published a Digital Taxonomy, which complemented existing taxonomies of learning outcomes with six levels of digital skills (Churches, 2007).

Since the mid-1950s, and all through the 1960s, there has been an ongoing, yet pivotal, shift in education psychology from teaching and towards learning. Learning has always been, and should continue to be, a way for society or an individual to adapt to socio-economic changes as well as to foster them, thus creating a cyclical and ever-evolving process. An increased interest in learning has also further steered academic discourse towards the potential of learning environments – both physical and social. Since the 1980s Technology Enhanced Learning (TEL), often used synonymously with Technology Enabled Learning (TEL) or Technology Enhanced Education (TEE), have all gained increasing focus in the field of educational research. TEL gained its popularity in adult training as well as school classrooms, thus constantly pushing researchers and practitioners to look for more effective ways to apply existing learning models as well as to understand where TEL should be positioned.

The use of a desktop computer was further revolutionised by the rapid development of user-friendly technological advances, thus further extending learning possibilities to online platforms, smartphones and tablets. These developments served as further stimuli for the advancement of digital learning content and its application and interaction in order to achieve learning objectives. There has been much discussion around the question of whether e-learning can, and should, completely replace traditional learning models. Thus, currently the concept of blended learning is at the forefront of this discussion.

“Blended learning designates the range of possibilities presented by combining Internet and digital media with established classroom forms that require the physical co-presence of teacher and students” (Friesen, 2012, p.1.).

These technologies have transformed learning and have changed its position from being a support tool (mainly for visual, audio and video materials), to asserting itself in the central role as a method of content delivery. In addition, this evolution has affected content creation itself, as there has been an increasing need for interactive content which would aid memory and attention retention (especially in younger learners), learner-friendly layouts and structures as well as formats (e.g. video lectures).

Since the early 2000s, one of the most notable shifts in education has been the increasing use of the ‘flipped classroom’ approach. This method of blended learning focuses on delivering content outside the classroom, often characterised as self-paced online lectures, thus allowing the classroom environment to become the primary platform for collaborative learning and further elucidation. This need to interact in tandem with the constant battle against the dehumanisation of the learning process has, in turn, directed the attention of instructional designers to the immense possibilities of computer-generated simulations, which have been used for complex learning skills in aviation, the army, the navy and engineering since the 1960s. These computer-generated simulations were an attempt to realise a presumption that a learner should have a stronger response (including memory and attention retention) to an experience, rather than to an abstract theoretical discussion of concepts, because, with simulation, (more precisely emulations) it is possible to fool the brain into believing it actually has had the real experience of performing a task or having had a certain remote or new experience. Thus, the name of the latest technology, which is the focus of this study, comes directly from the combination of two main attributing terms – ‘virtual’ and ‘reality’. Virtual Reality has fascinated people since the 1950s (e.g. Heling and Sutherland) and since then it has increased its presence in our lives, not only through entertainment, but also in the way it has affected and transformed medical procedures and services, first-responding and the military, engineering, architecture, businesses, sports, arts, and technologies. The Virtual Reality Society suggest that, “the definition of virtual reality comes, naturally, from the definitions for both ‘virtual’ and ‘reality’. The definition of ‘virtual’ is near and reality is what we experience as human beings. Respectively, the term ‘virtual reality’ basically means ‘near-reality’. This could, of course, mean anything but it usually refers to a specific type of reality emulation” (Virtual Reality Society, http://bit.ly/vrs_vr_definition).

There has been much excitement about the potential of VR technologies, and it must be noted that various ‘tech-gurus’ grew impatient during the continuous evolution of VR technologies and persistent attempts to make it accessible to the masses. One of the leading industries to be dramatically transformed by VR has been education (Kapp, 2017 and CB Insights, 2018 http://bit.ly/cbs_industries_to_transform) and, especially over the past decade, it is evident that VR indeed has transformed education in both main methods: traditional classroom education and

Technology Enhanced Learning. Nevertheless, recent educational research does agree that there is still immense potential for further applications of VR for learning and the solutions it can offer (see Salzman, 1999; Kapp, O'Driscoll, 2010).

VR is already showing its benefit in the flipped classroom model; for example, Google Expeditions is a software that enables students to virtually travel to exotic locations, adding context to history and geography lessons. Companies such as Immersive VR Education are using dynamic storytelling to better help students to engage with their subject material. Indeed, VR has captured people's imagination, and designers, developers, and enthusiasts have devoted many hours to design, code and explore the possibilities of this exciting emergence of a long dream about the medium. There are now various, affordable and fast hardware systems such as Google Cardboard, Google Daydream View, the Oculus Go, Oculus Rift, Oculus Quest, Oculus Vive, Samsung Gear VR and HTC Vive which enable consumers to experience high-quality VR at first hand.

Context of the problem

Virtual Reality has been used for learning since the 1970s for flight simulation and military training. Biocca noted that, "The Super Cockpit program (sic) at Armstrong Aerospace Research Laboratory at Wright-Patterson Air Force Base was a significant site for government-sponsored VR research. (…) Other military funded projects helped develop key components of VR technology: advanced simulation (Evans and Sutherland), distributed simulation (SIMNET), and tele-robotics (UtahArm, Sarcos)" (1994, p. 226). VR has been used to create learning experiences in various fields which require complex conceptualisation, drill-training (repetition and automation) and complex contextual problem-solving (individuals and teams). The emerging availability of low-cost, high fidelity VR environments has opened new possibilities for direct learning that are both cost effective and scalable. "Up until now teaching complex topics like medicine and engineering have been too costly or unfeasible at scale to teach directly, making us settle for an indirect approach through classroom lectures and books" (Elvestadt, 2016, p. 11).

Over the past decade VR has transformed the human-computer interface and it has humanised it. Immersive experiences – either reality or fantasy based - allow us to interact with content and other people in a way that previously could only have been possible in science fiction.

As Burns concluded in his foreword for *Learning in 3-D: Adding a New Dimension to Enterprise Learning and Collaboration* (Burns in Kapp, O'Driscoll, 2010): "Now learning in context will become the most empowering component for learning and collaboration for humans and the human computer interface will be more naturalistic." (p. xi). Currently, with the emergence of virtual learning environments the opportunity exists to cross beyond content, hierarchies and set-environments – classroom or desktop - and to focus on the context of learning. Against the general belief that VR has changed, or will completely change, the way we interact, entertain and learn, the researcher argues that VR offers the possibility of creating a more natural extension to existing modes of interaction, entertainment and learning content. This conviction also relates to the application and effectiveness of the existing approved instructional models in the VR environment. This view is also shared by the Vice President of Technology and Innovation Michael Mathews (2017) of the Oral Roberts University (Tulsa, Oklahoma) (one of the pioneering universities in the world to use VR in their programmes). The main benefit of introducing VR into a learning process is that there is no need to change the learning objectives and strategies; VR rather helps in achieving these objectives and amplifies (deepens) the 'residue' and speeds the learning process.

Significance of the Study

There is a significant body of research available on both the technical solutions and the limitations of VR technology; however, in 2020 it has become a major challenge for educators and instructional designers to find and to navigate the guidelines on how VR learning experiences should be designed in order to ensure that the set learning objectives would be achieved. Thus, a major problem of VR learning research seems to be the lack of understanding of the general principles that govern the process and how they are interconnected with existing knowledge about learning, instructional strategies and curricula. With this explosive development in the field of VR learning, there is a need for the systemisation of pedagogical and VR principles that govern and facilitate learning in VR.

While the field of VR research can be viewed in two main categories - technical solutions and applications - this study discusses the technical solutions in context, yet the focus of the research will be on the latter applications and specifically VR applications for learning purposes.

This study has been undertaken to inform educators and instructors, as well as VR technology developers and, potentially, learners, about the general principles which govern learning in VR. It provides an important contribution to the body of research into VR learning and its most important contribution is in systemising already existent, yet fragmented, knowledge and in developing a theoretical basis for applicable taxonomy, as well as defining the area for further research. Moreover, in the researcher's view, it is important to create sustainable linkages and to develop the terminology of Technology Enhanced Learning, including VR learning, which is rooted in pedagogic and learning domains rather than in technical VR technology terms, in order to ensure and foster its practical applications and a balanced transfer of knowledge across two dominant domains of VR learning – learning and VR technology. As an exploratory research, it draws on cross-analysis of both qualitative and quantitative data resulting in new insights and concepts related to systematisation and evaluation of learning in VR.

This research aims to develop a taxonomy of learning in VR research by answering three Research Questions:

1. *What are the general pedagogic principles involved in facilitating learning in VR?*
2. *What is the role of VR in facilitating learning and what are potentially the unique aspects of VR space that augment the learning experience?*
3. *What are the interconnections between the pedagogic principles and the unique aspects of VR space?*

This research presents analytical evidence and discussion in order to establish a taxonomy based on a theory devised by applying Mixed Method (exploratory) design**.** This methodology has been chosen for three main reasons: first, there is no significant body of research that deals with the defined research questions, thus the chosen structure for the design is sequential and it begins with a qualitative inquiry in order to map out the scope of further quantitative study; secondly it is felt that a broader inquiry should be conducted including both qualitative and quantitative data; and thirdly, in order to generate reliable theoretic basis all data and respective analytical results should be cross-analysed by applying (double) triangulation technique.

The *research problem* behind this thesis focuses on the lack of systemised pedagogical principles and technological affordances that govern and facilitate learning in VR, whereas the goal of this research is to develop the taxonomy of learning in VR. *The research object* of this inquiry is concerned with the systemisation and development of pedagogical principles and technological affordances that govern and facilitate learning in VR.

Research tasks

1. To analyse theoretical literature in the fields of pedagogy, instructional design and Virtual Reality for educational purposes;
2. To define VR learning ecosystem through cross-analysis of existing pedagogic and instructional frameworks as well as technological affordances of VR space;
3. To develop a VR learning experience evaluation tool for qualitative analysis of VR learning experiences;
4. To analyse VR learning experiences (quantitative and qualitative methods);
5. To triangulate all of the collected data and study the interconnections between pedagogic theories, various taxonomies and VR learning experiences; and
6. To generate a theory and construct a VR learning taxonomy.

The *purpose* of this research is to study and systemise pedagogical principles that govern and facilitate learning in VR in order to generate a substantive theory of taxonomy of learning in VR. A wide range of VR learning examples has been analysed in preparation for this research; nevertheless, the general body of knowledge in this field can be characterised as fragmented and case-oriented, as there has been no attempt to systemise the general pedagogic principles of learning in VR. Often this is because people who work with the technological side of VR are not experts on matters of pedagogy and educational research, whereas educators, instructors and education researchers often lack knowledge of VR technological aspects. Thus, the *idea* of this research is to fuse the best research available in fields of cognitive pedagogy, Technology Enhanced Learning and VR, including behaviour psychology, instructional design and complex learning in order to develop a taxonomy of learning in VR.

Methodology

This mixed method study has mainly used upon exploratory research design (Creswell and Plano Clark 2011; Teddlie and Tashakkori 2009; Johnson and Onwuegbuzie 2004). The research design consists of six stages and employs data collection followed by both qualitative and quantitative data analysis in order to draw conclusions through interpretation and triangulation of the entire range of the results. This research strategy is based on the pragmatic and constructivist paradigm.

The six stages of the research design are;

- Theoretical literature analysis in the fields of pedagogy, instructional design and Virtual Reality for educational purposes and a definition of the VR learning ecosystem through cross-analysis with existing pedagogic and instructional frameworks;
- Data collation;
- Qualitative and quantitative data analysis;
- Result triangulation;
- Construction of a VR learning taxonomy; and
- Formulation of conclusions and limitations.

Limitations:

The breadth and novelty of a chosen research goal in conjunction with the complexity of the research design present certain difficulty in presenting undeniable verification. Nevertheless, its explorative nature allows it to draw on existing knowledge and to cross-analyse the data in order to create a substantive theoretical foundation for the taxonomy. This study is based on devised theoretical findings and the scientific knowledge which is currently available. The devised evaluation tool was created by synthesising the existing scientific knowledge in the fields of education, cognitive psychology, instructional design and VR, yet it was constructed and described through the viewpoint and understanding of the researcher. The research has been conducted based on the researcher's expertise and experience and the empirical results are interpreted from the point of view of an educator and an instructional designer and does not include evaluations or analysis of VR learning experience development aspects, such as: hardware devices, programming languages, 3-D game engines and models, as well as Web VR, user interface (UI) and user experience (UX) - which also includes issues such as cybersickness and how this can potentially impact the efficiency of VR learning experiences.

This research explores a selection of thirty-two VR experiences that were chosen by the researcher based on criteria described in Chapter II. Nevertheless, the fact that the chosen selection may present certain biases and unique pre-requisites cannot be excluded entirely; thus further study should be conducted expanding the pool of VR experiences analysed through application of the devised evaluation tool. Fields of VR and VR learning continue to develop on a daily basis, therefore, this study includes the technological solutions and applications which are currently known and the eventual theory might be further improved and complemented with newly existent technical and practical solutions.

The following thesis statements are put forward for the defence:

Thesis – 1

Learning in VR is informed by a fusion of principles from multiple pedagogical perspectives and best characterised by the fluidity of VR learning strategy in terms of learning experience design.

Thesis – 2

The VR learning environment has the potential to facilitate learning opportunities that have the potential to achieve learning objectives in all cognitive processes and knowledge dimensions and place the learner at the forefront of the learning process, delivering opportunities for learner-driven complex, creative and collaborative learning in a virtual environment;

Thesis – 3

In order to deliver effective learning opportunities in the VR environment both characteristics – representational fidelity and learner interaction - must be utilised together to provide an immersive learning experience. In order to harness the full potential of the VR learning environment multi-user and synchronous interactions should be utilised. VR experiences which utilise the full potential of the VR learning space, including multi-user characteristics and associated affordances, have the potential to provide learning platforms for the highest cognitive development (knowledge and process) dimensions.

Thesis – 4

Looking at the opposite ends of the cognitive knowledge dimensions' continuum (as the most frequent applications), parallels can be drawn with the characteristics of 3D VR environment, as the factual dimension is highly dependent on representational fidelity (physical perception) and not necessarily learner interaction (embodied actions), while the meta-cognitive dimension is absolutely dependent on learner interaction (embodied actions) and must also entail representational fidelity to achieve immersion.

Thesis – 5

It is not possible to establish a hierarchy of principles in isolation; however, it is possible to establish the hierarchy of the horizontal synergies across multiple core criteria. Thus, an alignment hierarchy is established which highlights the high dependence of the core criteria on the mutually aligned synergy rather than standalone criteria.

Outline of the Thesis

Chapter I presents a Literature Review on a series of pedagogic and instructional design theories, as well as the application of VR for educational goals. Chapter II describes and unfolds the chosen methodology for this study and presents the devised Virtual Reality learning experience evaluation tool and the approbation analysis. Chapter III discusses the process underpinning the generation of theory for the proposed taxonomy. Chapter IV presents the findings of the research undertaken and outlines recommendations for its application as well as further research directions.

CHAPTER I - LITERATURE REVIEW

This chapter presents a literature analysis on a series of topics related to learning in VR. First it examines the theories of learning in the fields of pedagogy and psychology, then it examines Technology Enhanced Learning (TEL) and existing research on VR technologies. Next it examines existent taxonomies and classifications for learning objectives, development stages and VR. Finally, it offers a discussion on the parallels of discussed theories and provides a foundation for the proposed taxonomy model.

Theories of learning

In order to approach the systemisation of pedagogical principles that govern and facilitate learning in VR, there is a need to clarify the use of the word 'pedagogical'. Pedagogy is defined as the methods and practices of teaching, either as an academic subject or theoretical concept. Another, more accurate definition, is presented [in a research report *Researching Effective Pedagogy in the Early Years* published in 2002] by Siraj-Blatchford, Sylva, Muttock, Gilden and Bell (2002): "the instructional techniques and strategies that allow learning to take place. It refers to the interactive process between teacher/practitioner and learner and it is also applied to include the provision of some aspects of the learning environment (including the concrete learning environment, and the actions of the family and community)" (p.10).

There is an ongoing debate that has had varying impetus from different disciplines in recent decades, including linguists, philosophers, education researchers, practitioners and policy planners. Academics and educators have introduced varying applications and theoretical frameworks and thus varying definitions for key terms in the field, such as 'pedagogy', 'education', 'teaching' and 'learning'. Daniela (2018) proposes a model for understanding the application and differentiation of these terms, stating that "*education* is taken as the broader process which supports the student, but *pedagogy* is the driving force to reach this result, where different actors in the educational process interact actively" (p.3).

For the purposes of this study, one unifying term – 'pedagogy' - will be used, which aims to encompass both 'pedagogy' and 'andragogy', as the focus of the study is to examine and systemise the general principles that govern learning in VR environment. Thus, the findings of this research can be further applied to learning strategies for children (pedagogy), as well as adult learners (andragogy).

However, as with Daniela's proposed approach, terms such as 'teaching' and 'learning' are viewed as the two key active and inter-relating components of pedagogy, and 'education' is not to be confused with schooling and should be considered as a far broader process, which includes pedagogy, and thus also teaching and learning (Fig. 1). In addition to the adopted correlative levels (Fig. 1), similar to Daniela, 'pedagogy' in the context of this study is viewed through the definition provided by Siraj-Blatchford et. al (2002). The focus of this research is not separately teaching or learning, but rather principles of learning and thus pedagogy will be kept in focus of this work as a broader term summarising expertise in "teaching to support learning".

In order to establish and examine the general principles that govern the process of learning, first, it is necessary to look at the existing theories of learning, proposed models of their organization and how they inter-relate. In the past two centuries a significant number of theories on how learning occurs have been developed and introduced into international educational practice. It should be noted that there is no one single theory which would fit all, just as there is no one form of learning that fits all objectives and all learners. This study is grounded in two principal theories of learning - constructivism (including cognitive and social constructivism, as well as experiential learning) and constructionism. This study relies heavily on the body of work created by several prominent theorists, such as John Dewey (1902, 1916), Jean Piaget (1956), Lev Vygotsky (1962, 1978), Seymour Papert (1980, 1991, 1993a, 1993b), David Kolb (1984), John B. Biggs and Kevin F. Collis (1982), Robert Gagne (1985), Lorin Anderson and David Krathwohl (2001), David H. Jonassen (2000, 2004, 2007), M. David Merrill (1996, 2002), Paul Kirschner and Jeroen J. G. van Merriënboer (2008).

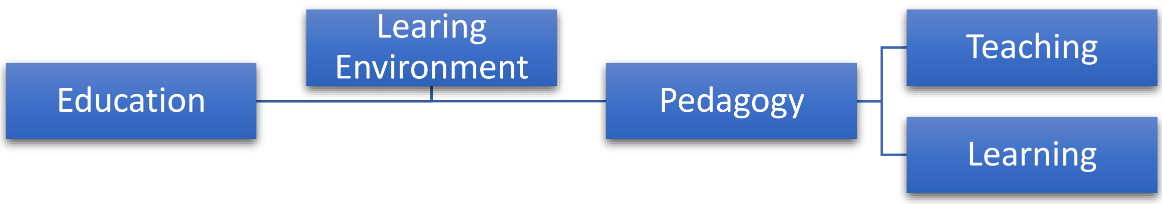


Figure 1
Interrelations: education, pedagogy, teaching and learning
Researcher's concept

Significance of Constructivism for learning in VR

The constructivist theory was developed in the mid-20th Century by several prominent educators, philosophers and academics. Two of the most prominent, who are often associated as synonyms of the theory itself, were Jean Piaget and Lev Vygotsky. Although their theories differ on a number of detailed principles, there is an intertwining set of general principles which are viewed as the general constructivist theory (See Fig. 2). Both theorists believed that learners generate new knowledge and comprehension through building upon previously existing experiences, and those interactions between the experiences and the new information serve the point of 'knowledge construction' (Vygotsky, 1962, Piaget, 1976). Constructivism also argues that each individual's set of experiences and prior knowledge is different and unique, and thus knowledge construction for each individual, or potentially a homogenous group, is different. Constructivism views learning as ‘active’ rather than ‘passive’; thus, one of the most significant contributions of this theory is the ‘learner-centred’ (sometimes also referred to as ‘student-centred’) approach in contrast to the content-centred approach to learning. In both Piaget and Vygotsky's proposed approaches, the educator’s role is primarily in support and guidance rather than teaching new knowledge and skills and thus determining the course of a learning experience.

Social constructivism, a branch of constructivism, emphasises the importance of socio-cultural contexts of learning. Vygotsky believed that learning is dependent on social interaction and that ‘social learning’ actually leads to cognitive development (Vygotsky, 1962). Vygotsky emphasised the role of an educator as a support, guide and scaffolding mechanism, as he believed that learners can perform tasks which, otherwise they could not complete on their own, if given the necessary guidance or scaffolding, or alternatively through collaboration with their peers. This can be seen as a significant step towards experiential learning and instructional design in the future, as Vygotsky's model for teaching stresses the importance of learning opportunities and indeed, their design. He also believed that the type and quality of social interactions (culture, language, role-models to the student) determine the design and degree of development.

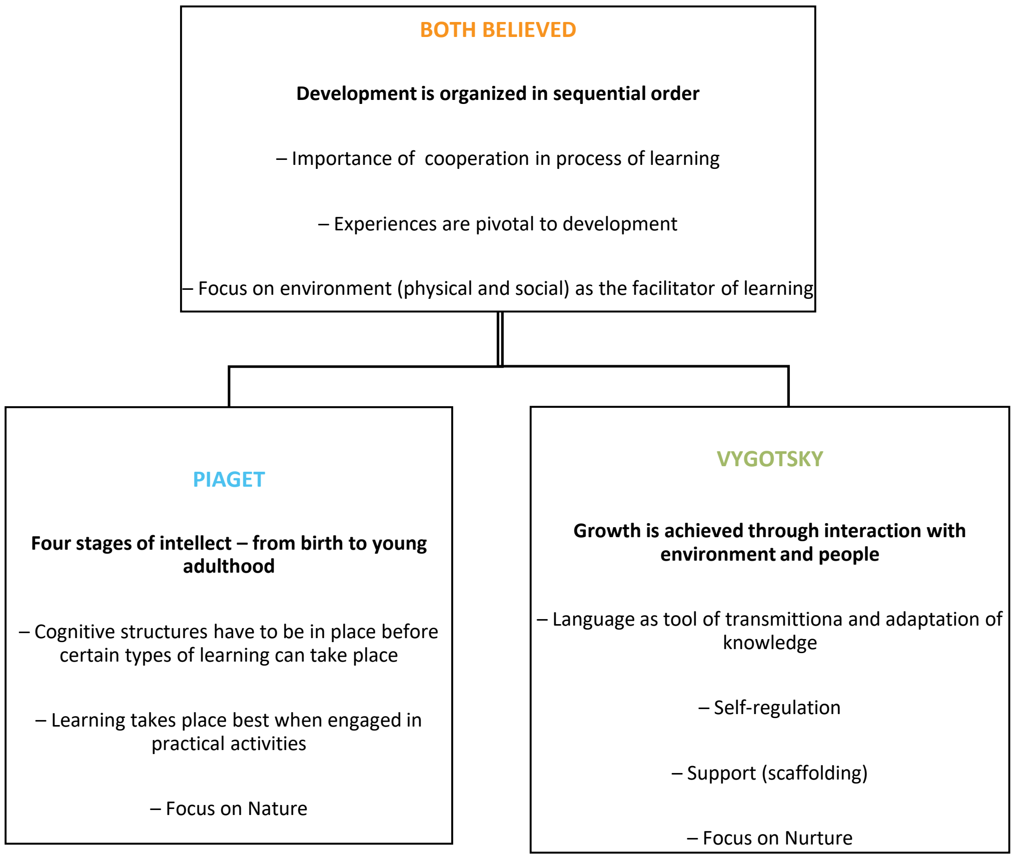


Figure 2
Overlap in Constructivist ideas – Piaget and Vygotsky
Researcher's concept

Constructivist learning theory is rooted in the premise that learning is an active process, where, through various supportive mechanisms (environment – both physical and social, information, guidance) learners develop connections with their prior experiences and knowledge and thus layer on or 'construct' the new knowledge, skills and attitudes. For the further development of learning in a virtual environment, this shift can be noted as one of the pivotal moments when the academic discourse of the early constructivists, such as Wittrock and later Bloom, shifts its attention from ‘teaching’ to ‘learning’. The course-changing impact of Piaget’s theoretical ideas in educational psychology has, in turn, generated a great deal of research which has furthered our understanding of cognitive development and learning processes. Nonetheless, it also generated a notable amount of criticism; for instance, Vygotsky and Bruner (1966), in contrast to describing the process as developmental stages, defined cognitive development as a continuum. Some later studies (Keating, 1979) criticised Piaget, for neglecting the impact of socio-cultural environment on the cognitive development including the defined age ranges and development stages and focusing only on biological factors.

Nevertheless, constructivism is based on similar founding assumptions about learning and is one of the foundational theoretical inputs for learning in VR. There are two significant reasons why these theories serve as the foundation for this inquiry. First, constructivism places a great deal of importance on the creation of a suitable environment for knowledge construction rather than for its mere transfer from educator to learner, as the theory advocates knowledge construction, not knowledge reproduction. Secondly, constructivism stresses the importance of collaborative learning. These aspects are key to the application of these pedagogical theories in order to study learning in VR as the significance of the learning environment and collaborative experiences draws direct parallels with the benefits of technology enhanced education including VR technology enhanced learning. Thus, this pedagogical framework will aid in designing and utilising VR learning experiences through learner engagement (environment) and prior experience-based knowledge construction, thus facilitating the development of new knowledge and competences, such as critical and analytical thinking.

Significance of Constructionism for learning in VR

Constructionist theory emphasises experiential discovery learning where individuals or groups can learn and construct knowledge through practical, real-world tasks and experiences (Papert, 1991). During the 1980s, Papert, who was also a mathematician, computer scientist, and one of the

Artificial Intelligence (AI) pioneers and educators, developed the theory of Constructionism. Papert believed in learning by doing (1980, 1993a, 1993b). He stressed that technology, together with the constructivist learning approach, created opportunities for learners to construct new knowledge and innovative ways of thinking. For Papert it was important to visualise the process of knowledge construction, thus allowing for a more engaging experience. A strong parallel with constructivist theory is that Papert viewed learning as a pro-active process rather than passive because constructionism stresses enabling and learning versus teaching. Papert is often given credit for utilising technology in learning. Another strong similarity is a learner-centred approach to learning. Constructionism can be viewed as a branch of a constructivist learning theory, yet constructionism focuses on instruction rather than studies the process of learning. If there is a notable difference in these two theories, it is that constructivism rather stresses the cognitive potential, whereas constructionism stresses the potential of the physical activity.

“Constructionism can mostly be found being used as an educational tool in science and math classrooms, though it is spreading to other subjects as well. Today, there is an increasing popularity for robotic technologies used in the classroom. Specifically, there has been a focus on “white-box” digital tools, which teach the user or builder about the structure of the technology itself, in contrast to “black-box” software or technology, which conceals the method of its creation and is closed to any modifications by the user or builder” (Alimisis and Kynigos, 2009, p.11).

In order to highlight the synergy with learning in VR, it must be noted that the core statement of constructionism is that learning transpires through the process of creation, both individually or collectively, and that creation and co-creation can be achieved as a result of the affordances of the learning environment. Both in constructionist learning theory and learning in VR it is pivotal that the process of learning enables learners to have a close-up ownership over the learning process and its outcomes, while the educators and the learning environment provide the necessary guidance through scaffolding and feedback.

Technology Enhanced Learning

As highlighted in the Introduction, there is a wide range of alternative terms used to discuss issues linked to technology and learning; however much of the discussion has been about how Technology Enhanced Learning has been used, which is viewed as the application of ICT to achieve learning objectives.

According to Salomon: “Computer-based learning environments are not learning environments to which computers have been added … Rather, these are relatively new environments in which computer-afforded activities have been fully integrated into other activities, affecting them and being affected by them” (1992, p. 252).

This principle directly transcends to the development and organisation of TEL, as there are similar considerations as well as benefits and limitations imposed by the application of technologies. Various researchers have asked how technology enhances the value of learners’ experiences. At the core of the TEL concept is the implication of a value ‘upgrade’ as a result of utilising technology for the betterment of the teaching and learning strategies. The description itself suggests that enhancement should be understood as a value judgement meaning improved quality or added value. Moreover, several academics (Kapp, O’Driscoll 2010; Kirkwood, Price, 2013) have raised questions, such as: *What exactly can and should be, or in particular instances, is enhanced when technology utilised? How can an enhancement be evaluated and monitored?*

These questions, as well as the potential benefits and risks concerned with the TEL approach are similarly relevant to learning in VR, as without a strategic understanding of how the affordances of VR learning environment can and should be utilised, as well as the ability to evaluate, potentially measure and analyse this enhancement it can be really easy to fall into a technology fascination effect. Furthermore, many of the TEL instructional design and teaching strategies can be applied to designing VR learning experiences and teaching using VR technology.

Taxonomies and classifications of learning outcomes

Various learning theories have been discussed in the previous sections and it is vital to emphasise the importance of the existing knowledge in this field, as it will be used to further develop a theory for the systemisation of learning principles governing learning in VR.

There is a significant body of research available on the subject, yet for the purposes of this study, the following theories, ideas and classifications have been explored and synthesised: Bloom, 1956; Gagne, 1985; Anderson and Krathwohl, 2001; Churches, 2007, Merrill, 2002, Kirschner and van Merriënboer, 2008. Some of the 'early' taxonomies include Bloom's taxonomy (1956), the ADDIE model (1957), SOLO taxonomy by Biggs and Collis (Biggs and Collis, 1982) and Gagne's taxonomy (1985).

In order to address the various classifications and taxonomies, Instructional Design (ID) will be introduced into the discussion, as it is often defined as the principal objective of such taxonomies and classifications, and also because it is often used in literature as an inter-changing alternative for learning – experiences, strategies, process mapping, management and monitoring.

Various taxonomies developed by ID practitioners and researchers (e.g. Bloom (1956) and Gagne (1985)) further reinforce the roots of Instructional Design, both as a concept and also a practice, reaching from cognitive and behavioural psychology, through constructivism, constructionism and TEL.

"Instructional design is intended to be an iterative process of planning outcomes, selecting effective strategies for teaching and learning, choosing relevant technologies, identifying educational media and measuring performance" (Branch and Kopcha, 2014, p. 77).

The objectives of ID, or instructional systems design (ISD), are “instructional experiences which make the acquisition of knowledge and skill more efficient, effective, and appealing” (Merrill, Drake, Lacy, Pratt, 1996, p. 5). The practice includes analysis of the learners’ (or group’s) current setting and prerequisites, later mapping out the needs of the learner, defining learning outcomes and the overall goals, followed by a designed learning experience, often described as an ‘intervention’. Since the 1950s there have been approximately two hundreds instructional design models; however, conceptually, there are four models (the Dick and Carey systems approach; Morrison, Ross and Kemp model (also known as the Kemp model); Guaranteed Learning / the Instructional Development Learning System (IDLS); the First Principle of Instruction); but most of them were derived from the ADDIE model, which is based on five stages of instruction: analysis, design, development, implementation, and evaluation. One of the most renowned early models, from the Centre for Educational Technology at Florida State University for the U.S. military sector – ADDIE - was developed in 1975.

Various taxonomies were developed by Instructional Design practitioners and researchers, including Gagne’s Taxonomy which defined five levels of learning: verbal information, intellectual skills, cognitive strategies, motor skills and attitudes, and nine events of instruction which correspond to learning processes (1985). Gagne’s Taxonomy classifies the learning process in terms of the degree of complexity of the mental processes involved, (see Figure 3). Subsequently, Churches further developed the taxonomy proposed by Bloom and Anderson and Krathwohl and published a digital taxonomy, which complemented existing taxonomies of learning outcomes with six levels of digital skills (Churches, 2007).

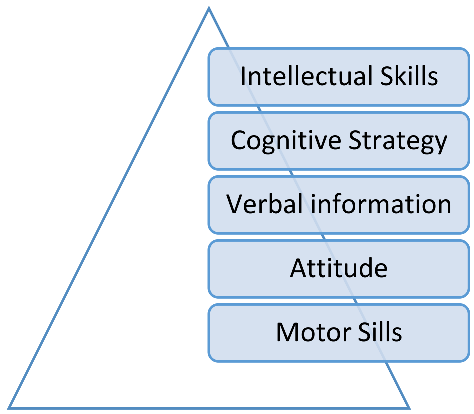


Figure 3
Gagne's Taxonomy
Researcher's concept

Another significant direction for more contemporary learning models has been developed by Merrill, followed by Kirschner and van Merriënboer. The First Principles of Instruction (Merrill, 2002) is a model based on a synthesis of many earlier ID theories. This model focused on those aspects which were common to the various ID theories, thus establishing the fundamental essence of ID through a set of principles. First Principles of Instruction can be applied in a task or problem-centred cycle of instruction (See Figure 4). This model draws close parallels with other task-centred instructional theories, such as Kirschner and van Merriënboer (e.g. Four Component Instructional Design Model – 4C ID) as it uses a real-world problem or task as an instrument for instruction. Students observe demonstrations of examples of real-world problem solving and are then given opportunities to solve these problems themselves, while being supported through feedback. Learning in context is pivotal in both the First Principles of Instruction and the 4CID model, as context becomes the core learning environment for deep learning.

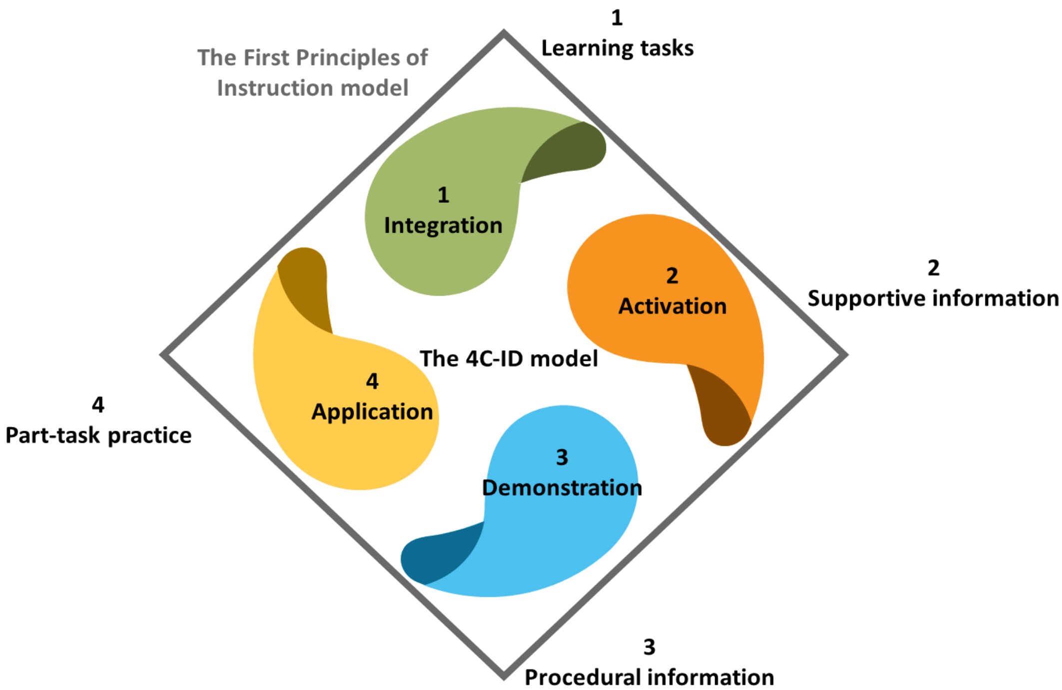


Figure 4
The First Principles of Instruction and the 4CID model
Researcher's concept

Research by Merrill (2002) and Kirschner and van Merrienboer (2008) is of great significance in the understanding of how learning in VR should be organised and utilised, for two main reasons:

- Merrill attempts to synthesise most prominent ID approaches and models, thus providing a crucial impetus in presenting a comprehensive model for how learning takes place and to highlight the most effective ways to organise the learning process.

- Kirschner and van Merrienboer's 4C ID model presents a blueprint for complex learning, which is real-world based problem-solving. The model emphasises the real-world setting and supporting contextual information as well as varying and with progress – reducing guidance to a learner.

Thus, Merrill's model allows understanding of the general principles of the creation of learning experiences, while Kirschner and van Merrienboer's model, draws strong parallels with the principles often attributed to learning in VR, such as real-world simulation, contextual learning and varying guidance levels.

VR technologies and learning

"At every level of education, virtual reality has the potential to make a difference, to lead learners to new discoveries, to motivate and encourage and excite. The learner can participate in the learning environment with a sense of presence, of being part of the environment" (Pantelidis, 2009, p. 61).

In order to approach the discussion on learning principles in VR, first, it is important to look at the variety of technological factors, which define the potential as well as the limitations of VR, and allow it to be the epitome of advancement and potential that it is today.

Research in VR technology can be viewed in three larger interconnected directions:

1. Hardware – including: lenses, headsets, connectors and transmissions, haptic VR technology, delay in input and output, potential and limitation of CAVE as an environment.

2. Software – including 3D design and functionality (interaction with objects), AI, analytics, hardware limitations and boundaries with software potential and limitations, collaboration potential and functionality.

3. Applications – including user demand, functionality, industry (specific fields oriented needs), learning and training.

It is important to distinguish the five technological levels of VR technology (see Figure 5) – which are more precisely described as:

1. Physical reality – no digital information overlay, interactions are entirely dependent on interaction in physical environment;
2. Augmented Reality (AR) – interaction with the real world while using an ‘additional’ digital information overlay;
3. Augmented Virtuality – a virtually augmented physical environment;
4. Mixed Reality (MR) – interaction with both real world and the digital (virtual), including the functionality of interaction and manipulation of objects; and
5. Virtual Reality (VR) – a completely digital environment, closed off from the physical environment.

VR, AR and MR have, respectively, already become multi-billion dollar industries, with a range of solutions starting with headsets for ten euros up to tech-kits that cost up to 7,000 euro. It must be noted that Microsoft Windows ecosystem has become the leading software platform for VR content. Currently there are wireless headsets with no need to be even connected to a computer, such as Oculus go (2018), which are totally portable - from haptic suits to various advanced controllers and built-in 360 headphones and microphones for even more realistic interactions. Other technological gems of the latest tech wave have been the Microsoft Holo Lense, Magic Leap, HMD Odyssey, Varjo VR-1 and 2, and Vive Focus – Mixed Reality headsets.

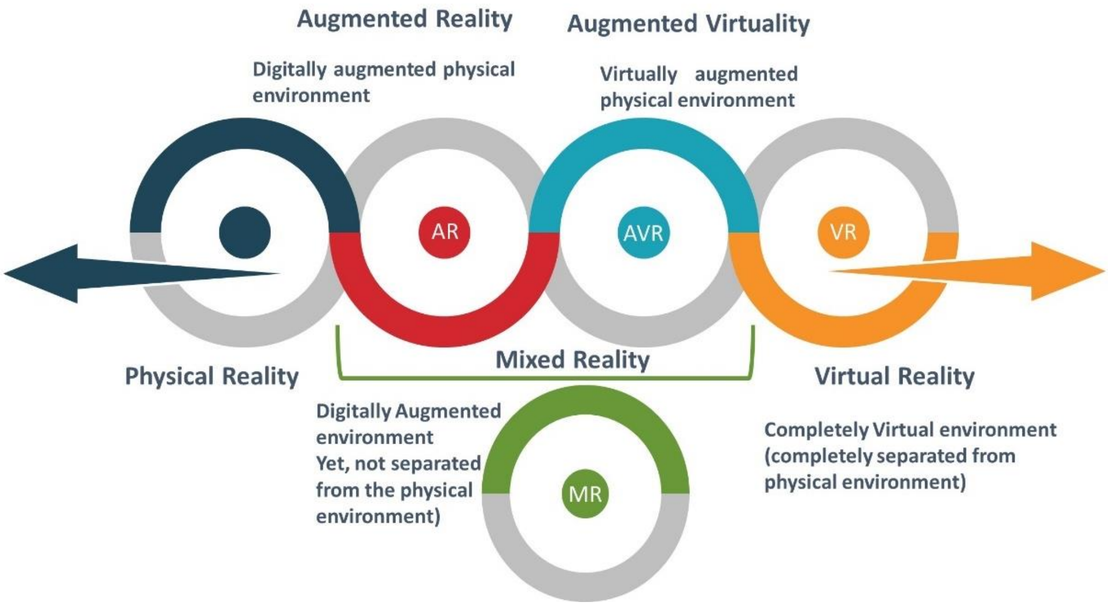


Figure 5
Levels of Virtuality – Immersive Technologies
Researcher's concept

VR has already shown great potential in recent decades; nevertheless immersive Virtual Reality technologies available in 2020 are respectively 'young' (especially learning analytics and haptics) and there is much more to be understood and studied on how to use these technologies effectively and to further incorporate VR technology into our daily lives in order to harness the unique affordances through diverse and informed applications. Several authors have argued that the success of VR learning relies on the quality of chosen visualisation and interaction modes (Erickson, 1993; Bryson, 1995). The VR technology industry is exceedingly competitive and has developed with remarkable speed. Nevertheless, there are still several significant technical limitations; for some users cybersickness, or simulation sickness (also called VR sickness) occurs when exposure to a virtual environment causes symptoms that are similar to motion sickness (Kolasinski, 1995; LaViola, 2000); quality of lenses, including the lack of comfortable and affordable optometric solutions for VR headsets (so there would be no need to wear glasses or lenses beneath the headset); the need to improve the resolution and display quality; and improvements in terms of latency (response) including spatial queues and haptic responses.

As Pantelidis (1993) noted, the reasons for using VR are in fact parallel to all the reasons for using a two-dimensional, computer-assisted instruction simulation. Thus, the main problem when applying VR to existing learning theories and methods is that most online learning developers have never experienced Virtual Reality and have a hard time applying traditional instructional design methods to the VR space. It is important to avoid mistakes early in the process, so designers do not end up creating elaborate VR classrooms. Virtual Reality design strategies must go beyond traditional instructions to truly leverage the advantages of Virtual Reality for learning. As Kapp noted (2017): “It will be important to know how to apply the correct pedagogy, how to choose the right software and hardware, and how to apply the right instructional strategy to ensure learning” (http://bit.ly/elearningindustry_kapp). This emphasises the necessity and urgency to review and systematise learning principles for Virtual learning; thus it is imperative to develop an up-to-date taxonomy in order to inform the technology developers and practitioners (Instructional Designers and educators) about the general overarching principles of VR learning.

Many studies have been conducted on the applications and effectiveness of Virtual Reality in education and training since the 1980s. Mclellan (1996, 2003) provides comprehensive and in-depth reviews of the literature related to the research and use of virtual reality for education and training. Mclellan traces the early use of Virtual Reality in training to flight simulators with head-mounted displays developed at Wright-Patterson Air Force Base in Ohio during the 1960s and 1970s (1996, p. 458). Youngblut (1998) conducted an extensive survey of research and educational uses of VR during the 1990s and this survey attempted to answer questions about the use and effectiveness of Virtual Reality in kindergarten through Grade 12 education (USA). Youngblut found that there are unique capabilities in Virtual Reality, and the majority of uses included aspects of constructivist learning (1998, p. 93). Studies showed potential educational effectiveness for special needs students (p. 98) and the role of the teacher changed to that of facilitator (p. 100). Students enjoy using pre-developed applications and developing their own virtual worlds (p. 100).

The majority of the teachers in the studies reviewed said that they would use Virtual Reality technology if it were affordable, available, and easy to use for students and teachers (p. 101).

A model developed by Salzman, Dede, Loftin, and Chen (1999) described how Virtual Reality aids complex conceptual learning, and how Virtual Reality's features and other factors shape the learning process and learning outcomes. The model resulted from a study to identify, use, and evaluate immersive Virtual Reality's affordances as a means of facilitating the mastery of complex, abstract concepts. Studies show that a virtual environment can “stimulate learning and comprehension, because it provides a tight coupling between symbolic and experiential information” (Bowman, Hodges, Allison, and Wineman, 1999). Many studies have focused on how children and young learners interact and learn in a 3D environment. Indeed, children and young learners have been studied in high-end projection environments, such as a CAVE (A cave automatic virtual environment) (Roussos, et al 1999). Their activity within interactive virtual environments was examined to learn how interaction and conceptual learning are related in the context of a virtual environment, namely the Virtual Playground.

Chee (2001) argued for the need to root learning in experience, using physics as an example. He explained that physics students have little “feel” and “understanding of the qualitative dimensions of the phenomena they study”. Chee believes that VR can be used to achieve this goal, “providing a foundation for students' conceptual and higher-order learning”.

Chen (2006) asserted that “although VR is recognized as an impressive learning tool, there are still many issues that need further investigation including, identifying the appropriate theories and models to guide its design and development, investigating how its attributes are able to support learning, finding out whether its use can improve the intended performance and understanding, and investigating ways to reach more effective learning when using this technology, and investigating its impact on learners with different aptitudes” (p.39). Her research provided insights to a feasible Instructional Design theoretical framework as well as an instructional development framework for VR-based learning environments.

Dalgarno, Hedberg, and Harper (2002) suggested that the most important potential contribution of 3D learning environments (3DLEs) to conceptual understanding is through the facilitation of spatial knowledge development. They identified aspects of a research agenda to test this, including “exploration of the characteristics of 3DLEs that are most important for spatial learning along with issues in designing appropriate learning tasks”. Selvarian (2004) discussed the potential of spatial and social technologies in a virtual learning environment through presence. She proposed a virtual learning environment model and offered hypotheses that correlate the spatial and social technologies with spatial and social presence with low- and high-level learning. Findings from her research offer educators “a valuable guide for the design of virtual learning environments that enhance low- and high-level learning through spatial and social presence”.

Reasons to use VR in education and training

The reasons for the use of VR in education and training relate particularly to its capabilities. In a conceptual basis for educational applications of virtual reality, Winn stated that:

1) “Immersive VR furnishes first-person non-symbolic experiences that are specifically designed to help students learn material.

2) These experiences cannot be obtained in any other way in formal education.

3) This kind of experience makes up the bulk of our daily interaction with the world, though schools tend to promote third-person symbolic experiences.

4) Constructivism provides the best theory on which to develop educational applications of VR.

5) The convergence of theories of knowledge construction with VR technology
permits learning to be boosted by the manipulation of the relative size of objects in virtual worlds, by the transduction of otherwise imperceptible sources of information, and by the reification of abstract ideas that have so far defied representation” (1993).

Winn concluded that “VR promotes the best and probably only strategy that allows students to learn from non-symbolic first-person experience. Since a great many students fail in school because they do not master the symbol systems of the disciplines they study, although they are perfectly capable of mastering the concepts that lie at the heart of the disciplines, it can be concluded that VR provides a route to success for children who might otherwise fail in our education system as it is currently construed” (1993).

Pantelidis (1995) gave the following reasons to use Virtual Reality in education (interpreted and conceptualised by the researcher);

- new forms and methods of visualization;
- an alternate method for presentation of material;
- in some instances, VR can more accurately illustrate some features and processes than by other means;
- motivation of students by means of immersive interaction;
- access to a learning experience during a broad time period not fixed by a regular class schedule and at their own pace;
- an inclusive approach (transcending geographical, physical disability and language barriers); and
- developing a deep first-person understanding, empathy and values by using avatars of different genders, social and cultural backgrounds.

Instructional strategies for learning approaches in VR

Before discussing instructional strategies for learning, it is crucial to establish a clear terminology which ranges from a more technological spectrum into pedagogic and more often instructional vocabulary. It is also important to note that since the late 1990s and early 2000s the new outlook on the prevailing importance of learning environments and Technology Enhanced Learning strategies led by the educational and immersive technology research community has offered new terminology to advance the discussion on immersive learning. Thus the new terms – *three-dimensional (3-D) virtual learning environments (VLEs)* (Dalgarno, Lee, 2010) and *virtual immersive environments (VIE)* (Kapp, O'Driscoll, 2010) – have allowed for new opportunities to further and more effectively structure the academic discourse on the educational potential and applications of VR technology.

In order to establish a clear understanding of terminology further used in this inquiry, the author offers an overview of various perspectives, which inspired and enriched the understanding of definitions and applications of these terms. It is crucial to understand the essence of each of the core terms individually in order to be able better understand their contextual frame and potentially their interconnections or combinations. The interrelations and overall hierarchy of terminology involved in VR learning discourse are shown in Figure 6.

As with Dalgarno and Lee, (2010), 3-dimensional virtual learning environment or 3-D VLE as defined by Wann and Mon-Williams is a learning environment which "capitalises upon natural aspects of human perception by extending visual information in three spatial dimensions, may supplement this information with other stimuli and temporal changes and enables the user to interact with the displayed data" (1996, p.833).

Immersion, (and sometimes *presence* is used as an alternative) embodies both the physical aspects of the environment and the psychological sense of being in the environment (Hedberg, Alexander, 1994), including the objective characteristics of the environment and the subjective experience of the learner (Whitelock, et. Al, 1996).

Dalgarno and Lee stressed that during the early days of modern VR – the 1990s - these terms were often used interchangeably, thus there was a strong need for clearer definitions in order to further advance the discourse (2010).

Slater defines *presence* as "the subjective sense of being in a place, and *immersion* as the objective and measurable properties of the system or environment" (2003).

Immersion according to Slater "relies on the technical capabilities of VR technology to render sensory stimuli, whereas *presence* is context-dependant and draws on individual's subjective psychological response to VR experience (2003).

On further looking into multi-user VR learning environments and experiences, the term *co-presence* is often encountered, which as defined by Dalgarno and Lee, is "an extension of social presence – a sense of 'being-there together' with other geographically dispersed users (Dalgarno, Lee, 2010).

Avatar is an "online identity, a visual representation of his / her real or surrogate identity and appearance" (Dalgarno, Lee, 2010).

According to Greeno (1994), an *affordance* "relates (the) attributes of something in the environment to an interactive activity by an agent who has some ability" (p.338). In comparison, Kirschner defines affordance as a "relationship between the properties of an educational intervention (learning experience) and the characteristics of the learner that enable certain kinds of learning to occur (2002).

Haptic VR technology includes gloves, vests and full body suits. As defined by the National Research Council, Computer Science and Telecommunications Board, Committee on Virtual Reality Research and Development "Haptic interfaces are devices that enable manual interaction with virtual environments (…) such as manual exploration and manipulation of objects" (1995, p.161).

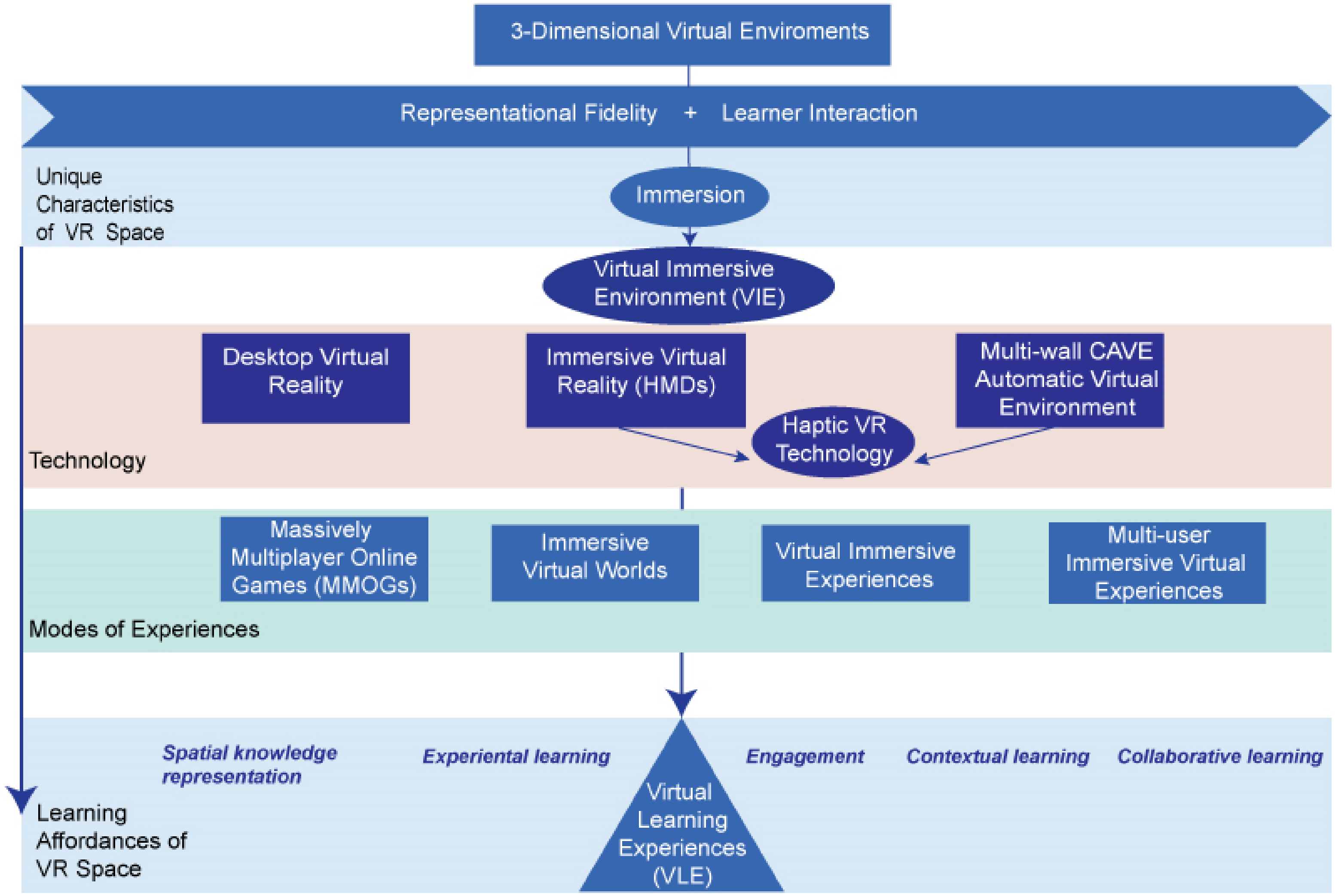


Figure 6

The interrelations and overall hierarchy of VR learning terminology

Researcher's concept

Any technological or pedagogical innovation exists in its own current conditions and often carries the knowledge of past discoveries, practices and flaws. Thus, the researcher believes that the established learning taxonomies and instructional design models present the most suitable platform for further discussion about the approaches towards learning in VR. To begin with, it is important to note that there is very little research available discussing the general principles which govern learning in VR. Nevertheless, there is a variety of field-specific (case-study) based inquiries which draw several field-specific principles (e.g. medical training, first-response teams, soldiers, pilots, navy and engineering).

One of the most prominent research enquiries which combines technological knowledge with instruction and learning approaches was presented by Kapp and O'Driscoll (2010). The authors present a model to approach learning in VR through a variety of components and levels. The model defines seven Sensibilities, nine Principles four Macro-structures and eleven Learning Archetypes (see Figure 7).

The seven Virtual Worlds' Sensibilities are:

1. The Sense of Self;
2. The Death of Distance;
3. The Power of Presence;
4. The Sense of Space;
5. The Capability to Co-Create;
6. The Pervasiveness of Practice; and
7. The Enrichment of Experience (Kapp and O'Driscoll, 2010, p.57).

The eleven Archetypes are:

1. Avatar Persona
2. Role Play
3. Scavenger Hunt
4. Guided Tour

5. Operational Application
6. Conceptual Orienteering
7. Critical Incident
8. Co-Creation
9. Small Group Work
10. Group Forums and
11. Social Networking (p. 90 –117)

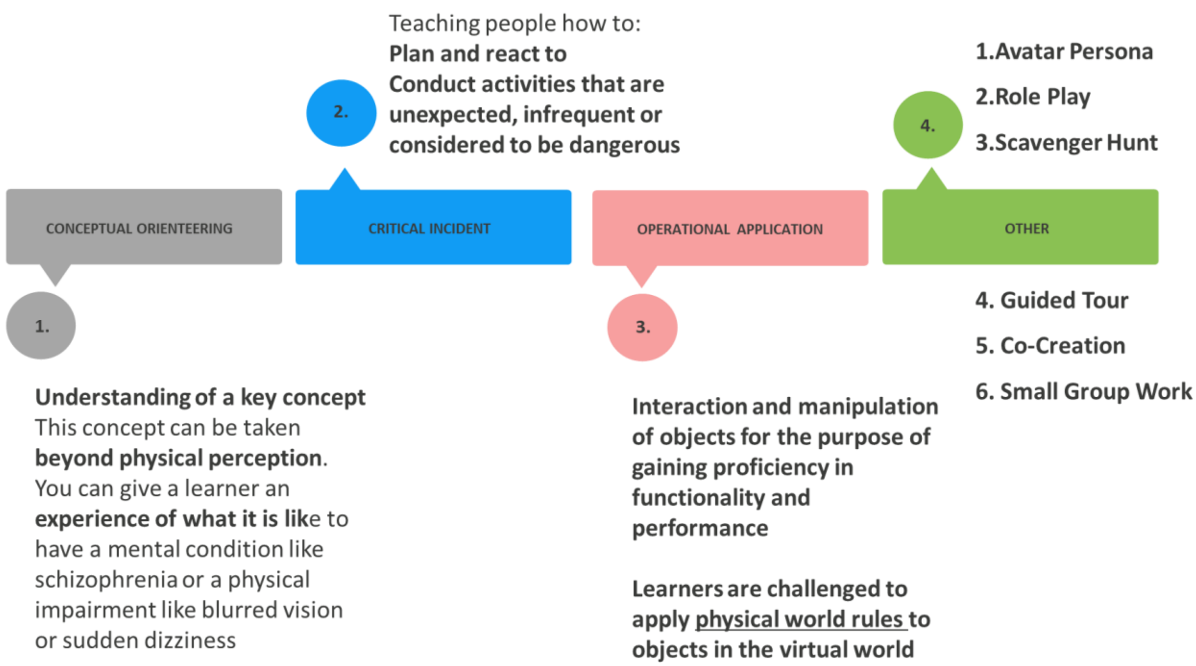


Figure 7
Instructional strategies for VR adopted from Kapp, O'Driscoll (2010)
Researcher's concept

Based on practical experience the researcher has established the use of three larger types of learning archetypes or learning strategies for VR and conceptual groups other smaller strategies into the fourth category – 'other'. The evaluation results presented in Chapter II "Quantitative analysis of VR learning experiences" - confirm the practicality of this grouping.

Taxonomy of Learning in Virtual Reality

1. Conceptual Orienteering

This instructional strategy involves the creation of a VR activity or situation in which learners are presented with examples for the purpose of creating an understanding of a key concept. This concept can be taken beyond physical items. It is possible to give a learner an experience of what it is like to have a mental condition such as schizophrenia or a physical impairment such as blurred vision or sudden dizziness (Kapp and O'Driscoll 2010, p 90 - 117).

2. Critical Incident

This instructional strategy involves teaching people how to plan for, react to, or conduct activities that are unexpected, infrequent or considered to be dangerous when practised in the real world. This could involve placing the learner into the middle of a disaster such as a chemical spill or the aftermath of a hurricane, or into a more benign environment such as a retail store where a person is in the process of shop lifting a smartphone (Ibid)

3. Operational Application

This instructional strategy is the interaction and manipulation of objects for the purpose of gaining proficiency in functionality and performance. The key to this instructional strategy for Virtual Reality is that learners are challenged to apply physical world rules to objects in the virtual world (Ibid)

Summary

Practitioners and researchers have been concerned with how learning takes place since the advent of civilisation. In order to design VR learning experiences as well as to effectively learn using VR technology, first, it has been necessary to look at the existing theories of learning, proposed models of the organisation of learning and the main shifts in academic discourse that have taken place since the 1950s.

To frame the discussion and in order to illustrate the tectonic shifts that have taken place in the fields of education, cognitive psychology, instructional design and VR technology, a historical development vignette is proposed by the researcher (see Figure 8).

The theories explored in this chapter all have one focal element in common – the potential of experience as an essential part of learning. However, it must be noted that there is no one single theory which would fit all, just as there is no one form of learning that fits all objectives and all learners.

Constructivism and constructionism provide the best theoretical foundation for the understanding of learning principles that govern learning in VR. Thirdly, Constructivism, Constructionism and TEL all emphasise the importance of a learner-centred approach to learning, where a learner takes an active role rather than a passive role. Next, the three learning theories all emphasise the crucial importance of the learning environment thus accentuating the potential of VR technology.

Meanwhile, the literature on VR learning argues that VR provides unique opportunities for learners to access learning experiences that otherwise would not be accessible as part of their formal classroom-based education and thus through VR to take part in that learning experience as it would have been a first-person experience.

This chapter has summarised current research on learning theories, Technology Enhanced Learning, VR technologies and VR learning, including how VR environments can affect learning, with the goal of providing a comprehensive view of the most prominent theories and most current research and though that to provide a roadmap for further study.

Taxonomy of Learning in Virtual Reality

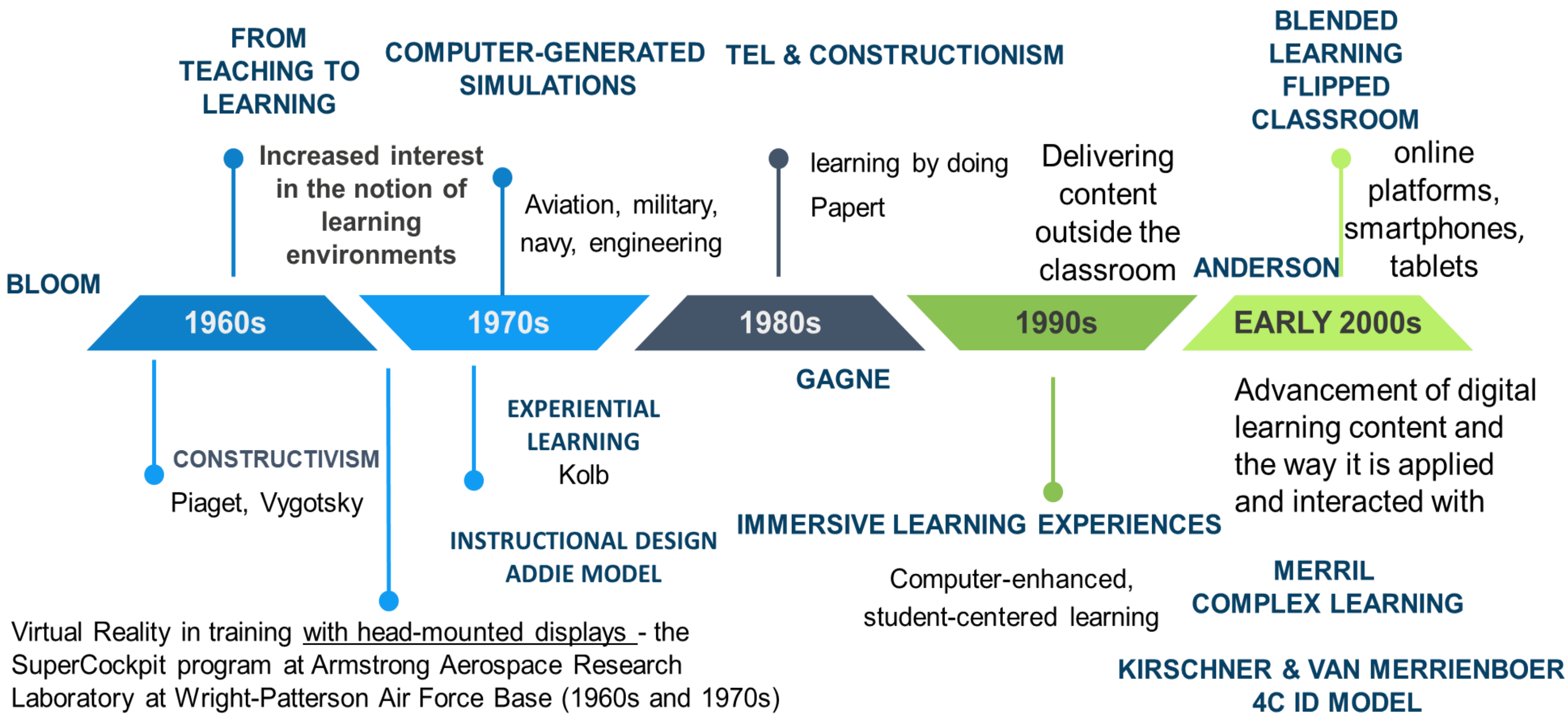


Figure 8
Development Vignette: Educational Psychology - Instructional Design - VR Technology
Researcher's concept

CHAPTER II – METHODOLOGY

Research Design

This section provides a detailed overview of the research design by outlining the steps taken in each of the stages. Figure 9 shows a conceptual map of the research design employed.

The six stages of the research design are:

1. Analysing theoretical literature in the fields of pedagogy, instructional design and Virtual Reality (VR) for educational purposes (presented in Chapter I);
2. Defining a VR learning ecosystem through cross-analysis of existing pedagogic and instructional frameworks as well as technological affordances of VR learning space;
3. Developing a VR learning experience evaluation tool;
4. Analysing VR learning experiences (quantitative and qualitative methods);
5. Triangulating all of the collected data and studying the interconnections between pedagogic theories, various taxonomies and VR learning experiences; and
6. Generating a theory and constructing a VR learning taxonomy;

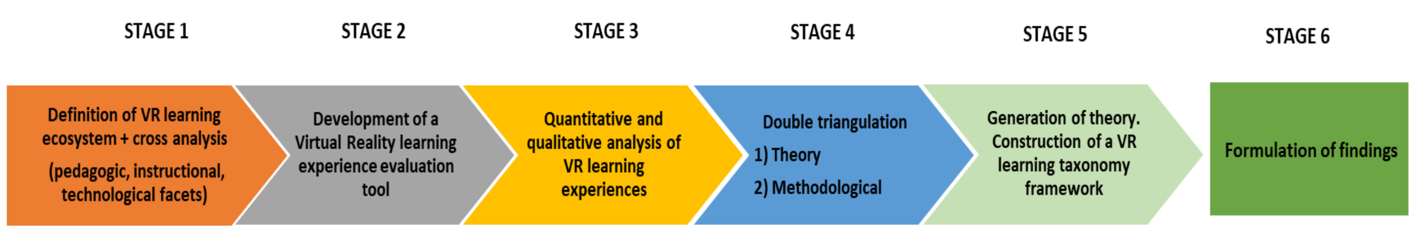


Figure 9
Research Design
Researcher's concept

Rationale for the chosen methodology

The purpose of this research is to study and systemise pedagogical principles that govern and facilitate learning in VR in order to generate a substantive theory of taxonomy of learning in VR. This study has used a mixed method concurrent approach resulting in exploratory design.

In order to answer the defined Research Questions and to advance the understanding of principles that govern the process of learning in VR this inquiry has adopted the perspective of the Third methodological movement (Tashakkori and Teddlie, 1998, 2003, 2009). Thus, the research design was developed based on the premise that the primary goal of the design is to apply the most effective strategy and methods that would be best suited to address the defined Research Questions.

This research strategy was devised based on the pragmatic and constructivist paradigm. Qualitative research methods are best suited to explore new knowledge, including theoretical developments, as well as to derive emergent phenomena and establish new theories, while quantitative methods allow the measurement of frequencies and the intensity of principles informing the newly established phenomena. The chosen research strategy was primarily devised in order to achieve the purpose of the research which is to generate a substantive theory; thus, the best set of methods to provide answers to the Research Questions employed mixed methods. For the purposes of this research, mixed methods were instrumental in devising the conceptual framework through literature analysis, cross-study of existing taxonomies and classifications, qualitative explorative evaluations and quantitative data analysis and subsequently double triangulation of all of the findings in order to construct theoretical findings and to devise a taxonomy.

A decades-long paradigm debate lead by such theorists as Kuhn (1962, 1970, 1996) has argued the incompatibility of qualitative methods with quantitative, describing them as incommensurable paradigms (1970) thus acknowledging and emphasising methodological purity or the mono-method versus multi-method approach. A decades-long paradigm debate lead by such theorists as Kuhn (1962, 1970, 1996) has argued the incompatibility of qualitative methods with quantitative, describing them as incommensurable paradigms (1970) thus acknowledging and emphasising methodological purity or the mono-method versus multi-method approach. On the other hand, Glaser and Strauss (1967) stated the following:

"There is no fundamental clash between the purposes and capacities of qualitative and quantitative methods or data. What clash there is concerns the primacy of emphasis on verification or generation of theory to which heated discussion on qualitative versus quantitative data have been linked historically. We believe that each form of data is useful for both verification and generation of theory….In many instances, both forms of data are necessary…both used are supplements, as mutual verification and, most important for us, as different forms of data on the same subject which when compared, will each generate theory" (p. 17-18).

Tashakkori and Teddlie (1998, 2003, 2009) argued that there are three independent research communities or approaches - quantitative, qualitative and mixed methods (MM) or the Third research community (2009) and the Third methodological movement (2009). In Creswell's view (2003) each method can be distinguished, not uniquely by the respective research paradigm or the outlook position, but also by the strategy, design, and data collection methods. As the chosen research design suggests, this researcher falls into the category of those researchers, described by Armitage (2007) as being "of a more practical and pluralistic persuasion, who hold that research should address real-life problems over the methodological pureness of mono-methodological positions, favour the adherence towards what has become known as the "Third Way" encapsulated within the pragmatic paradigm" (p.1).

Armitage provided a well-balanced discussion on the relationship between a chosen paradigm and a respective strategy and this relationship was at the core of various strategic considerations for the researcher. “Research is often multi-purpose and a ‘what works’ tactic will allow the researcher to address questions that do not sit comfortably within a wholly quantitative or qualitative approach to design and methodology” (p.3)”.

Defining VR learning ecosystem through cross-analysis of existing pedagogic and instructional frameworks, technological characteristics and affordances of VR space

Stage 1 involved three steps:

1) The first step involves constructing a VR learning ecosystem by considering literature in two broader but relevant domains – pedagogic and technological. In order to construct a VR learning ecosystem an extensive literature analysis and practical case analysis is carried out.

2) The second step consists of drawing a comparison through cross-analysis of the established learning theories and approaches of the Twentieth and Twenty-first centuries. Aspects and attributes that are fully or partially applicable to the process of learning in VR are shown in Table 1. The following pedagogic theories and approaches are analysed: Behaviourism, Cognitivism, Constructivism, Generative learning, Problem-based learning, Activity theory, Significant learning, Constructionism, Connectivism, Situated learning, Experiential learning, and Learning as a Network (LaaN) theory.

Table 1

Cross-analysis of the learning theories and approaches of the 20th and 21st century (Researcher's developed concept)

	20th century learning theories			**21st Century learning theories**
Theory / approach	**Behaviourism** TEACHING →	**Cognitivism**	**Constructivism** LEARNING	**Connectivism**
Theorists	I. Pavlov, E.Thorndike, B.F. Skinner	D. Merril, R.Gagne, J.Bruner	L. Vygotsky, A. Bandura, J. Piaget, J. Dewey, S.Papert, M.C.Wittrock, L.D.Fink D.H.Jonassen	Y.Engestrom, G.Siemens, S.Downes, J.Lave, D.A.Kolb, M.A.Chatti
Related approaches / theories	Cognitive Behaviourism	Instructional Theory	Constructionism Generative learning approach; problem-based learning (reflection, scaffolding); Significant learning – authentic experiential activity theory experiences + reflection, self-assessment	Situated Learning / Experiential learning, Active learning and learning-by-doing (such as role-play), scaffolded, collaborative learning, Learning as a Network (LaaN) theory, actor-network theory, gamification
Learner's role	Passive – reactive	Reactive	Active	Proactive
Main assumption	Correct instructional stimuli will elicit the desired learning outcomes, with an emphasis on practice and performance	Focus on understanding of mental processes; mind as an information processor	Student centred view the learner as an active participant in their own learning process and the teacher as a facilitator; learning occurs as a result of active engagement or experience in a social context; importance of social context in which the learning occurs	Knowledge and learning are today defined by connections; learning as a connection/network-forming process; the half-life of knowledge is shrinking; learning consists of the ability to construct and traverse networks; understands learning as a socially constructed process where learners interact in pursuit of a shared goal; the connections that enable us to learn are more important than our current state of knowing

			importance of interaction, communication, and experience; assistance of a more capable peer, scaffolding	Knowledge networks, fluidity, some learning environments with no spatial and time restrictions, collective value creation, exchange of knowledge and virtual co-construction
Types of learning facilitated	Task-based	Reasoning, problem-solving	Social, hands-on, contextual	Creation of knowledge through connection creating, creating collective knowledge, leveraging internal and external knowledge networks
How the learning environment is viewed	Design of learning environment as potential facilitator of learning	Learning environment is constructed as a projection of internal mental processes (schema)	Authenticity of learning environment Contextual learning Technology enhanced	Learning environment is fundamental and can be also viewed in multiple ways – internal, external, artefacts, groups of people, information, technology and activities.

3) The third step involves highlighting those aspects of the VR learning ecosystem that fit with the key aspects of each of the pedagogic and instructional design theory frameworks (see Table 2). This table maps out some of the aspects of the VR learning ecosystem that fit with the key facets of each of the learning frameworks set out in Table 1.

Table 2
Relation to learning in VR
(Researcher's developed concept)

Aspects of VR learning ecosystem that fit with the key facets of each of the learning frameworks			
BEHAVIOURISM	**COGNITIVISM**	**CONSTRUCTIVISM**	**CONNECTIVISM**
1. Stimuli are effective in controlling learning outcomes and learner behaviour – VR environment stimuli to guide learner through experience and potentially impact ones behaviour and values	1. Internalising knowledge construction - shift from teaching to learning 2. Emphasis on knowledge deconstruction / architecture – cognitive processes, knowledge dimensions	1. Authentic experiential experiences – learning environment becomes paramount 2. Personal interpretation and knowledge representation	1. Collective intelligence 2. Enabling internal and external knowledge networks of a learner in order to facilitate new knowledge building or constructing new

2. Focus on stimulation of learners' attention through reinforcement – stimulation of learner's attention is quintessential to VR learning 3. Achieving learning outcomes by stimulating learner engagement through presenting the correct stimuli 4. Thorndike and. Skinner – (the law of effect, Operant conditioning) Selective reinforcement – positive / negative response in VR learning environment (or avatars) 5. Thorndike and Skinner – learner must play an active role in order to acquire knowledge 6. Thorndike and Skinner – learners learn by doing – trial and error – VR presents a safe and engaging space for practical training 7. Evaluation of behaviour to measure learning progress and objectives – VR learning provides an opportunity to evaluate natural human interaction with artefacts and other humans, thus it is possible to evaluate not only separate forms of behaviour (e.g. writing, talking, movement), but rather enable to evaluate wholesome behaviour aspects – decisions,	3. Learning is change in cognitive processes and knowledge dimensions 4. Importance of differentiating short-term and long-term memory 5. By applying correct stimulus learner can be engaged in cognitive processes of different complexity in order to facilitate learning 6. Replicating mental models when constructing a learning experience 7. Organising new knowledge as 'related' to already existing	3. Learning in and from context 4. Reflection, self-assessment 5. Learning process is self-directed, experiment and discovery driven 6. Learning is facilitated and enabled by VR space 7. Online collaboration – VR artefacts (Vygotsky tools) 8. Sense of self (embodiment) (Bandura) – avatar persona 9. Sense of self-efficacy – engagement in VR learning through experimentation, engagement with other avatars, co-creation 10. Guidance (Vygotsky Zone of Proximal Development) 11. VR learning space and artefacts within shape cultural conditions of learning 12. Play as a significant element of learning, which also ensures learner engagement	meaning to existing knowledge 3. Shift of emphasis from knowing to ability to navigate through knowledge networks 4. Ability to incorporate and interpret new knowledge 5. Fluidity of self across the different networks 6. Personal knowledge network 7. Internal and external knowledge nodes 8. Networks of knowledge and applications

reaction time and collaboration		13. Importance of transfer and prior knowledge	

In addition, a literature review has been undertaken to define the aspects that are unique to the VR learning ecosystem and are not covered by the existing theoretical frameworks, (see Table 3).

When looking at VR learning ecosystems it becomes clear that VR as a learning environment presents a variety of distinctive characteristics and understanding what potentially can be done in 3D VR space means coming a step closer to fully recognising the uniqueness of this environment and successfully leveraging its affordances for learning purposes.

One of the key difficulties of VR learning research is clarity of the terminology used as, depending on the researcher's perspective and field of expertise (for instance field of immersive technology, pedagogy or instructional design), terms are often used interchangeably, sometimes conflicting or overlapping. Furthermore, in the researcher's view, it is important to establish clarity on the difference between levels of 3D VR space characteristics and the most pivotal terms, as some authors describe VR space on a macro-structural level, while other authors list micro-elements of VR space, without the needed cohesion between the two. A more detailed review of the literature on VR learning, including proposed terminology and hierarchy of terms can be found in Chapter I.

Table 3
Unique aspects of VR environment
(Researcher's developed concept)

<table>
<tr><th colspan="4">Single-user virtual environment</th></tr>
<tr><th>Aspect</th><th>Authors</th><th>Aspect</th><th>Authors</th></tr>
<tr><td>Immersion</td><td>Hedberg and Alexander (1994)</td><td>Presence</td><td rowspan="3">Whitelock, Brna and Holland (1996)</td></tr>
<tr><td>Fidelity</td><td>Hedberg and Alexander (1994)</td><td>Representational Fidelity</td></tr>
<tr><td>Active learner participation</td><td>Hedberg and Alexander (1994)</td><td>Immediacy of control</td></tr>
<tr><th colspan="4">Multi-user virtual environment (MUVEs)</th></tr>
<tr><th colspan="2">Aspect</th><th colspan="2">Author</th></tr>
<tr><td colspan="2">Social fidelity (social familiarity, social reality)</td><td colspan="2" rowspan="3">Brna (1999)</td></tr>
<tr><td colspan="2">Immediacy of discourse</td></tr>
<tr><td colspan="2">Social presence / co-presence</td></tr>
</table>

Table 3 identifies the terms used by Hedberg and Alexander (1994), Whitelock, Brna and Holland (1996) and Brna (1999). Immersion and presence are the same as fidelity and representational fidelity, but active learner participation and immediacy of control are used interchangeably. Hedberg and Alexander (1994), Whitelock, Brna and Holland (1996) also do not separate the characteristics of single-user and multi-user 3D VLE but rather view them together as characteristics of 3D VLE. Thus, the researcher also included a more detailed view on multi-user VLE characteristics presented by Brna (1999).

Looking beyond the clarification of similar terms and towards establishing a somewhat hierarchical frame of terms concerning 3D VLE, Dalgarno and Lee (2010) rejected the idea of immersion, presence, co-presence and identity construction being unique properties in their own right, but rather viewed them as a result of representational fidelity and learner interaction in the VR environment. When differentiating between the two main characteristics, there is a clear distinction between the physical perception (representational fidelity) and embodied actions (learner interaction) including control of environments and interaction.

For the purposes of this research, the hierarchy of the unique characteristics of VR space proposed by Dalgarno and Lee (2010) has been adopted. Thus the VR learning ecosystem in the context of the research from the technological characteristics perspective is made up of the core – representational fidelity and variety of learner interaction modes which in turn can result in the learner's sense of immersion, presence, co-presence and aid identity construction, embodiment, projection and perception. Furthermore, the results of interaction (immersion, presence, co-presence and identity construction) in VR experience are dependent not only on VR environment and these unique characteristics, but also on the learner's state of mind (Figure 10).

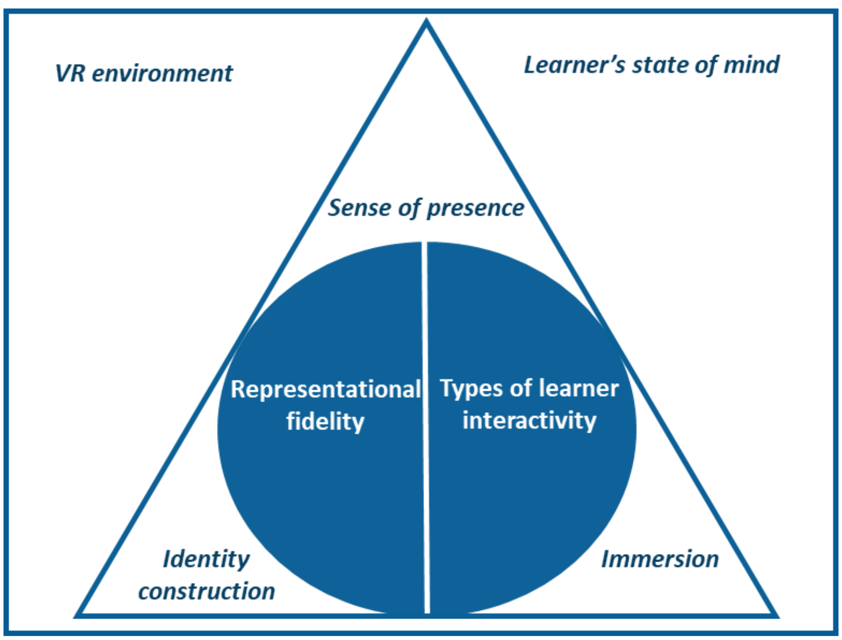


Figure 10
The technological perspective of VR learning ecosystem
Researcher's concept (adopted from findings of Dalgarno and Lee, 2010)

Once the main terms of 3D VLE environment characteristics are established, in the researcher's view it is important to highlight those technical characteristics that foster the unique learning environment characteristics (representational fidelity and learner interaction) for both single and multi-user VR learning experiences. Much research is available on the technical potential and characteristics of VR space; however, as highlighted earlier in this sub-section, the vocabulary and focus varies greatly depending on the primary research object and authors' perspectives.

After considering various authors' perspectives (Hedberg, Alexander, 1994; Whitelock, Brna, Holland, 1996'; Brna, 1999; Dickey, 2002; Dalgarno, Lee, 2010) and proposed terminology, the researcher has centred on the terminology presented by Dalgarno and Lee (2010). Although the adopted perspective was published in 2010, it is still concrete and accurate enough, as it was defined through an education research perspective and it presents a level of detail that is 'just-right' for applications in the subfield of VR learning. More technological possibilities have layered onto those which were proposed in 2010; for instance the recent developments in cognitive learning analytics and haptic gloves and haptic suits with hyper-fine feedback haptics including such technologies as HaptX and Teslasuit. However, in the researcher's view those have successfully layered into the proposed categories of technical characteristics.

Table 4
Unique characteristics of VR environment
(Researcher's developed concept, adopted from Dalgarno and Lee, 2010)

Unique characteristics of VR environment	**Technical characteristics that distinguish such environments**	Authors
Representational Fidelity	1. Realistic display of the environment, smooth display of view changes and object motion. 2. Display of objects using realistic perspective occlusion, realistic texture and lighting. 3. Object behaviours, including response to user actions and their autonomous (or modelled) behaviours. User representation (avatar). 4. Kinaesthetic and tactile feedback (haptics). 5. 3-D audio.	Dalgarno, Lee, 2010; Dickey, 2002.
Learner interaction	1. Embodied actions, including view control, navigation and object manipulation. 2. Embodied verbal and non-verbal communication. 3. Control of the environment attributes and behaviour. 4. Construction of objects, including scripting object behaviours.	
Social fidelity (social familiarity, social reality)		
Immediacy of discourse		
Social presence / co-presence		

In the researcher's view a clearer approach to VR experience typology is needed, thus six categories have been proposed defined by differentiating the learner interaction mode. The researcher has attempted to appropriate the terms familiar to pedagogic framework, as in her view these modes are still actual in various technological settings and present a more approachable rendition of terminology used in VR learning discourse rather than using new technology specific terms. The goal is to keep the focus of the current discussion on the pedagogic principles for the applications of VR for learning and not the other way round. Thus, the researcher believes that, by using the educational vocabulary in VR learning research, it will aid the transfer of knowledge into practice and more importantly ensure the healthy balance of attention between the technological fascination and correct pedagogic applications. Table 5 presents a cross-view of Dalgarno and Lee's (2010) learning affordances of 3D VR space, Kapp and O'Driscoll's (2010) instructional strategies for VR, and types of VR learning experiences proposed by the researcher in order to create a connective link between the more technical characteristics and the instructional approaches. More detailed information on the process of development of the proposed typology is presented in the sections on Macro Criteria and (Mezzo) Criteria, as well as Data Collection Procedures.

Table 5
Three dimensions of VR learning environment – environment, experience, strategy
(Researcher' developed concept, adopted from Dalgarno and Lee (2010), Kapp and O'Driscoll (2010))

Technological →		← **Instructional**
Dalgarno, Lee, 2010	**Dreimane, 2019**	**Kapp, O'Driscoll, 2010**
Affordances of 3-D VR environment	**Types of VR experiences**	**Instructional strategies for VR learning**
1. Spatial knowledge representation 2. Experiential learning 3. Engagement 4. Contextual learning 5. Collaborative learning	1. Activity 2. Lesson 3. Experience 4. Interactive simulation 5. Experience + activity 6. Experience + lesson 7. Immersive virtual world	1. Avatar Persona 2. Role Play 3. Scavenger Hunt 4. Guided Tour 5. Operational Application 6. Conceptual Orienteering 7. Critical Incident 8. Co-Creation 9. Small Group Work 10. Group Forums 11. Social Networking

Development of a Virtual Reality learning experience evaluation tool

Based on the Literature Review and extensive VR learning content testing, an evaluation tool was devised. Stage 2 of the research design includes the development of a qualitative analysis tool for evaluating VR learning experiences.

The proposed VR experience evaluation tool was essentially developed to serve as a purposeful quality control or a design development instrument that would inform instructional designers, educators, learners and VR content and technology professionals by providing a clear and multi-purpose framework that outlined the alignment between the instructional, pedagogical and VR learning environment in order to ensure and strengthen the efficiency of the VR learning design and instructional strategies.

The VR learning experience evaluation tool was developed and improved through an analysis of 130 VR learning experience designs and then drawing from similar characteristics of the learning environments and strategies applied in VR, thus establishing broader criteria for the creation and application of VR learning experiences. This tool has been further developed through rigorous approbation and modifications for variant use. Framework of the evaluation tool was drafted before the evaluation process was started. The evaluation tool was applied for each of the VR learning experiences and additional notes were collected if there were any additional features, elements, definition discrepancies or insufficiencies. Next, when the evaluation of the entire selection of the chosen thirty-two learning experiences (out of 130 different VR learning experiences) was completed, the evaluation tool was further modified by consolidating and restructuring several criteria, as well as clarifying the wording of the criteria and sub- criteria. Finally, small detailed improvements were added for criteria definitions, including standardization of criteria and sub-criteria definitions (consistency) as part of the development process for the scientific publication where the evaluation tool was presented.

The evaluation tool included three macro-criteria, twenty one criteria, and eighty-eight sub-criteria. A compact schema for the framework of the evaluation tool is provided in Figure 11. A complete design of the evaluation tool can be found in Appendix 1 “Evaluation tool”.

The VR learning experience evaluation tool aims to offer a ready-to-use and adaptable instrument for instructional designers, educators, VR technology developers and potential learners. It aims to highlight the pivotal aspects that should be considered by instructors and educators who wish to successfully design and/or apply VR learning experiences. As part of this research, a printable template was developed by the researcher for designing or analysing VR learning experiences and is available for re-prints via link: qrco.de/VRtool or QR code:

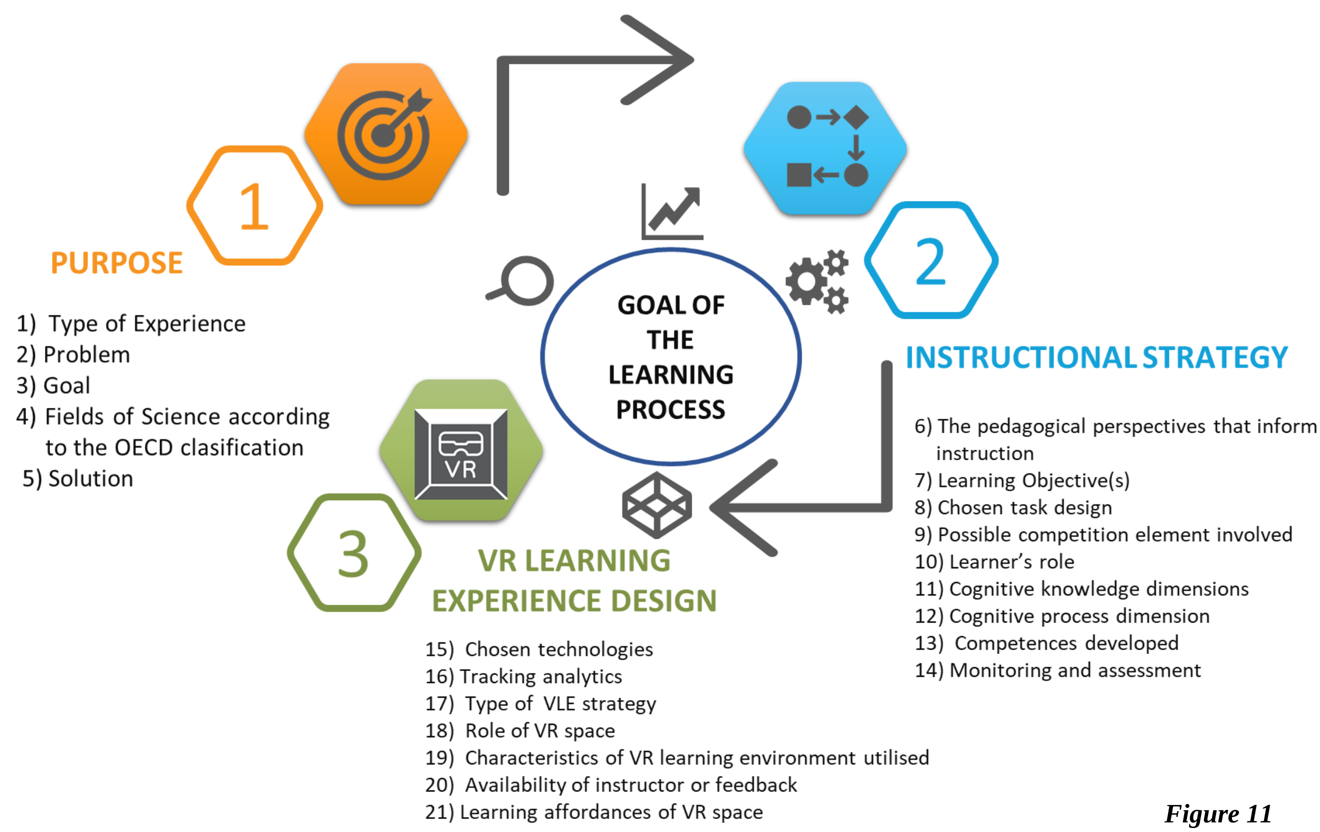


Figure 11
Framework of the Evaluation tool
Researcher's concept

Macro criteria

The first macro-criterion is labelled as 'Purpose' which includes five mezzo-level criteria (Table 6:

1) Type of Experience
2) Problem
3) Goal
4) Field (s) of Science according to Frascati Manual 2015 classification (OECD, 2015)
5) Solution

Table 6
The first macro criterion 'Purpose'
(Researcher's developed concept)

<table>
<tr><th>Macro-criterion</th><th colspan="2">Criterion</th><th colspan="7">Sub-criteria</th></tr>
<tr><td rowspan="9">1. Purpose</td><td colspan="2">1) Type of Experience</td><td>Activity</td><td>Lesson</td><td>Experience</td><td>Interactive simulation</td><td>Experience + activity</td><td>Experience + lesson</td><td>Immersive virtual world</td></tr>
<tr><td colspan="2">2) Problem</td><td colspan="7">Learning problem that has to be addressed</td></tr>
<tr><td colspan="2" rowspan="3">3) Goal</td><td colspan="7">Single</td></tr>
<tr><td colspan="7">Multiple / interdisciplinary</td></tr>
<tr><td colspan="7">Adjustable</td></tr>
<tr><td rowspan="3">4) Fields of Science according to the OECD classification</td><td rowspan="3">(Primary FOS / if applicable secondary or interdisciplinary)</td><td>1. Natural Sciences</td><td colspan="2">2.Engineering and Technology</td><td>3.Medical and Health Sciences</td><td>4. Agricultural Sciences</td><td>5. Social Sciences</td><td>6.Humanities</td></tr>
<tr><td colspan="7">Primary FOS[1]</td></tr>
<tr><td colspan="7">Secondary FOS[2]</td></tr>
<tr><td colspan="2">5) Solution</td><td colspan="7">Presented learning solution</td></tr>
</table>

The second-macro criterion proposes nine mezzo-level 'Instructional Strategy' criteria (Table 7):

1. What are the pedagogical perspectives that inform instruction?
2. Learning Objective(s)
3. Chosen task design
4. Possible competition element involved
5. Learner's role
6. Cognitive knowledge dimensions
7. Cognitive process dimensions
8. Competences developed
9. Monitoring and assessment

[1] Field (s) of Science according to Frascati Manual 2015 classification (OECD, 2015)
[2] Field (s) of Science according to Frascati Manual 2015 classification (OECD, 2015)

Table 7
The second macro criterion 'Instructional Strategy'
(Researcher's developed concept)

Macro-criterion	Criterion		Sub-criteria	
2. Instructional Strategy	6) What are the pedagogical perspectives that inform instruction?		Single	
			Multiple	
			Mixed	
			Behaviourism	
			Cognitivism	
			Constructivism	
			Connectivism	
	7) Learning Objective(s)		Single	
			Multiple	
	8) Chosen task design		Sequential	Interrelated
	9) Possible competition element involved		Individual	Ranking
			Team	Time-count Score
			Adjustable	Other
	10) Learner's role		Passive explorer – learner absorbs the experience, yet has no additional control over the environment in the speed or mode of interaction	
			Reactive – learner is actively responding and interacting with the learning environment	
			Proactive – learner drives and controls the learning environment	
	11) Cognitive knowledge dimensions		Factual	
			Conceptual	
			Procedural	
			Meta-cognitive	
	12) Cognitive process dimension		Remember	
			Understand	
			Apply	
			Analyse	
			Evaluate	
			Create	
	13) Competences developed	Knowledge	Disciplinary knowledge	
			Interdisciplinary knowledge	
			Practical knowledge	
			Cognitive and meta-cognitive skills	

		Skills developed	Social and emotional
			Physical and practical skills
		Attitudes and values	Attitudes and values
	14) Monitoring and assessment		Learner is assessed in real-time (wright or wrong signals, score, points, levels, number of errors, completion time, other real time metrics)
			Learner is assessed after completing several sessions
			Self-assessment
			No assessment is incorporated into the experience

The third-macro criterion proposes six mezzo-level criteria for evaluating VR learning experience designs (Table 8):

1) Chosen technologies
2) Tracking analytics (e.g. attention, eye-movement, facial expressions including electro-encephalogram which detects electrical activity of the brain (EEG), electro-cardiogram which measures electrical activity of the heart (ECG) - electro-dermal activity which detects skin response to emotional stimuli (EDA) and electro-myography which detects facial muscle movement (EMG)).
3) Type of VR learning experience
4) Role of VR space (including artefacts within the space) in achieving learning objectives
5) Characteristics of VR learning environment utilised
6) Availability of instructor or feedback

Table 8
The third macro criterion 'VR learning experience design'
(Researcher's developed concept)

Macro-criterion	Criterion	Sub-criteria
3. VR learning experience design	15) Chosen technologies	High compatibility (numerous headsets devices / platforms)
		Low compatibility
		Web VR friendly
		VR / AR / MR mode
	16) Tracking analytics (e.g. attention, eye-movement, facial	Engagement, interaction
		Eye-tracking, view-point monitoring
		Sensory tracking (facial expressions, EEG, ECG, EMG, EDA)
		Haptic interaction

	expressions, EEG, ECG, EMG, EDA)[3]	
	17) Type of VLE strategy	Individual
		Group
		Adjustable (1 real-time; 2. multi-user; 3.synchronous)
		Avatar persona
		Role play
		Scavenger hunt
		Guided tour
		Operational application
		Conceptual orienteering
		Critical incident
		Co-creation
		Small group work
		Group forums
		Social networking
	18) Role of VR space (including artefacts within the space) in achieving learning objectives	Primary significance – learning occurs from interaction with the space
		Important – not a primary driver of learning experience, yet important in conveying contextual knowledge and cues
		Supportive / entertaining
	19) Characteristics of VR learning environment utilised	Representational fidelity
		Learner interaction
		Social fidelity (including social familiarity and social reality)
		Social presence
		Immediacy of discourse
	20) Availability of instructor or feedback	Yes
		No
		Correct / incorrect guide, success rate, progress
		Test, quiz
	21) Learning affordances of VR space	Spatial knowledge representation
		Experiential learning
		Engagement
		Contextual learning
		Collaborative learning

[3] EEG (electroencephalogram) – detects electrical activity of the brain; ECG (electrocardiogram) – measures electrical activity of the heart; EDA (electrodermal activity) – detects skin response to emotional stimuli; EMG (electromyography) – detects facial muscle movement.

(Mezzo) Criteria

Types of VR learning experiences

In order to approach learning in VR, either as an educator, designer or a learner, it is important to understand the potential for learning and diversity of facets that a virtual environment allows.

The first criterion suggests the typology of VR learning experiences. These typologies were developed through analysing 130 VR learning experience designs and drawing similar characteristics of learning environments and strategies applied in VR, thus establishing broader types of VR learning experiences. The researcher suggests seven broader types of learning experiences:

1) Activity
2) Lesson
3) Experience
4) Interactive simulation
5) Experience + activity
6) Experience + lesson
7) Immersive virtual world

Five of the established types are distinct in their nature: activity, lesson, experience, interactive simulation and immersive virtual world, while the other two present a combination of two (and potentially can combine more of the initial five): experience + activity, experience + lesson.

These types have been proposed based on current technology and learning needs but this only means one thing – these types will evolve hand-in-hand with the development of VR technologies and the ever-evolving labour-market appetite for knowledgeable and skilled professionals. When defining these typologies, it must be emphasised that these types can be combined and fused with one, or several elements, of the prevailing types. Nevertheless, in order to fully leverage the potential of these VR learning experience typologies, it is important to recognise their individual characteristics and in-built toolkits for the learning designers, educators and learners.

Thus, the type ‘Activity’ implies a practical engagement with virtual content, yet does not necessarily support any contextual conditions of action and often does not include instruction, thus this is best used when prior knowledge is already acquired and can be used to construct new knowledge nodes, or if a student requires a learning environment for practice or collaboration; for example – VR experience Xennial – Skeleton assembly, Engine Assembly.

‘Lesson’ implies a virtual lecture either involving a human or a non-human avatar, or a voice recorded instruction with visual imagery and other forms of visual and audio examples, yet the student has no free-form interaction with content; thus this type best provides the introductory instructional guided learning opportunities. See screenshots of examples of this type in Appendix 2 “Exploring Venus by Oxford University” and the VR learning experience which is not included in this section for a full analysis – “A study of the American Revolution War”.

In contrast, the typology labelled as ‘Experience’ suggests a virtual environment which provides learning opportunities from the experience itself. This can include a diverse range of visual, textual, audio, haptic and cognitive cues, yet it involves very limited or no operational interaction or practical activity within the virtual environment. This type serves a broad range of purpose and cognitive dimension that can be tailored and tuned to specific needs. This also allows an experiential and creative discovery learning process to take place which fosters non-linear knowledge construction. See screen shots of examples for this type in Appendix 2 – “Explore the International Space Station”.

‘Interactive simulation’ was defined as a separate typology in order to emphasise the physical attributes assigned to the virtual environment. The principles of the experiential learning and constructionism are applicable and knowledge construction and skill development can occur involuntarily in VR simulations as a result of the deeply immersive nature of the technology, yet the core purpose of this learning experience design is to provide a safe environment in which to practise skills and competences, as well as to gain an understanding of an environment, concept or a situation in certain pre-defined conditions. See screen shots of examples for this type in Appendix 2: “Lab safety simulation (Labster)”, “Surgera VR”, “Trauma simulator by Exonicus”, “Xennial – Pig Dissection”, “Xennial – Chemistry reactions”, “Virtual Speech (Public Speaking)”, “Mondly: Learn Languages in VR”.

‘Immersive virtual world’ stands out from other types because of its open nature for interaction and the learning process. This type should be viewed rather as a platform for contextual, collaborative and creative learning opportunities, than a specific pre-determined learning experience. The main strengths of learning experiences created in immersive virtual world environments lie in multi-user interaction and networking (social fidelity and social familiarity) and they present limitless opportunities for collaborative and complex learning (social constructivism including Connectivism, Generative learning). Two larger immersive virtual world platforms that present social VR experiences, which are both owned by Linden Labs, are Second Life and Sansar. Although Second Life was launched seventeen years ago and is only desktop-based VR, it still presents a great platform including an abundant pre-sets library for educators. For a more current ‘take’ on social VR experience creation, Sansar is an immersive platform, which is also compatible across desktops and various headsets to interact with various communities across the world and is capable of holding several virtual events monthly. See screen shots of examples for this type in Appendix 2 - “Second Life-Syrinx Viking Village[4]”.

The final two types are combined – ‘Experience + activity’ and ‘Experience + lesson’. These are more characteristic for complex topics and unique experiences (For example - Mars Rover and the

[4] Second Life “Syrinx – Viking Village” (https://secondlife.com/destination/syrinx; https://maps.secondlife.com/secondlife/Syrinx/197/91/22)

Large Hadron Collider) where the learning experience designer's goal is to introduce a unique environment, and it is also supported by instruction (verbal or non-verbal) which implies 'Experience + lesson'. See screen shots in Appendix 2: "Xennial - Fungi World", "Unimersiv "A Journey into the Brain". Furthermore, an alternative is to follow up the experience with learner engaging and interacting with the newly introduced environment, results in the 'Experience + activity' type. See screen shots of examples for this type in Appendix 2 - "Trauma simulator by Exonicus" (learning mode).

Problem

This criterion identifies learning problems that have to be addressed as defined from the standpoint of instructional designers and educators. The reason for including such an open-ended strategic criterion is that, in order to create an effective learning experience, an educator or a designer must first clearly identify and define the reasons for using VR as the medium in order to be able to further choose the correct strategy and methods.

Goal

Although VR learning environments sometimes encounter criticism for lacking flexibility in terms of their purpose applications, this criterion seeks to identify whether the experiences are aimed at achieving a single, or multiple, goal(s) or whether it allows for the educator or learner to adjust and choose either one specific, or multiple, goal(s) to be achieved.

Fields of Science according to the OECD classification[5]

This criterion aims to identify in which fields of science the virtual learning experience can be applied. Sometimes the experience, largely depending on its type, will be applicable in only one field (for instance medical simulation) and sometimes it will present knowledge and experiences

[5] https://www.oecd-ilibrary.org/docserver/9789264239012-en.pdf?expires=1578168008&id=id&accname=guest&checksum=CDC3DA234A8B46AF8A4D4F6D32D37B3D (page 59)

that cross multiple fields of science. For example the “Explore the International Space Station” and the “Malaysian Cats Conservation by Oxford University” experiences, where the values and knowledge presented aim to build a broader understanding of the value of knowledge and natural conservation and thus shape the attitudes of a learner which can further be applied in a variety of fields.

Solution

This open-ended criterion aims to define the solutions provided by utilising the VR learning environment. This allows the instructional designers and educators to either design or evaluate the focal strategy or learning activity which is at the centre of the VR learning experience.

What are the pedagogical perspectives that inform instruction?

This criterion aims to identify the pedagogical frameworks that inform the design of instructional strategy and is in two parts – whether there is a single, multiple or mixed perspectives involved and then identifies which of the main Twentieth Century perspectives are in action: Behaviourism, Cognitivism, Constructivism or Connectivism (or a mixture)

Learning Objectives

As with any design, it is important to clearly set out the objectives to be achieved. Thus, this criterion looks more deeply into the instructional domain and aims to identify whether one or multiple learning objectives can be achieved.

Chosen task design

This criterion is concerned with the chosen task design. VR space allows for a broad variety of interaction modes and designs; however, in order to achieve the goals and learning objectives set out, an instructional alignment is crucial. Therefore, this criterion explains whether the chosen task design is sequential or interrelated.

Is there a competition element involved?

This criterion identifies whether there is a competition element involved in instructional strategy. It consists of three pairs: 1) individual or team; 2) ranking / score or time-count, and 3) adjustable or other (for example quiz to get to the next room or level).

Learner's role

This criterion looks further into the pedagogic and instructional domains as it is concerned with the role of the learner and analyses how instructional strategy supports, facilitates and utilises that role. The criterion proposes three sub-criteria:

1) Passive explorer – the learner absorbs the experience, yet has no additional control over the environment in the speed or mode of interaction;

2) Re-active – the learner is actively responding and interacting with the learning environment; and

3) Proactive – the learner drives and controls the learning environment.

Cognitive knowledge dimensions

This criterion is based on the taxonomy of educational objectives presented by Bloom (1956) and Anderson and Krathwohl‘s revision (2001) of Bloom's taxonomy. Bloom (1956) identified four cognitive knowledge dimensions: 1) Factual, 2) Conceptual, 3) Procedural, and 4) Meta-cognitive. These categories represent a range of cognitive knowledge types from concrete (factual knowledge) to more abstract (meta-cognitive knowledge). In turn, conceptual and procedural dimensions might overlap as some procedural knowledge could be more practical and concrete while others are more abstract and conceptual (Anderson et al., 2001).

Cognitive knowledge dimensions are defined by Anderson and Krathwohl as:

A. Factual knowledge – "the basic elements students must know to be acquainted with a discipline or solve a problem in it" (terminology, specific details and elements)
B. Conceptual knowledge – "the interrelationships among the basic elements within a larger structure that enable them to function together" (classifications, categories, principles and generalisations, theories, models and structures)
C. Procedural knowledge – "how to do something, methods of inquiry, and criteria for using skills, algorithms, techniques, and methods" (subject specific skills and algorithms, subject specific methods and techniques, criteria for determining when to use appropriate procedures)
D. Meta-cognitive knowledge – "knowledge of cognition in general as well as awareness and knowledge of one's own cognition" (strategic knowledge, cognitive tasks including appropriate contextual and conditional knowledge, self-knowledge) (2001, p.29).

Cognitive process dimension

This criterion is based on a taxonomy of educational objectives presented by Bloom (1956) and Anderson and Krathwohl's revision of Bloom's taxonomy (2001). Anderson and Krathwohl identified six cognitive process dimensions: 1) Remember, 2) Understand, 3) Apply, 4) Analyse, 5) Evaluate, 6) Create.

Cognitive process dimensions are defined by Anderson and Krathwohl as:

1) Remember – "Retrieve relevant knowledge from long-term memory"

2) Understand – "Construct meaning from instructional messages, including oral, written, and graphic communication"

3) Apply – "Carry out or use a procedure in a given situation"

4) Analyse – "Break material into its constituent parts and determine how the parts relate to one another and to an overall structure or purpose"

5) Evaluate – "Make judgements based on criteria and standards"

6) Create – "Put elements together to form coherent or functional whole' reorganize elements into a new pattern or structure" (2010, p. 31).

Competences developed

This criterion is concerned with competences and sub-divides those into knowledge and skills as well as attitudes and values. The sub-criteria further identify: 1) Disciplinary knowledge, 2) Inter-disciplinary knowledge, 3) Practical knowledge, 4) Cognitive and meta-cognitive skills, 5) Social and emotional skills, 6) Physical and practical skills, and 7) Attitudes and values.

Monitoring and assessment

This criterion aims to identify the mode of built-in monitoring and assessment. There are three sub-criteria

1) The learner is assessed in real-time (right or wrong signals, score, points, levels, number of errors, completion time, other real time metrics);

2) The learner is assessed after completing several sessions; and

3) Self-assessment.

Chosen technologies

This criterion identifies the chosen VR technologies and technological aspects, such as high compatibility (including a wide range of headsets, devices and platforms) or low compatibility, (also Web VR friendly or VR / AR / MR modes)

Tracking analytics (xAPI[6], other)

This criterion aims to analyse the involvement of experience tracking and analytics, such as engagement, interaction (facial expression, xAPI), eye-tracking or viewpoint monitoring, sensory tracking such as electro-encephalograms which detect electrical activity of the brain (EEG) and electro-cardiogram which measures electrical activity of the heart (ECG), electro-dermal activity which detects skin response to emotional stimuli (EDA) and electro-myography which detects facial muscle movement (EMG)) and haptic interaction (haptic response speed and intensity).

Type of VR learning experience

This criterion considers the eleven VR learning archetypes defined by Kapp and O'Driscoll (2010), (see Figure 6)

Role of VR space (including artefacts within the space) in achieving learning objectives

This criterion is concerned with analysing the role of VR space in facilitating learning strategy. It has three sub-criteria:
1) Primary significance – learning occurs from interaction with the space;
2) Important – not a primary driver of learning experience, yet important in conveying contextual knowledge and cues; and
3) Supportive or entertaining.

Characteristics of VR learning environment utilised

This criterion is based on characteristics or affordances of 3D virtual environments identified by Dalgarno and Lee (2010) and these include Fidelity of representation and types of interactivity that lead to a sense of presence: 1) representational fidelity, 2) social fidelity' (including social

[6] https://xapi.com/overview/

familiarity and social reality), 3) increased 'immersion' increased 'fidelity', 4) presence, 5) social presence, 6) real-time interaction, 7) immediacy of control, and 8) active learner participation immediacy of discourse.

Availability of instructor or feedback

This criterion considers the built-in options of instructional support or feedback, including avatar lecturers and voice guides that allow for the scaffolding method to be utilised and offering the potential for generating feedback such as correct or incorrect guides, success rates and progress monitoring of the learner as well as tests and quizzes.

Learning affordances of VR space

This criterion is devised from Dalgarno and Lee's proposed affordances of 3D learning environment (2010), is also shown in Table 5 and evaluates the correspondence of each VR learning experience to one or multiple affordances. The five affordances are: 1. Spatial knowledge representation; 2. Experiential learning; 3. Engagement; 4. Contextual learning; and 5. Collaborative learning.

Data collection procedures and analysis

Using the devised evaluation tool, the thirty-two VR learning experiences included in the selection were evaluated in order to develop a substantive theory of taxonomy of learning in VR.

Stage 3 of the research design includes data collection procedures comprising of explorative evaluations of a set of thirty-two VR learning experiences followed by a quantitative and qualitative analysis of the evaluation data. This selection was made by choosing the VR learning content which, from an Instructional Design point of view, presents structured and purposeful learning experiences rather than artefacts and 3D models or tools that can be incorporated within a learning experience. The chosen VR learning experiences can be used as the primary learning method and medium, as well as being combined with other methods and forms. Other criteria for including these VR learning experiences in the analysis were ease of accessibility including open access or affordable low-priced subscription or trial options, as well as the diversity of learning goals and designs, fields of science, forms, cognitive complexity and content creators.

The explorative evaluations are based on selection of VR learning experiences and include the following VR learning experiences:

1. Exploring Venus by Oxford University (ENGAGE[7])
2. Mars Curiosity Rover (ENGAGE)
3. Skeleton assembly (ENGAGE)
4. “Life” medical care for a new-born infant by Oxford University[8] (ENGAGE)
5. Engine Assembly (ENGAGE)
6. Great White Sharks by Curioscope (ENGAGE)
7. Attenborough and the Giant dinosaur (ENGAGE)
8. The large Hadron Collider and the beginning of physics (ENGAGE)
9. Rocket launch Delta IV (ENGAGE)
10. Radiology 101 by Oxford University (ENGAGE)
11. Sharecare VR real-time simulation of the human body[9]
12. Malaysian Cats Conservation by Oxford University (ENGAGE)
13. Environmental CatAstrophy by Oxford University (ENGAGE)
14. Unimersiv[10] “A Journey into the Brain”
15. DINOS by Unimersiv
16. Explore the International Space Station by Unimersiv
17. Unimersiv “Stonehenge”
18. Unimersiv “International Space Station (Units)”
19. Lab safety simulation (Labster)[11]
20. Surgera VR[12]

[7] https://engagevr.io/ (free version available)
[8] About the learning experience: https://www.youtube.com/watch?v=l5Szr9A6ZQY
[9] https://www.sharecare.com/pages/vr (free)
[10] https://store.steampowered.com/search/?term=unimersiv (3,99 € licence)
[11] https://www.labster.com/vr/ (trial version available)
[12] https://store.steampowered.com/app/763860/Surgera_VR/ (free)

21. Titanic by Unimersiv
22. Ancient Rome by Unimersiv
23. Trauma simulator by Exonicus[13]
24. Xennial[14] - Doppler Effect (Train)
25. Xennial - Fungi World
26. Xennial – Pig Dissection
27. Xennial – Chemistry reactions
28. Xennial – Doppler Effect and Echolocation
29. Xennial - Electricity Physics: Circuits and Ohm's Law
30. Virtual Speech (Public Speaking course)[15]
31. Mondly: Learn Languages in VR[16]
32. Syrinx – Viking Village (Second Life)[17]

Evaluation was conducted over a period of three months. The author recorded all data after each virtual learning experience according to criteria defined in the evaluation tool. Video recordings of the virtual learning experiences were used to check for errors and to further analyse micro details, as well as compared with newer findings. Re-evaluation was conducted after all data was collected and recorded for two main reasons – to check for errors and to attune the denominations used in the evaluation tool and to better adapt it for practical use.

Evaluations were conducted based on researcher's expertise and experience and the results were interpreted from the point of view of an educator and a designer and thus are rooted in phenomenological approach. Eberle refers to phenomenology affirming that it aids in clarifying "what happens when we constitute empirical data by our practices of recollection, analysis and interpretation. Phenomenologists are always aware that they interpret on the basis of their own subjective experiences, and that a linguistic representation never really catches what was experienced" (Eberle in Flick, 2014, p. 9). More specifically, an approach to phenomenological

[13] https://store.steampowered.com/app/1169340/Trauma_Simulator/ (24,99 € licence)
[14] https://www.xennialdigital.com/xd-learning/ (free 30 day trial available)
[15] https://virtualspeech.com/courses/public-speaking (140 € licence includes 6 VR scenarios, 58 lessons) https://www.youtube.com/embed/xAb54ayW4lE?autoplay=1&rel=0&showinfo=0
[16] https://store.steampowered.com/app/1141930/Mondly_Learn_Languages_in_VR/ (6,59 € licence)
[17] Second Life "Syrinx – Viking Village" (https://secondlife.com/destination/syrinx; https://maps.secondlife.com/secondlife/Syrinx/197/91/22)

analysis 'life-world analytic ethnography' developed by Hitzler and Honer emphasizes the subjective experience of the researcher in the field which essentially is utilised (explicitly and reflexively) as a tool for collection and interpretation of data (Honer, 2004; Eberle in Flick, 2014).

Quantitative analysis of VR learning experience evaluation data:

In order to answer the Research Questions and to demonstrate purposeful application and the potential of the devised evaluation tool the researcher has conducted explorative evaluations of the thirty-two VR learning experiences.

The VR learning experience evaluation was conducted over a period of seven months (from November 2018 until May 2019) using a desktop computer for Web VR based experiences and professional VR equipment, including various headsets and platforms at the VR arcade "Portāls - Virtual Reality Arcade[18]" (Riga, Latvia) for an immersive VR experiences. The evaluation results were recorded by entering data into a digital template of the evaluation tool (discussed in Chapter II) directly after each VR learning experience was undertaken and then analysed by the researcher. The data were further standardised, clearing insufficiencies and adjusting them to the uniform format for further comparative analysis. The results were recorded in concurrence to the criteria fields and later transformed into numerical values and coded for quantitative analysis of the results. This section presents that quantitative analysis.

When devising the evaluation tool, the researcher established seven types of VR learning experiences. The results were calculated by adding up the number of frequencies for each of these seven types of learning experiences. Evaluation results show that the majority were identified as Experience + lesson type - ten experiences (31%) and interactive simulations – nine experiences (28%), and more detailed proportions of the selection are presented in Figure 12.

[18] https://portalsvr.lv/english-1; located: Tērbatas street 55, Riga, Latvia, LV-1001

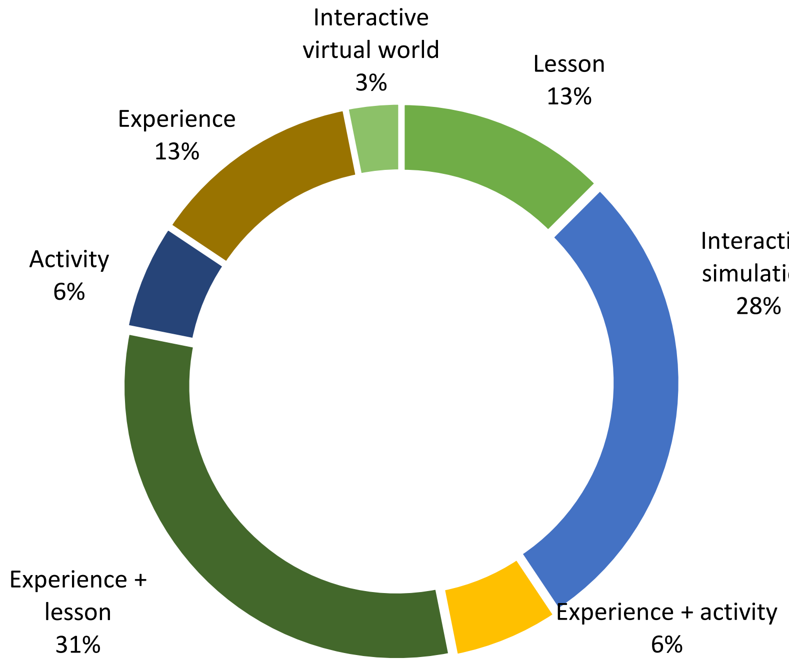


Figure 12
Types of VR learning experiences

The next criterion allowed for the analysis of the potential of VR learning experience in terms of the learning goals or goals' flexibility, (see Figure 13). Evaluations present evidence of high fluidity in the applications of the VR learning experiences which also deliver a counter-balance to the criticism VR often receives for being an excessively costly and time-consuming endeavour.

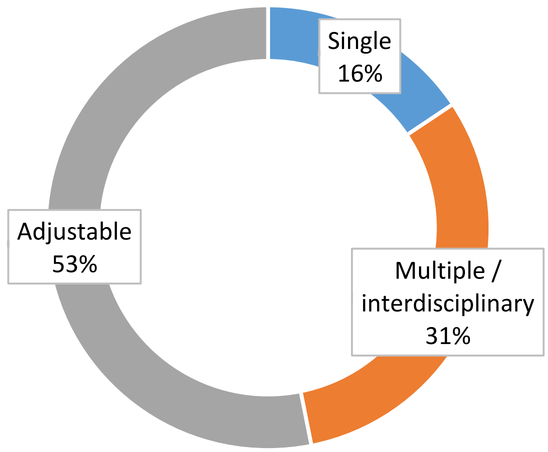


Figure 13
Goal of the experience

In terms of the application for concrete learning goal or goals, an absolute majority (53%) were in fact adjustable and can be used as for factual knowledge delivery and to develop certain sets of values and attitudes, as well as delivering contextual experiences and knowledge. Meanwhile VR learning experiences that aim to deliver solutions for multiple goals, or are interdisciplinary in their nature, comprised 31% of the evaluated experiences, while VR learning experiences that have a clear single goal also included adjustability characteristics; thus the merely single goal VR learning experiences comprised only 16% of all evaluated experiences. It must be noted that the identified diversity in learning goal focus or flexibility is also closely related to the overall costs of creating the VR learning experience and its application potential, as the majority of the adjustable-goal or multi-goal VR learning experiences were available for higher costs or long-term licences (for example Labster and Trauma Simulator experiences).

The chosen range of VR learning experiences provided learning environments and instruction in five out of six Fields of Science according to the OECD Field (s) of Science according to the Frascati Manual 2015 classification (OECD, 2015), (see Figure 14). Evaluation shows great potential for VR learning experiences in practical applications for various levels of learning in natural sciences, engineering and technology, as well as the medical and health sciences. In addition, there is a notable degree of fluidity and multi-disciplinary applications that VR learning environment affords as several inter-disciplinary solutions which have been identified including learning experiences for engineering and technology as well as humanities and the arts, and natural sciences and engineering and technology.

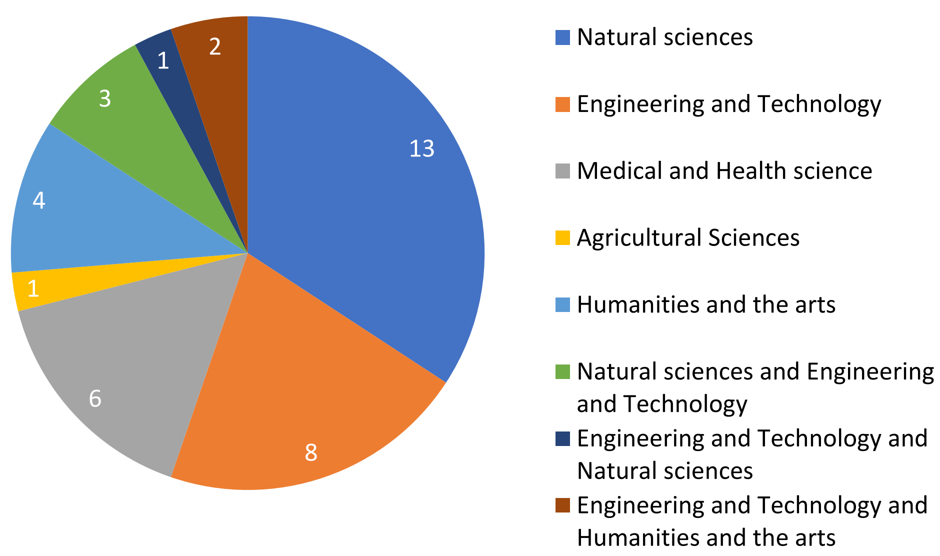


Figure 14
Fields of Science according to the OECD classification

Explorative evaluations have also highlighted some of the most common solutions (afforded by VR learning experiences) and according to the evaluation results these are: *"Presenting 3D imaginary while explaining complex new concepts. Vivid animation and storytelling. Light form of interaction with 3D models"; "Virtual teacher (avatar) gives instruction which allows for distance learning option"; "3-D simulation allows to develop understanding of the unknown and rare concepts"; "Virtual simulation which offers instruction and authentic conditions as well as timing component to the task"; "Close up interaction with study object joined by instruction, effective use of visuals especially to highlight separate aspects described by instructor"; "Close up interaction with a study object. Opportunity to experience a guided tour through authentic environment. A cost effective alternative to visiting a physical location / exhibit"; "Virtual simulation which allows to practice in introductory practice and critical incident modes*".

Table 9 presents an overview of some variants of learning solutions presented by the evaluated VR learning experiences and their frequency, while Figure 15 illustrates the share proportion (frequency) across the variant solutions (summarised from the evaluation results).

Table 9
Frequency of solutions afforded by VR learning experiences

Solutions	**Frequency**
Close up interaction with study object	2
Close up interaction with study object joined by instruction effective use of visual especially to highlight separate aspects described by instructor	7
Large scale immersive 3D imagery and descriptive storytelling. Voice guide gives instruction which allows for distance learning option	1
Close up interaction with study object. Opportunity to experience a guided tour through authentic environment. A cost effective alternative to visiting a physical exhibit	2
Practical simulation	2
Virtual simulation which offers instruction and authentic conditions as well as timing component to the task	1
Virtual simulation which allows to practice in introductory practice and critical incident modes	3
Collaborative immersive environment. Embodied actions including verbal and non-verbal communication. Possibility for international collaboration and peer-learning.	1
The 3D simulation allows to develop understanding of the unknown and rare concepts	1
Presenting 3D imagery while explaining complex new concepts. Vivid animation and storytelling. Light form of interaction with the 3D models. Virtual teacher (avatar) or voice guide gives instruction which allows for distance learning option	12

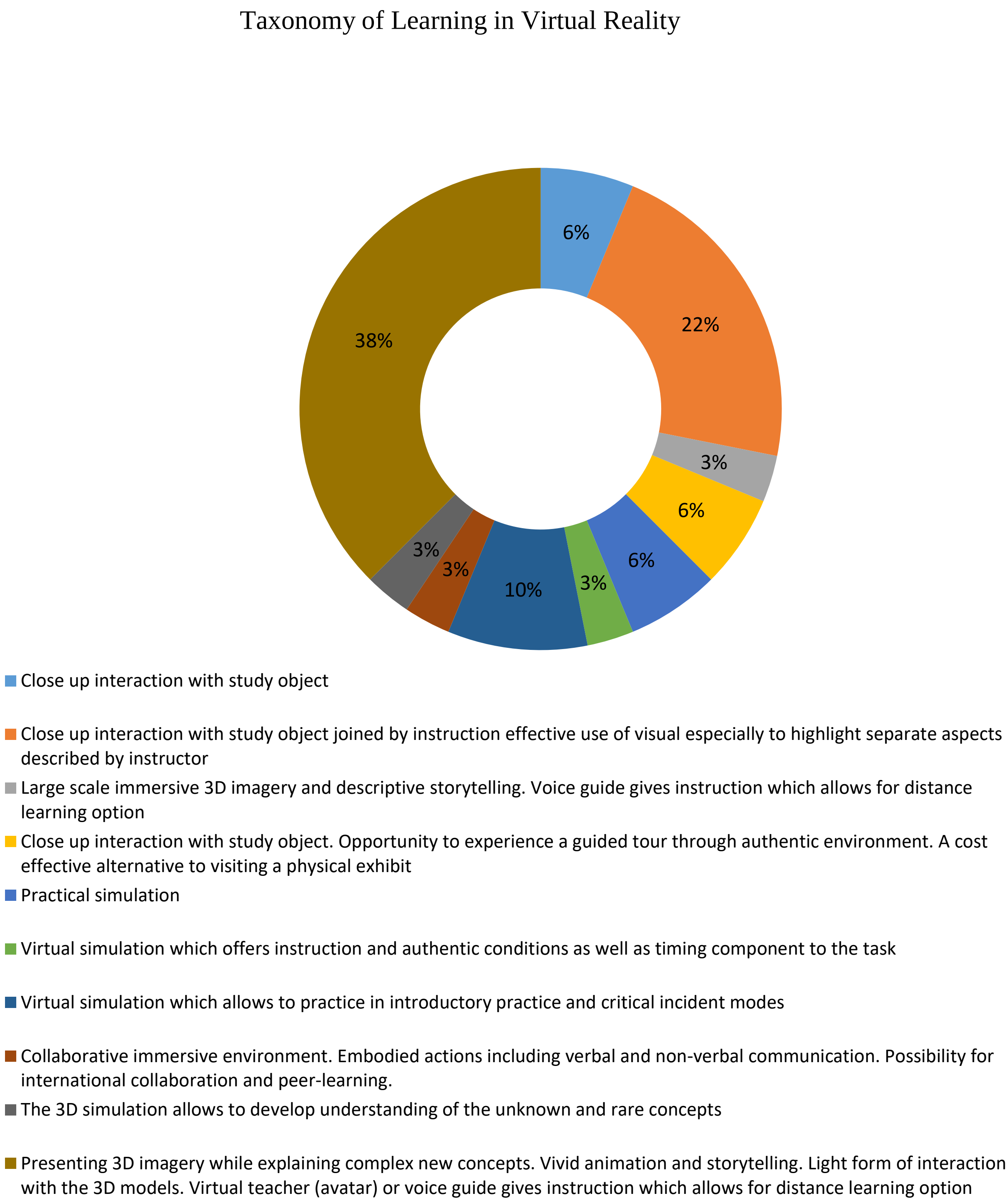


Figure 15

Proportions of solutions afforded by VR learning experiences

The evaluation results also confirm the discussion, presented in the section "Defining VR learning ecosystem" in Chapter II, that learning in VR is informed by multiple pedagogical perspectives or a fusion of aspects from multiple perspectives as instructional strategies of all of the thirty-two learning experiences are indeed informed by a blended or mixed approach. Taking into account that all of the evaluated VR experiences' instructional strategies were mixed, Figure 16 highlights the proportion of pedagogic perspectives in the mixed approaches, where the top share was sub-divided between Constructivism, Cognitivism and Behaviourism (for a more detailed approach to pedagogic perspectives see Chapter I and Tables 1 and 2.).

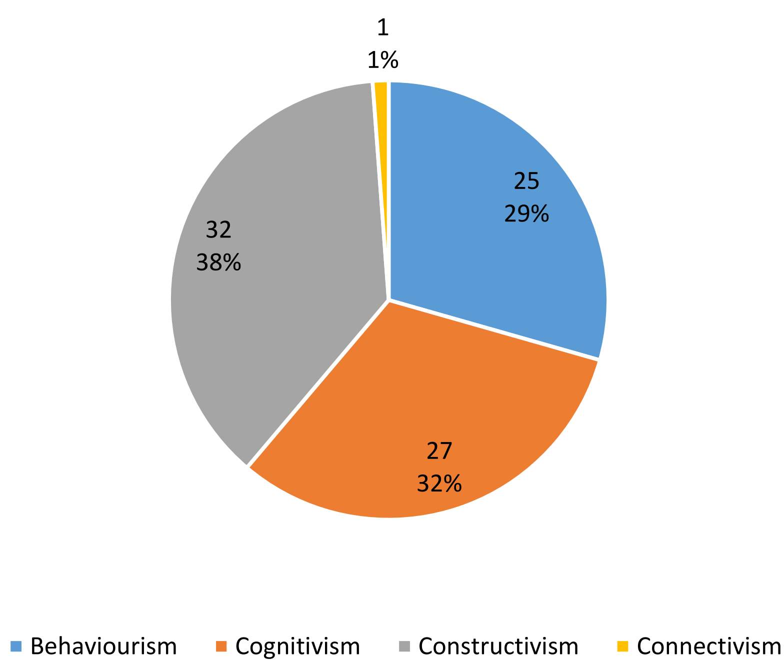


Figure 16
Pedagogical perspectives

Another highly significant criterion both in terms of instructional strategy and VR learning environment use is the role of the learner. The results of the evaluation show that none of the evaluated VR experiences identified the learner role as “Passive explorer where the learner absorbs the experience but has no additional control over the environment in the speed or mode of interaction”. This once again confirms the benefits of VR learning environment highlighted in Chapter I Sections “VR technologies and learning” and “Instructional strategies for learning in VR” and Chapter II Section “Defining VR learning ecosystem”. Figure 17 shows the proportional division between the reactive and proactive learner’s role in VR learning experiences.

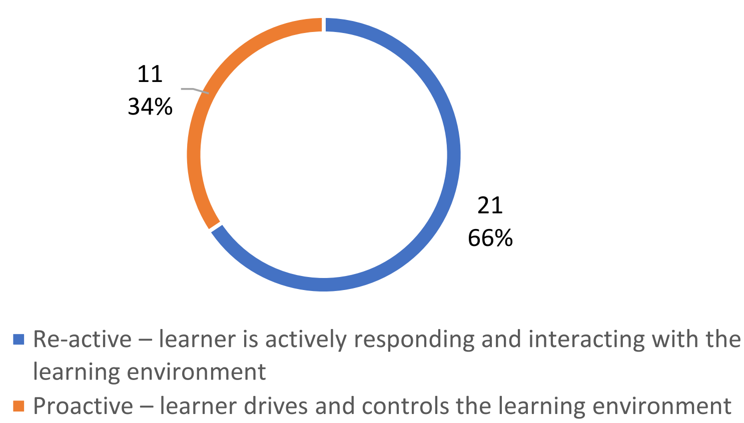


Figure 17
Learner’s role in VR learning experiences

When devising the evaluation tool both criteria of cognitive knowledge dimensions and cognitive process dimensions were adopted from Bloom‘s Taxonomy (1956) revised by Anderson and Krathwohl(2001) The evaluation results show that immersive VR environments have the potential to facilitate learning experiences for all cognitive knowledge dimensions and cognitive process dimensions. All of the thirty-two evaluated experiences targeted multiple knowledge dimensions (a minimum of two and a maximum of four) as well as multiple cognitive process dimensions (a minimum of two and a maximum of six). Figure 18 shows that the most frequent knowledge dimensions which can be developed by VR learning experience designs are the meta-cognitive and factual dimensions. Looking at the two opposite ends of the cognitive knowledge dimensions' continuum as the most frequent applications, the researcher draws parallels with the characteristics of the 3D VR environment, as the factual dimension is highly dependent on representational fidelity (physical perception) and not necessarily learner interaction (embodied actions), while meta-cognitive dimensions are absolutely dependent on learner interaction (embodied actions) and must also entail representational fidelity to achieve immersion (a more detailed view of the characteristics of 3D VR environment is in the section "Defining VR learning ecosystem" in Chapter II). The researcher suggests that both criteria should be viewed jointly as separating the two components would distort the purpose of the evaluation tool.

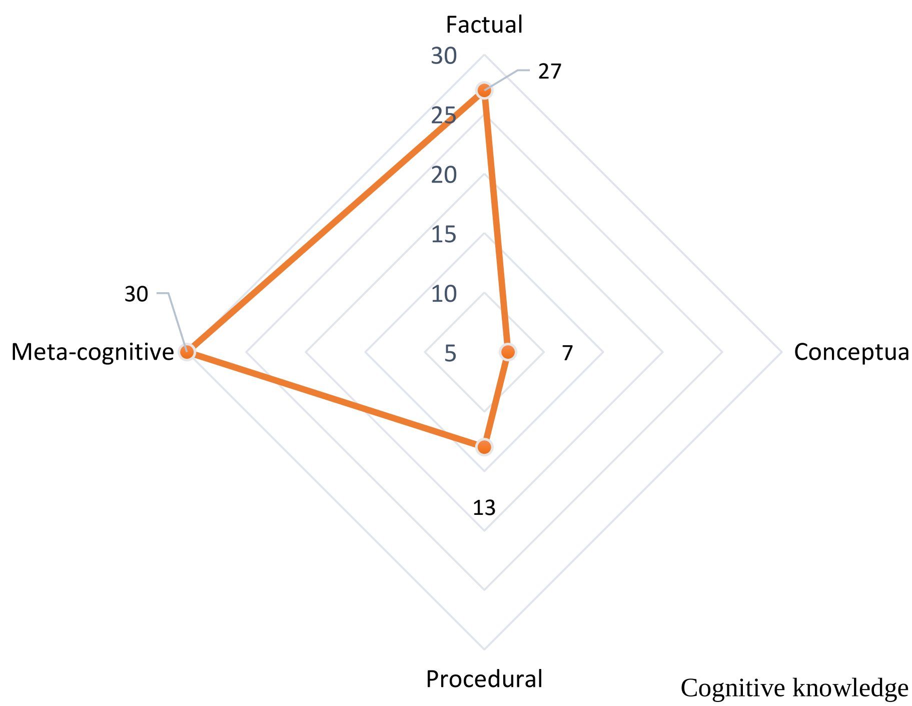


Figure 18
Cognitive knowledge dimension (frequency)

Figure 19 presents a stacked colour chart of cognitive process dimensions facilitated by each of the thirty-two VR learning experiences. The researcher had highlighted the area with VR learning experiences where the design of experience makes it possible to reach the highest level of cognitive process – Create (Anderson, et.al, 2001). Furthermore, there is a fit between the higher levels of cognitive knowledge dimensions and cognitive process dimensions in VR learning experiences – experiences which, in evaluation, were identified as higher (procedural and meta-cognitive) knowledge dimensions which were also identified as having the potential to develop higher cognitive process dimensions in learners. In addition, similar to the correlation identified between the licence costs and goal flexibility, the experiences which allow the learner to reach higher levels of cognitive development were available for a higher cost or long-term licences (for example Trauma Simulator experiences, Xennial, Mondly, Virtual Speech).

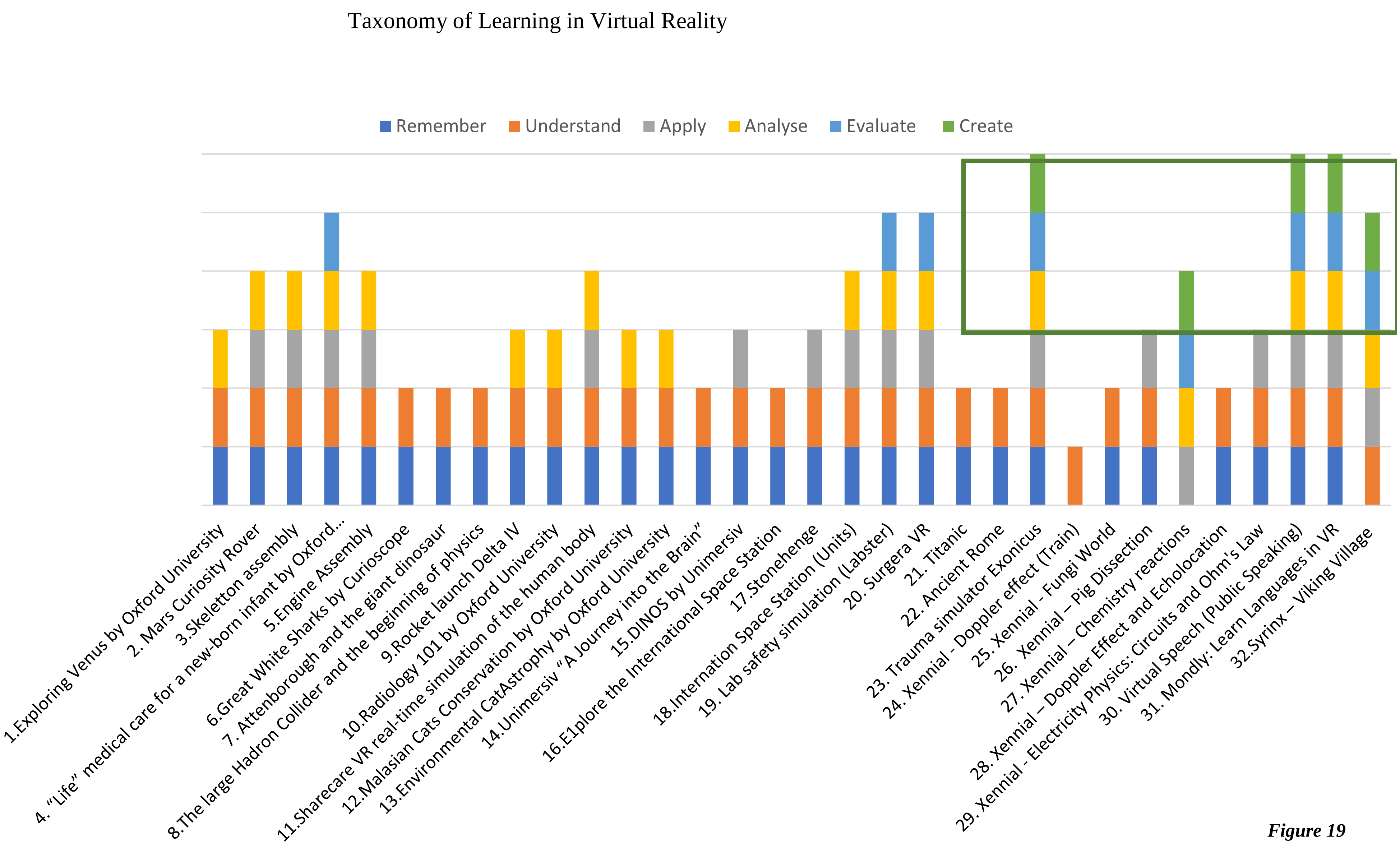


Figure 19
Cognitive process dimension

When evaluating the potential to develop certain competences, the tool sub-divides these competences into types of knowledge, skills and attitudes and values. The tendency illustrated in the spider chart (Figure 20) shows that VR learning experiences have the potential to develop both disciplinary and inter-disciplinary knowledge, as well as cognitive and meta-cognitive skills including attitudes and values. In the researcher’s view this tendency will be shifting in the near future as a result of hyper-active developments in sub-fields of cognitive learning analytics and VR haptics (bio-sensor platforms such as Imotions, haptic gloves and haptic suits with hyper-fine feedback haptics including such technologies as HaptX and Teslasuit).

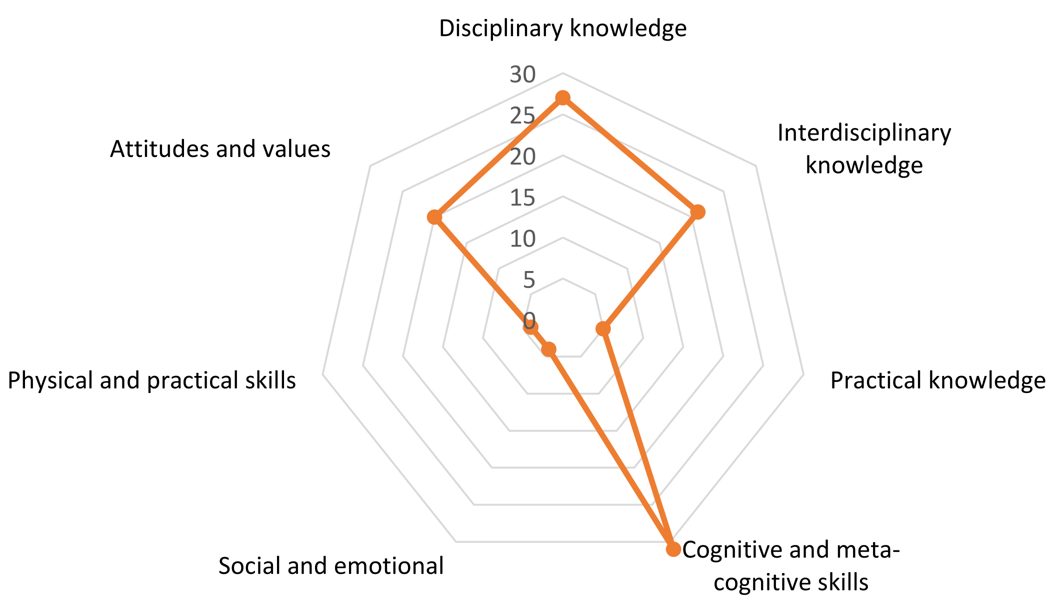


Figure 20
Competences – knowledge, skills, attitudes and values

Evaluation results of the criterion - type of VLE strategy - show that almost half of the experiences include an option to adjust the instructional strategy between the individual and a group. Figure 21 illustrates the frequency of the types of VLE applied, where individual or group types can also be mixed together depending on how the experience is utilised in the learning process, whereas the in-built function to adjust is limited to VR experiences with an intentional design. The chart in Figure 21 is a layered representation of the frequency of the type of VLE strategy applied and, thus, should be viewed as a set of overall principles of learning in VR rather than separate aspects. Evaluation results permit the deduction that the fluidity of VR learning experience strategy in terms of design is highly important.

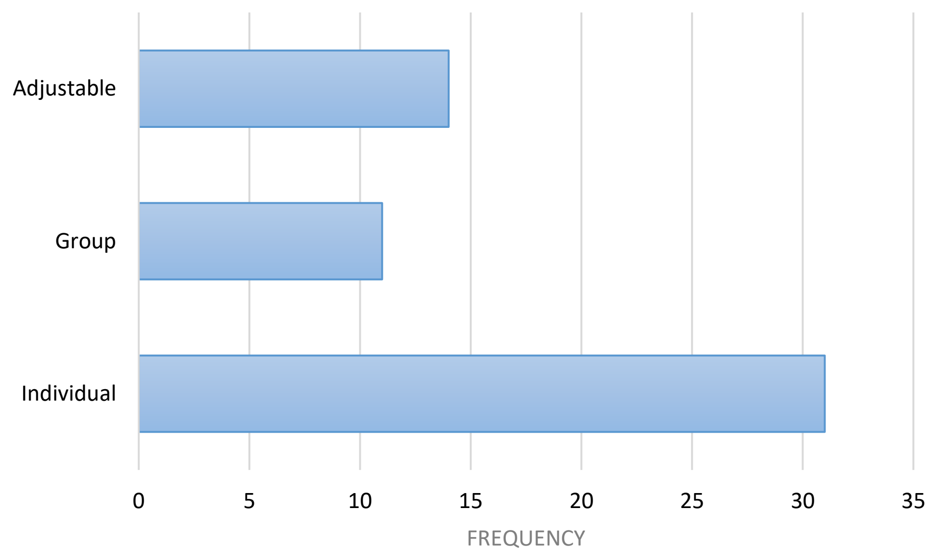


Figure 21
Type of VLE strategy – Individual, Group, Adjustable

An analysis of the results of interactivity more utilised in VR learning experiences (see Figure 22) shows that only four experiences utilised the technical possibilities of the VR environment. While the most frequently applied interactivity mode is real-time interaction (physical real-time interaction with environment), in order to harness the full potential of the VR learning environment, multi-user and synchronous interaction should also be utilised.

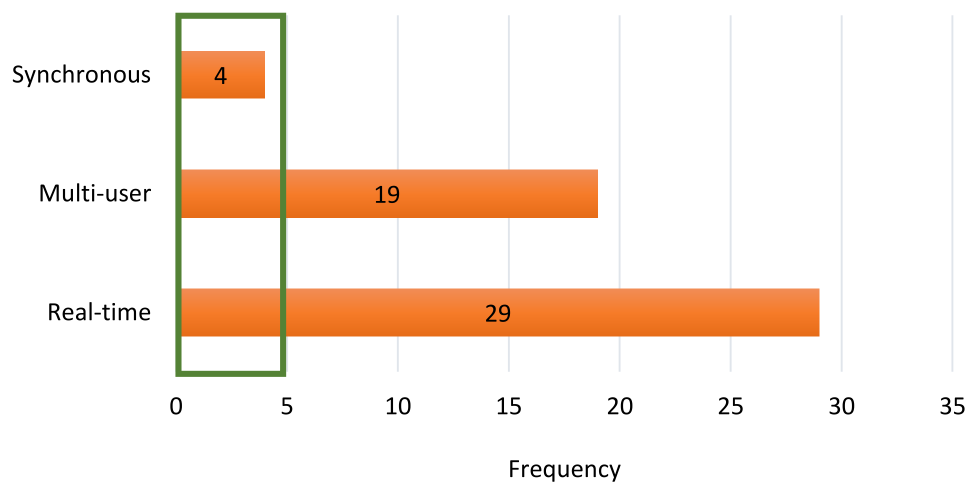


Figure 22
Type of VLE strategy – Interactivity mode

The next sub-criterion analyses various types of the instructional strategies applied. The eleven types of instructional strategy were adopted from Kapp and O'Driscoll (2010). Amongst the most frequently employed instructional strategies were the Guided Tour, Conceptual Orienteering, Operational Application, and Avatar Persona - all together representing a total of 72% of all instructional strategies employed. The majority of VR learning experiences combine two or more instructional strategies, depending on the objectives of the learning experiences and how long or complex the experience framework and design is, but while in the initial tool design the eleven strategies were left fully unfolded and were evaluated across all eleven types. The results confirm the researcher's view, discussed in the section "Instructional strategies for learning" in Chapter I, that other less frequently employed strategies should be viewed as elements of the larger three (Conceptual Orienteering, Critical Incident and Operational Application) rather than strategies on their own as in practice those are included and combined within the larger three types.

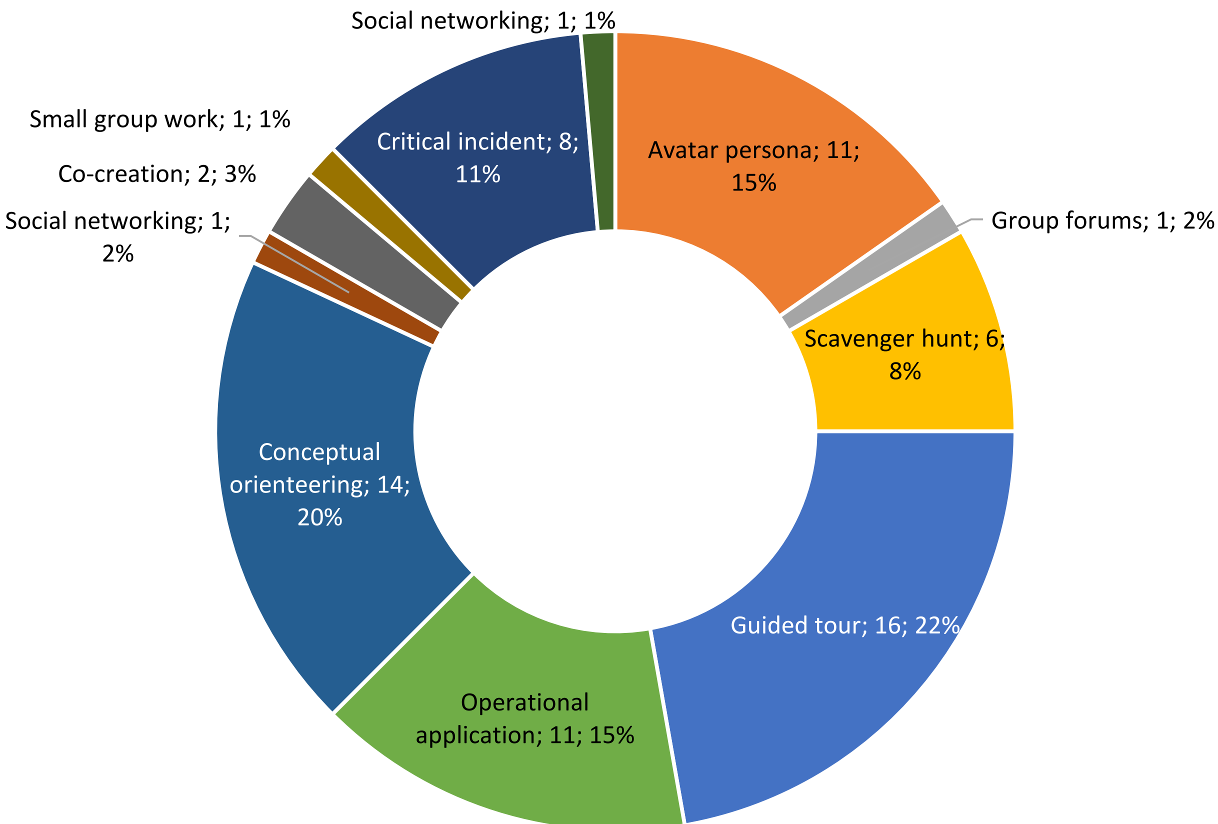


Figure 23
Types of VLE instructional strategy

Looking at the role of VR technology in the process of learning, evaluation results depicted in Figure 24 show that all thirty-two VR experiences utilised the VR learning environment which was identified as “Primary significance” or “Important – not a primary driver of learning experience, yet important in conveying contextual knowledge and cues”. Only two of those were also identified as supportive or entertaining. In addition, in both of those examples VR learning experiences, where the role of the VR environment was identified as supportive or entertaining, are combined with an evaluation of “Important – not a primary driver of learning experience, yet important in conveying contextual knowledge and cues” and both correspond to the VR type “Experience + lesson” and instructional strategy “Guided tour”.

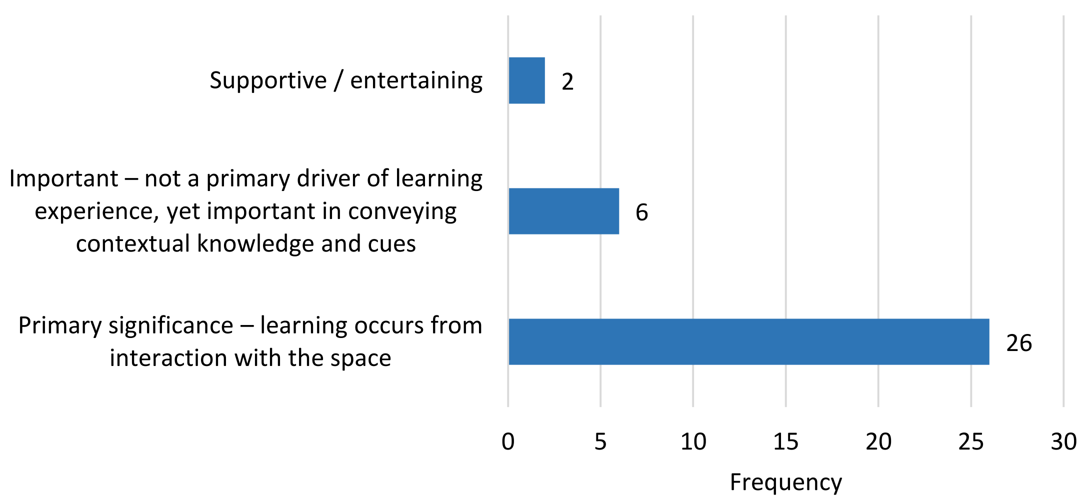


Figure 24
Role of VR space (including artefacts within the space) in achieving learning objectives

Figure 25 illustrates the unique characteristics of VR environment utilised across all of the thirty-two evaluated VR learning experiences. This inquiry adopted a framework of characteristics and affordances of 3D VLE (VR learning environment) by Dalgarno and Lee (2010), discussed in the section “Defining VR learning ecosystem” Chapter II and illustrated in Figure 10 “The technological perspective of VR learning ecosystem”. Both characteristics – representational fidelity and learner interaction - are viewed as the fundamental building blocks, which, in combination, allow the opportunity for immersion, identity construction and a sense of presence. In order to verify this approach the two sub-elements were evaluated separately and further supplemented with Brna's proposed multi-user VR environment characteristics (1999) such as social fidelity (including social familiarity and social reality), social presence and immediacy of discourse.

The staked colour chart in Figure 25 shows a straightforward picture of the characteristics employed in all thirty-two VR learning experiences. The chart visualises the respective characteristics for each of the VR learning experiences evaluated. The evaluation results confirm that, in order to deliver learning opportunities in VR environment, both characteristics – representational fidelity and learner interaction - must be utilised together in order to provide an immersive learning experience. Hence, all of the learning experiences utilise at least both of the fundamental characteristics of VR environment. Moreover, VR experiences which, according to the evaluation data, successfully utilised multi-user characteristics of VR environment, also showed that those had the potential to achieve higher cognitive development dimensions.

It is important to keep an open mind about how the learning objectives, design and VR environment can be effectively aligned for all sorts of learning goals and purposes; however what can be seen from the evaluation analysis is that, sadly, only a small fraction of VR learning experiences utilise the full potential of the immersive environment characteristics that VR technology allows. There are not nearly enough VR learning experiences that place multi-user collaborative and creative learning at the forefront of their VR learning strategy; thus the potential, also highlighted by the pedagogic frameworks such as Social Constructivism and Connectivism, is rarely harnessed. There is still much fascination with the depiction of 3D objects and interaction with 3D environments rather than exploring and employing strategies for human interaction in 3D learning environments.

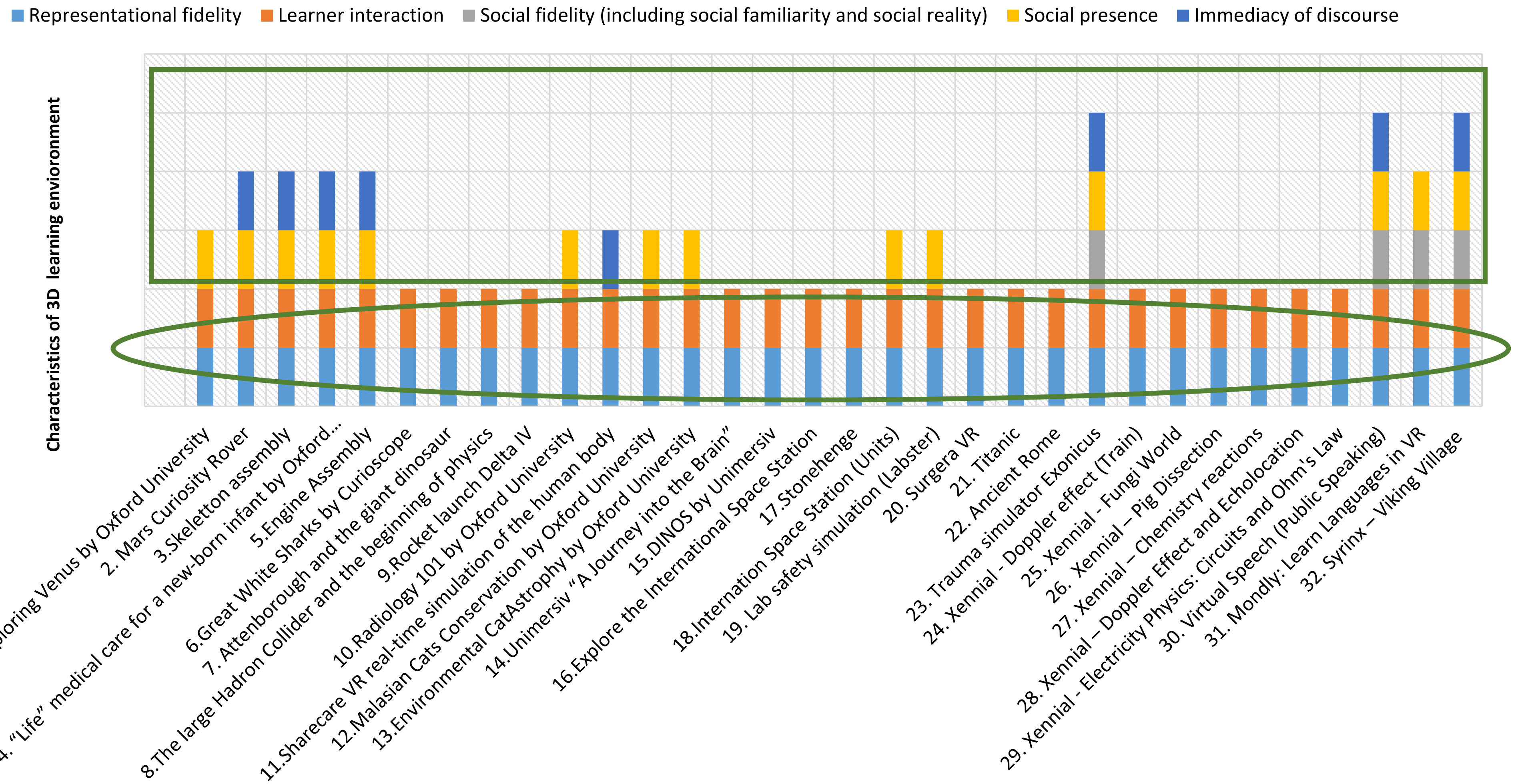


Figure 25
Characteristics of VR learning environment

When evaluating the potential of the VR learning environment, the availability of a built-in instructional support or feedback tools was analysed. Figure 26 illustrates the share (51%) of VR experiences which did not employ built-in instructional support. However, 26% of all evaluated VR experiences did employ instructional support tools such as avatar lecturers (human and non-human), voice guides and verbal and non-verbal clues. Meanwhile, of the two types of built-in feedback tools, tests and quizzes, as well as correct and/or incorrect guides, success rates and continuous progress monitoring tools were almost equally prevalent resulting in 13% and 10% of applications.

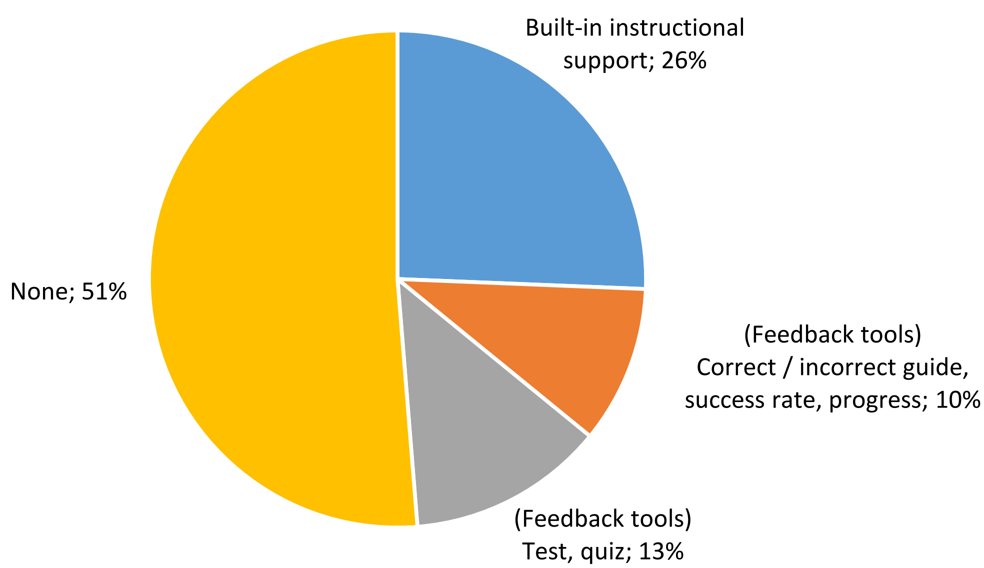


Figure 26
Availability of built-in instructional support or feedback

Qualitative analysis of VR learning experience evaluation data:

This research was carried out by utilising the developed evaluation tool (see section "Development of a Virtual Reality learning experience evaluation tool" Chapter II) and conducting full explorative evaluations of the thirty-two VR learning experiences. This section presents qualitative analysis of the evaluation results.

The aim of employing qualitative methods for the analysis of the evaluation results was to study the interconnections across twenty criteria in order to establish and understand the meaning of such inter-relations and to translate the established principles into a pedagogic theory framework.

The qualitative analysis was grounded in the researcher's interpretation based on pedagogical expertise and experience as well as the findings of the quantitative analysis. Qualitative analysis has confirmed multiple concordances with the existing pedagogic theoretical frameworks, findings of the quantitative analysis as well as the researcher's previous theoretical assumptions.

Table 10 presents an overview of several key criteria evaluation results which, in juxtaposition to each other, present qualitative evidence for their mutual inter-relations.

As a result of qualitative analysis, a hierarchical continuum of the proposed types of VR learning experiences was established. Evaluation results highlighted different strengths and more effective uses of the types, although there is a naturally occurring overlap between the associated cognitive process dimensions. Knowledge dimension analysis has been removed, as all of the VR learning experience types have the potential for all dimensions of knowledge depending on the purpose of application of VR learning experience, as well as the various ways that the learning process can be structured including different combinations of VR learning experience as a tool with other learning environments, methods and tools.

Table 10 highlights the hierarchy across the key criteria of VR learning experience design and delivery modes. Hierarchy is underpinned by the cognitive process dimensions (1-6) and ranges from yellow fields (highlighting the absence of certain characteristics) to light green (highlighting first levels of hierarchy) to medium green (second level), and deep green highlights the strongest level of immersive learning potential and the highest cognitive development dimensions. It is crucial to emphasise that (as shown in Table 10) none of the key evaluation criteria represent a set hierarchy on their own, thus the aim of Table 10 foremost is to highlight the significance of alignment across learning objectives, VR environment and learner interaction. Hence, Table 10 presents an alignment hierarchy.

Table 10

Alignment hierarchy of VR learning experience criteria

	Type of Experience	Cognitive process dimension (1-6)	Includes multi-user characteristics of VR environment	Affordances	Interaction mode	Role of VR	Role of learner
1	Lesson	1-2	No multi-user characteristics utilised	1) Spatial knowledge representation	Real-time	Not primary / supportive	Re-active
2	Experience	1-2	No multi-user characteristics utilised	2) Experiential learning 3) Engagement	Real-time	Primary	Re-active
3	Experience + lesson	1-3	No multi-user characteristics utilised	1) Spatial knowledge representation 2) Experiential learning 3) Engagement	Real-time	Primary	Pro-active
4	Activity	3	**Utilises multi-user characteristics**	2) Experiential learning 3) Engagement	Real-time Multi-user	Primary	Pro-active
5	Experience + activity	3-5	**Utilises multi-user characteristics**	1) Spatial knowledge representation 2) Experiential learning 3) Engagement 4) Contextual learning 5) Collaborative learning	Real-time Multi-user	Primary	Pro-active
6	Interactive simulation	6	**Utilises multi-user characteristics**	1) Spatial knowledge representation 2) Experiential learning 3) Engagement 4) Contextual learning 5) Collaborative learning	Real-time Multi-user Synchronous	Primary	Pro-active
7	Immersive virtual world	6	**Utilises multi-user characteristics**	1) Spatial knowledge representation 2) Experiential learning 3) Engagement 4) Contextual learning 5) Collaborative learning	Real-time Multi-user Synchronous	Primary	Pro-active

From the standpoint of learning and instruction, the evaluation highlighted some of the most commonly encountered learning challenges: *Complex knowledge, potentially costly learning process; Inaccessible dangerous authentic environment; Not possible to replicate the environment by any other physical forms* (for example the surface of Mars and the Curiosity Rover); *Dangerous, high stress-high skill demanding task, which cannot be practised in the usual learning environment; 3-dimensional interaction with objects is needed to gain in-depth understanding;* and *Impossible to replicate the environment at the necessary scale for learning purposes.*

In order to highlight aspects that are most often associated with immersive VR environments and their potential to offer solutions for learning, Figure 27 presents a word cloud summary for the analysis of the mezzo-level criterion Learning Problems that are addressed or solved by the VR learning experience design. Analysing the open-ended evaluation answers, the word cloud highlights also the frequencies of the keywords. Using Tag Crown, all of the evaluation answer texts were analysed. Pre-sets for word cloud analysis included grouping similar words (e.g. learn, learned, learning = learn), with a maximum of ten keywords, and a minimum frequency of #five).

Figure 27
Word Cloud summary of analysis for criteria - Problems
Generated using www. tagcrowd.com

The most recurrent learning problems addressed by VR learning experiences have been identified. These are;

1. complex knowledge, potentially costly learning process;
2. not possible to replicate the environment by any other physical forms (e.g. dinosaurs, Mars, Curiosity Rover)
3. dangerous, high stress-high skill demanding tasks, which cannot be practised in a traditional classroom learning environment;
4. 3-dimensional interaction with objects is needed to gain in-depth understanding;
5. inaccessible dangerous authentic environment;
6. impossible to replicate the environment at the necessary scale for learning purposes (e.g. inside the human brain, amplifying the structures of fungi); and
7. authenticity of the historic environment.

Table 11 presents an overview of the variants of solutions and their association with the affordances of 3D VR environment (adopted from Dalgarno and Lee, 2010).

Table 11
Interconnections of solutions and affordances of VR learning environment

Solutions	**Affordances of 3-D VR environment**
Close up interaction with study object	Spatial knowledge representation
Close up interaction with study object joined by instruction effective use of visual especially to highlight separate aspects described by instructor	
Large scale immersive 3D imagery and descriptive storytelling. Voice guide gives instruction which allows for distance learning option	
Close up interaction with study object. Opportunity to experience a guided tour through authentic environment. A cost effective alternative to visiting a physical exhibit	Experiential learning
Practical simulation	Engagement
Virtual simulation which offers instruction and authentic conditions as well as timing component to the task	
Virtual simulation which allows to practice in introductory practice and critical incident modes	

Collaborative immersive environment. Embodied actions including verbal and non-verbal communication. Possibility for international collaboration and peer-learning.	Collaborative learning
The 3D simulation allows to develop understanding of the unknown and rare concepts	Contextual learning
Presenting 3D imagery while explaining complex new concepts. Vivid animation and storytelling. Light form of interaction with the 3D models. Virtual teacher (avatar) or voice guide gives instruction which allows for distance learning option	

Figure 28 translates the frequency of solution variants analysed in the quantitative analysis section and presents a spider chart of the frequencies of affordances of 3D VLE environments which are associated with the solutions identified through the evaluation. Across the thirty-two VR learning experiences the majority are associated with contextual learning, followed by solutions associated with spatial knowledge representation affordance.

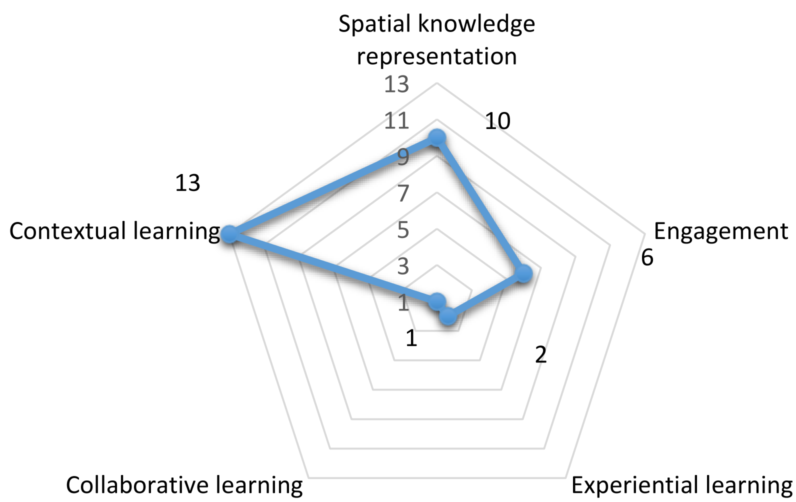


Figure 28
Affordances of 3D VR environments in association to solutions

Triangulation

Triangulation can be used for validation or to broaden the scope of understanding especially when it comes to generating new theoretical knowledge. For instance, Flick (2002) emphasised that triangulation is more of an "alternative to validation which increases scope, depth and consistency in methodological proceedings" (p. 227). In order to develop a unifying theory for learning in VR, this research has employed a double triangulation technique - theory triangulation (Figure 29) and methodological triangulation (Figure 30).

In this research, theory triangulation has been applied to develop an understanding of VR learning eco-systems and process, through perspectives of pedagogy, instructional design and VR learning environments, while methodological triangulation has been chosen to study the inter-connections between the three data input sources and to establish an integrated substantive theoretical frame. Triangulation includes;

(1) findings from the Literature Review, including cross analysis and adoption of existing taxonomies and classifications (theory triangulation see Figure 29),

(2) definition of the VR learning ecosystem and the development of an evaluation tool for VR learning experiences (see Appendix 2), and

(3) exploratory evaluations of VR learning experiences.

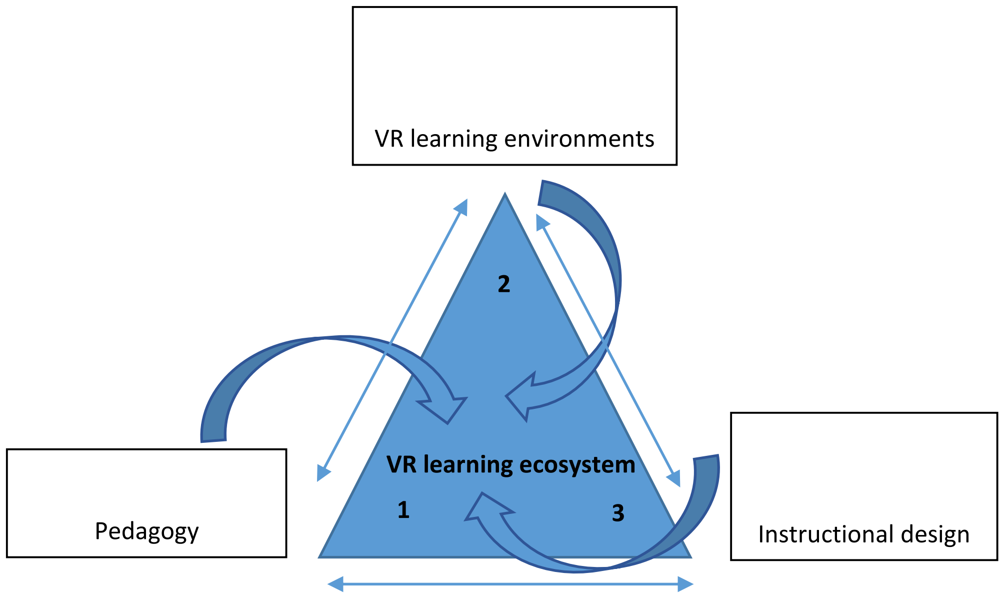


Figure 29
Theory triangulation
Researcher's concept

Triangulation of theories of the three areas – pedagogy, VR learning environments and instructional design - allows for a definition of the VR learning ecosystems, discussed in section "Defining VR learning ecosystem" Chapter II. More importantly, in comparison with analysing each of the areas in their own right, triangulation, as a method, can highlight those aspects which are the most significant to the overall frame of the ecosystem rather than the unique context of the single area. Therefore, triangulation offers an opportunity to 'distil' the characteristics and principles of each area which gravitate towards each other; for examples see Table 2. The three core areas (pedagogy, VR learning environments and instructional design) and their respective theoretical frameworks are fundamental to understanding the principles of learning in VR, yet there are many more questions and connected areas of VR learning research. However, the researcher emphasises that further research must also employ at least one mode of triangulation as VR learning is a phenomenon which at present exists on the cross-lines of various areas, disciplines and theoretical approaches.

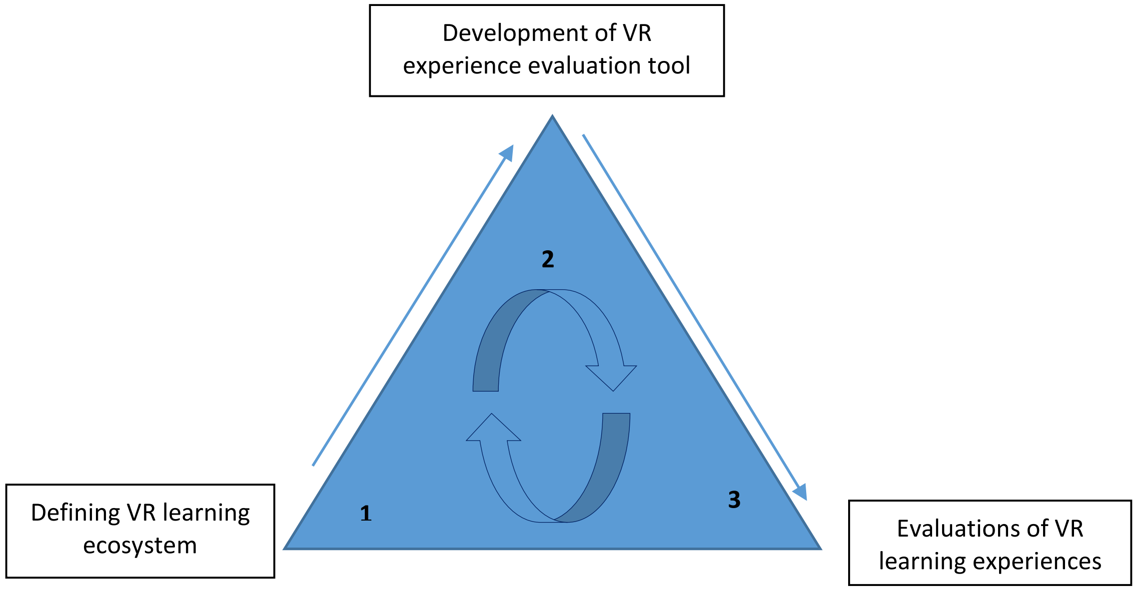


Figure 30
Methodological triangulation steps
Researcher’s concept

On the other hand, methodological triangulation in the context of this study allows verification of the principles and uncovers the inter-connections and the effects on each other. Defining the learning ecosystem has allowed the opportunity to develop and structure the VR experience evaluation tool which was then able to evaluate VR learning experiences. However, the most significant benefit of methodological triangulation in this study is that it also creates a return response and analytical feedback, as evaluations continue to improve the evaluation tool which, in combination, is able to understand the principles of the ecosystem more clearly and to verify their inter-connections.

CHAPTER III – GENERATING A THEORY

This explorative study draws on the cross-analysis of both qualitative and quantitative data resulting in new insights and concepts related to the systemisation of learning in VR. This research aims to develop a taxonomy of learning in VR by answering three Research Questions:

1. *What are the general pedagogic principles involved in facilitating learning in VR?*
2. *What is the role of VR in facilitating learning and what are the potentially unique aspects of VR space that augment the learning experience?*
3. *What are the interconnections between the pedagogic principles and the unique aspects of VR space?*

This chapter presents answers to these questions and summarises the evidence already presented - Quantitative and Qualitative Analysis of VR Learning Experiences, which guides the development of the theoretical framework for learning in VR. First, summaries of the principles informing each of the research questions are presented and this is followed by construction of the taxonomy.

Summary of the principles informing each of the research questions

1. 1. What are the general pedagogic principles involved in facilitating learning in VR?

1.1. VR learning experiences place the learner at the forefront – whether in a reactive role where the learner reacts and thus learns from this interaction with a virtual learning environment or a proactive role where the learner has the opportunity to be in the ‘driving seat’ of his or her learning experience and thus can learn from limitless creative and collaborative encounters in virtual environment (in concurrence with Constructivist and Constructionist theory - Vygotsky, Piaget, Dewey and Papert). (Figure 17 and Table 10)

1.2. All the evaluated VR experiences’ instructional strategies were mixed - learning in VR is informed by a fusion of aspects from multiple pedagogical perspective**s** as instructional strategies of all the thirty-two learning experiences are indeed informed by blended or mixed approach (in concurrence with Hartwick and Nowlan, 2019). (discussed in Chapter II section "Defining VR learning ecosystem" and shown in Figure 16)

1.3. Evaluations present evidence of high fluidity in various applications of VR learning experiences which also delivers a counter balance to the criticism VR often receives for being excessively costly and time-consuming. (Figures 12 and 13)

1.4. In terms of application for concrete learning goal or goals, an absolute majority (53%) were in fact adjustable and this can be used for factual knowledge delivery and to develop certain sets of values and attitudes, as well as to deliver contextual experiences and knowledge. (Figure 13)

1.5. All the thirty-two evaluated experiences targeted multiple knowledge dimensions (a minimum of two and a maximum of four) as well as multiple cognitive process dimensions (a minimum of two and a maximum of six). (Figures 18 and 19)

1.6. The most frequent knowledge dimensions which can be developed by VR learning experience designs are the meta-cognitive and factual dimensions (Figure 18). This also signals to a potentially large scale gap in VR learning content available for transitional dimensions - conceptual and procedural. This gap presents a significant challenge for educators, as rapid shift to metacognitive knowledge dimension without the gradual learner knowledge development and relevant support can seriously impact the level of a learner's motivation.

1.7. There is a fit between the higher levels of cognitive knowledge dimensions and cognitive process dimensions in VR learning experiences – experiences which after evaluation were identified as higher (procedural and meta-cognitive) knowledge dimensions and were also identified as having the potential to develop higher cognitive process dimensions in learners. (Figures 18 and 19)

1.8. Evaluation results suggest that the fluidity of VR learning experience strategy in terms of design is highly important. (Figure 21)

2. What is the role of VR in facilitating learning and what are the potentially unique aspects of VR space that augment the learning experience?

2.1. Learning solutions can be associated with, and defined through, learning affordances of 3D VLE (as defined by Dalgarno and Lee, 2010). (Table 11 and Figure 27)

2.2. In order to harness the full potential of VR learning environment multi-user and synchronous interaction should be utilised. (Figures 22 and 25, Table 10)

2.3. The majority of VR learning experiences combine two or more instructional strategies, depending on the objectives of the learning experiences and how long or complex is the experience framework and design. (Figure 23)

2.4. Three core types of VR instructional strategies have been established from the eleven strategies defined by Kapp and O'Driscoll, 2010 – Conceptual Orienteering, Critical Incident and Operational Application, while the other eight should be viewed as smaller elements rather than strategies on their own as in practice they are included and combined within the larger three types. (Figure 23)

2.5. The evaluation results confirm that in order to deliver learning opportunities in the VR environment both characteristics – representational fidelity and learner interaction - must be utilised together in order to provide an immersive learning experience. Hence, all the learning experiences utilise both of the fundamental characteristics of VR environment. (Figure 25)

2.6. VR experiences which, according to evaluation data successfully utilised multi-user characteristics of VR environment, also showed that these had the potential to achieve higher cognitive development dimensions. (Figures 18, 19 and 25)

2.7. Diversity in learning goal focus or flexibility is also closely related to the overall costs of creating the VR learning experience and its application potential, as the majority of the adjustable-goal or multi-goal VR learning experiences were available at higher costs or long-term licences; for example Labster and Trauma Simulator experiences). (Figure 13 and the footnotes of section "Data collection procedure and analysis" Chapter II)

3. What are the interconnections between the pedagogic principles and the unique aspects of VR space?

3.1. Looking at the opposite ends of the cognitive knowledge dimensions' continuum as the most frequent applications, the researcher draws parallels with the characteristics of the 3D VR environment, as the factual dimension is highly dependent on representational fidelity (physical perception) and not necessarily learner interaction (embodied actions), while the meta-cognitive dimension is absolutely dependent on learner interaction (embodied actions) and must also entail representational fidelity to achieve immersion. (Figures 18 and 25)

3.2. It is not possible to establish a hierarchy of principles in isolation; however, it is possible to establish the hierarchy of the horizontal synergies across multiple core criteria. Thus, an alignment hierarchy is established which highlights the high dependence of the core criteria on the mutually aligned synergy rather than a single criterion. (Table 10 demonstrates the alignment hierarchy of VR learning experience criteria.)

3.3. Experiences that utilise the full potential of VR learning space, including multi-user characteristics and associated affordances, have the potential to provide learning platforms for the highest cognitive development dimensions. (Figures 22 and 25).

VR learning taxonomy

"A taxonomy is a special kind of framework. In a taxonomy the categories lie along a continuum. The continuum (…) becomes one of the major organizing principles of the framework" (Anderson et al., 2001).

This section presents a VR learning taxonomy framework. The core organizing principles of the taxonomy are alignment synergies and inter-connections (discussed in the section "Summary of the principles informing each of the research questions" Chapter III). The devised taxonomy is essentially a map of synergies, which are formed as a result of the choices of tools and the unique alignments they form. The taxonomy frame presents a tool-map, which offers an opportunity to oversee the instruments involved in constructing an effective VR learning experience.

In order to utilise the full potential of the VR learning environment, a clear pedagogic frame must be established, including setting out learning objectives, instructional strategy and implementing a mixed or fused approach when appropriate. The presented VR learning taxonomy aims to enable educators, instructors, VR content creators to effectively develop and apply VR learning experiences as a result of the fine-tuning and horizontal synergies of principles which inform learning in VR (discussed in the section "Summary of the principles informing each of the research questions" Chapter III).

The taxonomy is based along two axes – Learning dimension and VR learning environment dimension. See the taxonomy framework in Table 12 and a full taxonomy map is presented in Table 13, where the key elements along the two axes are specified as L1-9 for Learning dimension and V1-6 for VR learning environment dimension. Full taxonomy presents a detailed tool map which allows educators and VR learning content developers to choose and 'fine-tune' different key tools and combinations in order to achieve the synergies needed for reaching the set learning objectives.

Learning dimension encompasses nine key elements:

1. Problem
2. Learning objectives
3. Task design
4. Knowledge dimensions
5. Cognitive dimensions
6. Role of learner
7. Task engagement mode
8. Competition element.
9. Monitoring and assessment

VR learning environment dimension encompasses six key elements:

1. Type of VR Experience
2. Unique characteristics of VR environment
3. Affordances of VR learning environment
4. Instructional Strategies
5. Tracking analytics
6. Learner - educator feedback.

Table 12
Taxonomy framework

Learning dimension		***VR learning environment dimension***					
		Type of VR Experience	**Unique characteristics of VR environment**	**Affordances of VR learning environment**	**Instructional Strategies**	**Tracking analytics**	**Learner - educator feedback**
Problem							
Learning objectives							
Task design							
Knowledge dimensions							
Cognitive dimensions							
Role of learner							
Task engagement mode							
Competition element							
Monitoring and assessment							

Table 13
Full taxonomy map

		VR learning environment dimension					
	V1		V2	V3	V4	V5	V6
	Learning dimension	Type of VR Experience	Unique characteristics of VR environment	Affordances of VR learning environment	Instructional Strategies	Tracking analytics	Learner - educator feedback
		1. Lesson 2. Experience 3. Experience + lesson 4. Activity 5. Experience + activity 6. Interactive simulation	1. Authenticity 2. Immersion 3. Real-time interaction	1. Spatial knowledge representation 2. Experiential learning 3. Engagement 4. Contextual learning 5. Collaborative learning	1. Avatar Persona 2. Role Play 3. Scavenger Hunt 4. Guided Tour 5. Operational Application 6. Conceptual Orienteering 7. Critical Incident 8. Co-Creation 9. Small Group Work 10. Group Forums 11. Social Networking	1. Engagement interaction 2. Eye-tracking 3. View point monitoring 4. Sensory tracking 5. Cognitive analytics 6. Haptic interaction	1. Success rate 2. Progress report 3. Testing
L1	**Problem**						
	1. Complex knowledge, potentially costly learning process 2. Inaccessible dangerous authentic environment Not possible to replicate the environment by any other physical form 3. Dangerous, high stress- high skill demanding task, which						

	cannot be practised in the usual learning environment 4. 3-dimensional interaction with objects is needed to gain in-depth understanding						
L2	**Learning objectives**						
	1.Single; 2. Multiple						
L3	**Task design**						
	1.Sequential; 2. Interrelated; 3. Adjustable						
L4	**Knowledge dimensions**						
	1.Factual; 2.Conceptual; 3. Procedural; 4. Meta-cognitive						
L5	**Cognitive dimensions**						
	1.Remember; 2.Understand; 3.Apply.; 4.Analyse 5.Evaluate; 6.Create						
L6	**Role of learner**						
	1.Re-active, 2.Pro-active						
L7	**Task engagement mode**						
	1.Individual; 2.Group						
L8	**Competition element**						
	1.Score; 2.Ranking; 3.Completion time; 4. Correct response						
L9	**Monitoring and assessment**						
	1.Real-time assessment; 2. After completing several sessions; 3. Self-assessment; 4. Peer-assessment						

Methods for Verification

The taxonomy was created as a ‘live’ and easy to adopt tool which permits a balance of ‘just enough’ detail and flexibility to better serve the context of its application. The core purpose of the taxonomy is to allow educators, designers and potential learners to work within the framework, or more specifically, the map of the general principles which guide learning in a 3D immersive learning environment and thus utilize its full potential to achieve set-out learning objectives.

In the context of usability evaluation and sample size in usability testing, Virzi has highlighted that up to 80%, or the most notable product usability problems, can be detected with four to five subjects and additional subjects are less and less likely to reveal new information (1992). Virzi made three claims regarding sample size for usability studies: "1. Observing four or five participants allows practitioners to discover 80% of a product’s usability problems, 2. observing additional participants reveals fewer and fewer new usability problems, and 3. observers detect the more severe usability problems with the first few participants.” (Turner, Nielsen, 2002).

A primary verification exercise was undertaken during an evaluation process of the thirty-two VR learning experiences as the criteria constituting the taxonomy were established based on the analysis of evaluation results. Evaluations were rooted on a phenomenological approach (Honer, 2004; Eberle in Flick, 2014) and thus conducted based on the researcher’s expertise and experience and the results were interpreted from the point of view of an educator and a designer. See more on the approach to data collection and interpretation in Chapter II section “Data collection procedures and analysis”. Furthermore, according to Nielsen (1992), evaluators with expertise in either the product domain or usability had higher problem discovery rates than novice evaluators.

At the core of the taxonomy are the most significant principles informing VR learning; alignment synergies and interconnections which were discussed in the section “Summary of the principles informing each of the research questions” Chapter III.

Undeniably further longitudinal, interdisciplinary and mixed method research concerning approbation and adaptation of the devised taxonomy is necessary. Chapter IV section Limitations and Further Research offers suggestions for further research and explains the limitations of this research.

CHAPTER IV – CONCLUSION

This study has presented evidence to increase the understanding of the general principles that govern and facilitate learning in VR and how they are interconnected with the existing knowledge about learning, instructional design and virtual environments. The most important contribution of this research is in systemising already existing, but fragmented, knowledge and developing a theoretical basis for applicable taxonomy, as well as defining the areas for further research.

This research aims to inform educators and instructors, as well as VR technology developers and potential learners, about the alignment synergies and inter-connections of VR learning principles by generating a substantive theory for the taxonomy of learning in Virtual Reality. A taxonomy framework is devised as an adaptable guidance tool on how VR learning experiences should be designed and applied in order to ensure that the set learning objectives are achieved.

VR learning taxonomy is essentially a map of synergies, which are formed following the choice of tools and the unique alignments that they form. The taxonomy frame creates an opportunity to oversee the core instruments involved in constructing an effective VR learning experience. It provides an important contribution to the body of research on VR learning.

By completing all the outlined tasks, the research goal was achieved. The Literature Review, explorative mixed method empirical research and double triangulation of the results supported the development of theory for the construction of the taxonomy of learning in VR as well as providing answers to the Research Questions.

Findings

Table 14 presents a summary of the findings that support the answers to each of the Research Questions:

Table 14
Summary of findings in correspondence to Research Questions
(Researcher's developed concept)

Research Question 1	Findings
What are the general pedagogic principles involved in facilitating learning in VR?	1) Learning in VR is informed by a fusion of principles from multiple pedagogical perspectives, as instructional strategies of all evaluated VR learning experiences are informed by a blended or mixed approach. 2) VR learning experiences have the potential to achieve learning objectives in all cognitive processes and knowledge dimensions. 3) In terms of applications for concrete learning goals, VR learning experiences can be applied for factual knowledge delivery and the development of different sets of values and attitudes as well as contextual experiences and knowledge. 4) The most frequent cognitive knowledge dimensions which can be developed by VR learning experience designs are the meta-cognitive and factual dimensions. 5) The fluidity of VR learning strategy in terms of learning experience design is highly important. The majority of VR learning experiences combine two or more instructional strategies, depending on the objectives of the learning experiences and how long or complex is the experience framework and design.
Research Question 2	**Findings**

What is the role of VR in facilitating learning and what are potentially the unique aspects of VR space that augment the learning experience?	1) The VR learning environment has the potential to facilitate learning opportunities that place the learner at the forefront of the learning process, delivering opportunities for learner-driven complex, creative and collaborative learning in a virtual environment. 2) Because of the interactive ‘first-person experience’ nature of VR learning, the experiences which target higher levels of cognitive knowledge dimensions also present learning opportunities targeting learning objectives in higher cognitive process dimensions. 3) In order to harness the full potential of the VR learning environment multi-user and synchronous interactions should be utilised. 4) In order to deliver effective learning opportunities in the VR environment both characteristics – representational fidelity and learner interaction - must be utilised together to provide an immersive learning experience. Therefore, all the learning experiences utilise both of the fundamental characteristics of the VR environment. 5) VR experiences which utilise multi-user characteristics of VR environment also have the potential to achieve higher cognitive development (knowledge and process) dimensions.
Research Question 3	**Findings**
What are the interconnections between the pedagogic principles	1) Experiences that utilise the full potential of the VR learning space, including multi-user characteristics and associated affordances, have the potential to provide learning platforms for the highest cognitive development dimensions.

and the unique aspects of VR space?	2) Looking at the opposite ends of the cognitive knowledge dimensions' continuum as the most frequent applications, the researcher draws parallels with some characteristics of 3D VR environment, as the factual dimension is highly dependent on representational fidelity (physical perception) and not necessarily learner interaction (embodied actions), while the meta-cognitive dimension is absolutely dependent on learner interaction (embodied actions) and must also entail representational fidelity to achieve immersion. 3) Learning solutions can be associated with, and defined through, learning affordances of 3D VLE (as defined by Dalgarno and Lee, 2010). 4) It is not possible to establish a hierarchy of principles in isolation; however, it is possible to establish the hierarchy of the horizontal synergies across multiple core criteria. Thus, an alignment hierarchy is established which highlights the high dependence of the core criteria on the mutually aligned synergy rather than standalone criteria. 5) Applications of VR learning experiences are highly versatile and fluid, which delivers a counter argument to the criticism of excessive costs and the time required for VR learning delivery and content creation.

Recommendations

General recommendations

VR learning experiences can be used for all cognitive processes and knowledge dimensions; however, if the aim is to utilise the specific and unique affordances of the virtual learning environment, then the most beneficial choice of learning objectives for such experiences would be the higher cognitive dimensions starting with remembering factual knowledge and moving all the way to the creation of metacognitive knowledge.

It is especially beneficial to utilise VR learning technology in order to develop a learner’s ability for creation, critical thinking and innovation, as VR learning experiences allow students to express and create complex metacognitive concepts, as well as to perfect complex procedural knowledge including the point where procedural and cognitive processes intertwine together.

Much of the current research on learning in VR draws some connection with learning the principles of Constructivism, Constructionism and Connectivism theories; however, this often disregards other learning frameworks such as Behaviourism and Cognitivism. For this reason, the researcher argues that all the relevant learning facets should be taken into account when approaching learning in VR from the pedagogic perspective, as the teachings of each of the learning frameworks discussed in cross-analysis should be fully leveraged in order to better understand how learning takes place in relation to the affordances of VR technology and user experience (UX).

The researcher believes that, by using the educational vocabulary in VR learning research, it will aid the transfer of knowledge into practice and, more importantly, ensure the healthy balance of attention between the technological fascination and correct pedagogic applications.

This research highlights several significant aspects of the VR learning eco-system that are, as yet, missing from the established theoretical learning frameworks. Thus, in attempting to define the most appropriate pedagogic theory outlook, the researcher recommends a mixed or fused theoretical framework approach in order to leverage the full potential of immersive (VR) technologies and this particular mode of learning process.

Practical considerations

This research presents two practical tools for instructional designers, educators, VR technology developers and potential learners – the VR learning taxonomy and evaluation tool for VR learning experiences. For practical applications, especially VR learning content design and evaluations, the researcher recommends: first, undertaking a preliminary cross-analysis to establish how VR as a learning environment can contribute to the defined learning goals and deliver opportunities to incorporate prior knowledge of learners (discussed further in this section), secondly, this should be followed by an application of the VR learning taxonomy map for the development of experience design schema, and thirdly, by utilising the VR learning experience evaluation tool for further calibration and user-experience fine-tuning.

Evaluation tool for VR learning experiences

The VR learning experience evaluation tool aims to offer a ready-to-use and adaptable instrument for instructional designers, educators, VR technology developers and potential learners. This VR learning experience evaluation tool aims to highlight the pivotal aspects that should be considered by instructors and educators who wish to successfully design and/or apply VR learning experiences. The printable template for designing or analysing VR learning experiences is available for re-prints via this link: qrco.de/VRtool or QR code:

TEMPLATE

VR learning taxonomy

This research presents the taxonomy framework for ensuring an alignment between learning goals (pedagogy), instructional strategy and the affordances of VR environment. The VR learning taxonomy aims to enable educators, instructors, VR content creators to effectively develop and apply VR learning experiences because of the fine-tuning and horizontal synergies of principles which inform learning in VR. To ensure the alignment across learning objectives, VR environment and learner interaction the taxonomy should be viewed together with the alignment hierarchy map presented in Table 10 "Alignment hierarchy of VR learning experience criteria".

The taxonomy frame allows the assembly of the design frame and tailors the core decisive elements of the VR learning experience design schema by providing a selection of pre-defined sets of sub-criteria located across both axes – Learning dimension and VR learning environment dimension. Furthermore, it makes it possible to view the sub-criteria from the two axes in juxtaposition to each other as well as various combinations in order to rule out the design flaws (overlaps and insufficiencies) on both axes. Table 15 presents an application example for developing a VR learning experience design using the taxonomy framework. This particular example is designed to foster competences needed in order to carry out a wildfire rescue mission, ranging from practical skills important for individual learners up to collaborative and strategic actions in order to deliver a co-ordinated team response in various scenarios. The sub-criteria fields show choices of selected pre-defined sub- criteria along both axes, while the combinations and suggested juxtapositions of sub-criteria and how to best implement those within particular learning experience design are provided in the form of formulae. For practical applications, these fields are designed to be filled in free form to allow a more hands-on, creative and flexible yet co-ordinated and effective design process, also highly important in co-ordinating ideas across a team of experts usually involved in the creation of VR learning content creation (client communicating the learning needs, technical and instructional experts, as well as educators actually delivering and monitoring the learning).

Table 15
Taxonomy application example

Taxonomy of Learning in Virtual Reality

	VR learning environment dimension		**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
Learning dimension	**Learning experience profile:** **Wildfire rescue mission co-ordinated team response**		**Criteria**					
			Type of VR Experience	**Unique characteristics of VR environment**	**Affordances of VR learning environment**	**Instructional Strategies**	**Tracking analytics**	**Learner - educator feedback**
			1. Lesson *2. Experience* *3. Experience + lesson* *4. Activity* *5. Experience + activity* *6. Interactive simulation*	*1. Authenticity* *2. Immersion* *3. Real-time interaction*	*1. Spatial knowledge representation* *2. Experiential learning* *3. Engagement* *4. Contextual learning* *5. Collaborative learning*	*1. Avatar Persona* *2. Role Play* *3. Scavenger Hunt* *4. Guided Tour* *5. Operational Application* *6. Conceptual Orienteering* *7. Critical Incident* *8. Co-Creation* *9. Small Group Work* *10. Group Forums* *11. Social Networking*	*7. Engagement interaction* *8. Eye-tracking* *9. Viewpoint monitoring* *10. Sensory tracking* *11. Cognitive analytics* *12. Haptic interaction*	*4. Success rate* *5. Progress report* *6. Testing*
			Chosen subcriteria from VR learning environment dimension					
	Criteria	**Chosen sub-criteria from Learning dimension**	4. Activity 5. Experience + Activity 6. Interactive Simulation	1. Authenticity 2. Immersion 3. Real-time interaction	2. Experiential learning 3. Engagement 5. Collaborative learning	5. Operational Application 7. Critical incident	1. Engagement interaction 6. Haptic interaction	1. Success rate 2. Progress report
L1	**Problem**							
	1. Complex knowledge, potentially costly learning process *2. Inaccessible dangerous authentic environment. Not possible to replicate the environment by any other physical form* *3. Dangerous, high stress-high skill demanding*	2.Inaccessible dangerous authentic environment. Not possible to replicate the environment by any other physical form	***L1 (2) + V1 (4,5,6)***	***L1 (2) + V2 (1, 2, 3)***	***L1 (2) + V3 (2, 3, 5)***	***L1 (2) + V4 (5, 7)***	***L1 (2) + V5 (1, 6)***	***L1 (2) + V6 (1, 2)***

	task, which cannot be practised in the usual learning environment 4. *3-dimensional interaction with objects is needed to gain in-depth understanding*							
L2	**Learning objectives**							
	1.Single; 2.Multiple	2.Multiple	***L2 (2) + V1 (4,5,6)***	***L2 (2) + V2 (1, 2, 3)***	***L2 (2) + V3 (2, 3, 5)***	***L2 (2) + V4 (5,7)***	***L2(2) + V5 (1,6)***	***L2 (2) + V6 (1,2)***
L3	**Task design**							
	1.Sequential; 2.Interrelated; 3.Adjustable	2.Interrelated	***L3 (2) + V1 (4,5,6)***	***L3 (2) + V2 (1, 2, 3)***	***L3 (2) + V3 (2, 3,5)***	***L3 (2) + V4 (5,7)***	***L3(2) + V5 (1,6)***	***L3 (2) + V56 (1,2)***
L4	**Knowledge dimensions**							
	1.Factual; 2.Conceptual; 3.Procedural; 4.Meta-cognitive	3.Procedural 4.Meta-cognitive	***L4 (3,4) + V1 (4,5,6)***	***L4 (3,4) + V2 (1, 2,3)***	***L4 (3,4) + V3 (2, 3,5)***	***L4 (3,4) + V4 (5,7)***	***L4 (3,4) + V5 (1,6)***	***L4 (3,4) + V6 (1,2)***
L5	**Cognitive dimensions**							
	1.Remember; 2.Understand; 3.Apply.; 4.Analyse 5.Evaluate; 6.Create	3.Apply.; 4.Analyse 5.Evaluate; 6.Create	***L4 (3,4,5,6) + V1 (4,5,6)***	***L4 (3,4,5,6) + V2 (1, 2,3)***	***L4 (3,4,5,6) + V3 (2, 3,5)***	***L4 (3,4,5,6) + V4 (5,7)***	***L4 (3,4,5,6) + V5 (1,6)***	***L4 (3,4,5,6) + V6 (1,2)***
L6	**Role of learner**							
	1.Re-active, 2.Pro-active	2.Pro-active	***L6 (2) + V1 (4,5,6)***	***L6 (2) + V2 (1, 2,3)***	***L6 (2) + V3 (2, 3,5)***	***L6 (2) + V4 (5,7)***	***L6 (2) + V5 (1,6)***	***L6 (2) + V6 (1,2)***
L7	**Task engagement mode**							
	1.Individual; 2.Group	2.Group	***L7 (2) +***	***L7 (2) +***	***L7 (2) +***	***L7 (2) +***	***L7(2) +***	***L7 (2) +***

			V1 (4,5,6)	***V2 (1, 2, 3)***	***V3 (2, 3,5)***	***V4 (5,7)***	***V5 (1,6)***	***V6 (1,2)***
L8	**Competition element**							
	1.Score; 2.Ranking; *3.Completion time;* *4.Correct response*	1.Score (consisting of completion time and error count)	***L8 (1)*** + ***V1 (4,5,6)***	***L8 (1)*** + ***V2 (1, 2, 3)***	***L8 (1)*** + ***V3 (2, 3,5)***	***L8 (1)*** + ***V4 (5,7)***	***L8 (1)*** + ***V5 (1,6)***	***L8 (1)*** + ***V6 (1,2)***
L9	**Monitoring and assessment**							
	1.Real-time assessment; *2. After completing several sessions;* *3.Self-assessment;* *4.Peer-assessment*	1.Real-time assessment 2.After completing several sessions	***L9 (1,2)*** + ***V1 (4,5,6)***	***L9 (1,2)*** + ***V2 (1, 2,3)***	***L9 (1,2)*** + ***V3 (2, 3,5)***	***L9 (1,2)*** + ***V4 (5,7)***	***L9 (1,2)*** + ***V5 (1,6)***	***L9 (1,2)*** + ***V6 (1,2)***

Preliminary cross-analysis

The effectiveness of the VR learning environment is rooted in the authenticity of first-person interactions with the environment itself and other users. As the evaluation results show in Figure 17 and Table 10 the learner is at the centre of VR learning thus, when developing VR learning experiences or utilizing the VR learning environment within an ongoing learning process, it is important to take into consideration prior knowledge and the experiences of a learner, including cultural identity.

There are several options with regards to establishing and using a learner's prior knowledge in VR learning design and process itself:

1) designing a VR learning experience with variable difficulty levels and conducting preliminary tests or a survey to establish the most appropriate level;
2) delivering immersive content as part of a VR learning experience before engaging in immersive tasks – video, audio, visual or verbal clues - to trigger prior knowledge and establish context (e.g. DINOS by Unimersiv, Unimersiv "International Space Station"); and
3) delivering introductory activity – Orientation Maze (as suggested by Hartwick and Nowlan, 2019) (e.g. Lab safety simulation (Labster), Xennial - Fungi World, Trauma simulator by Exonicus).

In order to avoid the risks of creating ineffective VR learning content and wasting time and resources it is immensely important to ensure the efficient use of VR technology in order to achieve the desired learning outcomes. Thus, it is important, before undertaking the creation of VR learning content (including instructional design and 3D visual and multi-media content creation), to analyse and map out the characteristics of the strategically set learning objectives and the role of the VR learning environment.

The researcher proposes that preliminary cross-analysis should be conducted in order to ensure further effectiveness and the successful alignment of all the affordances involved in VR learning experience. Table 16 presents a template, which for practical applications is available for re-prints as part of the evaluation tool template via QR code: or the link: qrco.de/VRtool.

Table 16
Preliminary cross-analysis
(Researcher's developed concept)

	Criterion	**Sub-criteria**
Preliminary cross-analysis	How did the affordances of space contribute to the qualities of active, collaborative learning?	*(Free form)*
	Is/was the learning strategy successful because of the affordances of 3DVLE?	*(Free form)*
	VR user experience (What is the role for learner using the VLE?)	*(Free form)*
	How does the VR learning experience allow for opportunities to take into consideration or to incorporate the prior knowledge of a learner?	*(Free form)*
	Does the learning experience clearly manifest the benefits of using VR as the learning mode?	1) Yes, the reasons for choosing VR as the learning mode are clear
		2) Reasons for choosing VR as the learning mode can be identified
		3) Reasons for choosing VR as the learning mode cannot be identified

Further research directions

This research has presented a range of findings on the principles that facilitate learning in VR and systemises the existing knowledge about learning, instructional design and virtual environments. However, further empirical research is needed in order to increase the validity of the theoretical findings by approbating the devised taxonomy frame and evaluation tool on a larger scale and by investigating the practical applications of the distinctive technology areas of VR learning processes, (for example, such as cognitive learning analytics and haptic VR technology), including a variety of fields and learner groups over a longer period (ranging from at least two to five years) of time.

The researcher suggests four broader directions for further research into VR learning:

1) Instructional (teaching) strategies for VR learning;

2) Learning outcomes of VR learning (including monitoring and assessment);

3) Cognitive learning analytics (such as attention, eye-movement, facial expressions including electro-encephalograms which detects electrical activity of the brain (EEG), electro-cardiograms which measure the electrical activity of the heart (ECG) - electro-dermal activity which detects skin response to emotional stimuli (EDA) and electro-myography which detects facial muscle movement (EMG);

4) Haptic VR technology (including vests, gloves, full body suits with hyper-fine feedback haptics); and

5) Internationally comparative longitudinal studies informing best-practice principles and inter-disciplinary application potential.

BIBLIOGRAPHY

1. Alimisis, D. and Kynigos, C. (2009). Constructionism and Robotics in Education. In D. Alimisis (Ed.), *Teacher Education on Robotic-Enhanced Constructivist Pedagogical Methods* (pp. 11-27). Athens: School of Pedagogical and Technological Education (ASPETE).

2. Anderson, L. W.; and Krathwohl, D. R., (Eds). (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. New York: Addison Wesley Longman, Inc.

3. Armitage, A. (2007). *Mutual research designs: redefining mixed methods research design*. British Educational Research Association Annual Conference, Institute of Education, University of London. Retrieved: http://www.leeds.ac.uk/educol/documents/167799.htm

4. Biggs, J. B., and Collis, K. (1982). *Evaluating the Quality of Learning: the SOLO taxonomy*. New York, Academic Press.

5. Biocca, F. (1994). Virtual Reality. In A. E. Grant. *Communication technology update and fundamentals*. (3rd Ed.). Newton, Massachusetts: Butterworth-Heinemann.

6. Bloom, B. S.; Engelhart, M. D.; Furst, E. J.; Hill, W. H.; Krathwohl, D. R. (1956). *Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain*. New York: David McKay Company.

7. Bower, M. (2017). *Design of technology-enhanced learning – Integrating research and practice*. Bingley, UK: Emerald Publishing Group.

8. Bowman, D.A., Wineman, J., Hodges, L.F., and Allison, D. (1999). The Educational Value of an Information-Rich Virtual Environment. *Presence: Teleoperators & Virtual Environments*, 8, 317-331.

9. Branch, R. M., and Kopcha, T. J. (2014). Instructional design models. In J. M. Spector, M. D. Merrill, J. Elen, J. Bishop (Eds.), *Handbook of research on educational communications and technology* (pp.77–87). New York: Springer.

10. Brown, J., Collins, A., Duguid, P. (1989). Situated Cognition and the Culture of Learning. *Educational Researcher*, 18(1), 32-42. Retrieved: http://www.jstor.org/stable/1176008.

11. Brna, P. (1999). Collaborative virtual learning environments for concept learning. *International Journal of Continuing Education and Lifelong Learning, 9* (3/4), 315–327. Retrieved: https://www.inderscienceonline.com/doi/pdf/10.1504/IJCEELL.1999.030158.

12. Bruner, J. S. (1966). *Toward a theory of instruction*. Cambridge, Massachusetts: Belkapp Press.

13. Bryson, S. (1995). Approaches to the successful design and implementation of VR applications. *Virtual Reality Applications*. London: Academic Press Limited.

14. CB Insights, (2018, October 25). Retrieved: http://bit.ly/cbs_industries_to_transform

15. Chee, Y. (2001). Virtual reality in education: Rooting learning in experience. *Proceedings of the International Symposium on Virtual Education 2001*. (pp. 43–54). Busan, South Korea: Symposium Organizing Committee, Dongseo University. Retrieved: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.95.5948&rep=rep1&type=pdf

16. Chen, C. J. (2006). The design, development and evaluation of a virtual reality based learning environment. *Australasian Journal of Educational Technology*, 22(1). Retrieved: https://ajet.org.au/index.php/AJET/article/download/1306/678

17. Chickering, A. (1977). *Experience and Learning*. New York: Change Magazine Press.

18. Churches, A. (2007). *Bloom's Digital Taxonomy*. Retrieved: https://www.pdst.ie/sites/default/files/BloomDigitalTaxonomy-AndrewChurches.pdf;

19. Creswell, J. W. (2003). Research Design: Qualitative, Quantitative and Mixed Methods Approaches (2^{nd} Ed.). London: Sage Publications Ltd.

20. Creswell, J. W., and Plano Clark, V. L. (2011). Designing and Conducting Mixed Methods Research (2nd Ed.). London: Sage Publications Ltd.

21. Dalgarno, B., Hedberg, J., & Harper, B. (2002). The contribution of 3D environments to conceptual understanding. *Proceedings of the 19th Annual Conference of the Australian Society for Computers in Tertiary Education (ASCILITE)*. Auckland, New Zealand: UNITEC Institute of Technology. Retrieved: http://www.ascilite.org.au/conferences/auckland02/proceedings/papers/051.pdf

22. Dalgarno, B., Lee, M. (2010). What are the learning affordances of 3-D Virtual environments?. *British Journal of Educational Technology*, 41(1), 10-32. Retrieved: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1467-8535.2009.01038.x

23. Dang-xiao, W., Yuan, G., Shi-yi, L., Yu-ru, Z., Wei-liang, X., & Jing, X. (2019). Haptic display for virtual reality: progress and challenges. Virtual Reality & Intelligent Hardware.

2019, 1(2): 136-162 Retrieved: http://vr-ih.com/vrih/html/EN/10.3724/SP.J.2096-5796.2019.0008.

24. Daniela, L. (2018). Smart Pedagogy for Technology Enhanced Learning. In L.Daniela (Ed.) *Didactics of Smart Pedagogy: Smart Pedagogy for Technology Enhanced Learning*. (pp. 3-21) Springer. Retrieved: https://www.springer.com/gp/book/9783030015503.
25. Dewey, J. (1902). *The child and the curriculum*. University of Chicago Press. Retrieved: https://archive.org/details/childandcurricu00dewegoog/page/n10/mode/2up .
26. Dewey, J. (1916). *Democracy and education: An introduction to the philosophy of education.* (2009 edition) New York: WLC Books.
27. Dickey, M. D. (2002). *Constructing the user: the impact of the design of three-dimensional virtual worlds on user representation*. Retrieved: https://www.academia.edu/20960421/Constructing_the_user_the_impact_of_the_design_of_three-dimensional_virtual_worlds_on_user_representation.
28. Dreimane, L.F. (2019) “Understanding the Educational Rationale Behind Learning in Virtual Reality: a Historical Development Vignette” In Daniela, L. *Proceedings of ATEE Spring Conference 2019: Innovations, Technologies and Research in Education*. (p.23-37) University of Latvia Press;
29. Dreimane, L.F. (2020). Virtual reality learning experience evaluation tool for instructional designers and educators. In L.Daniela *New Perspectives on Virtual and Augmented Reality: Finding New Ways to Teach in a Transformed Learning Environment.* Taylor&Francis. Retrieved: https://www.routledge.com/New-Perspectives-on-Virtual-and-Augmented-Reality-Finding-New-Ways-to/Daniela/p/book/9780367432119
30. Eberle, T. S. (2014). Phenomenology as a Research Method. In U. Flick (ed.) *The SAGE Handbook of Qualitative Data Analysis*. (p. 184-202) . London: Sage Publications.
31. Elvestadt, E. O. (2016). *Evidence of Learning in Virtual Reality: A literature review*. Norway,Department of Computer Science. Norwegian University of Science and Technology, (p.11.) Retreived: http://www.idi.ntnu.no/~krogstie/project-reports/2016/elvestad/Litteraturstudie%20-%20Endre%20Elvestad%20-2016.pdf.
32. Erickson, T. (1993). Artificial Realities as data visualization environments: problems and prospects. In A. Wexelblat, (Ed.) *Virtual Reality - Applications and explorations*. London: Academic Press.
33. Flick, U. (2002). *An introduction to qualitative research* (2nd ed.). London: Sage Publications.

34. Friesen, N. (2012). *Report: Defining Blended Learning*. Retrieved: https://www.normfriesen.info/papers/Defining_Blended_Learning_NF.pdf.

35. Gagne, R. (1962). *Military training and principles of learning*. American Psychologist, 17, 263-276. Retrieved: https://psycnet.apa.org/doiLanding?doi=10.1037%2Fh0048613

36. Gagne, R. M., and Briggs, L. J. (1979). *Principles of instructional design* (2nd ed.). New York: Holt, Rinehart and Winston.

37. Gagne, R. (1985). *The Conditions of Learning* (4th ed.). New York: Holt, Rinehart and Winston.

38. Gagne, R. (1987). *Instructional Technology Foundations*. Hillsdale, New Jersey: Lawrence Erlbaum Assoc.

39. Gagne, R. and Driscoll, M. (1988). *Essentials of Learning for Instruction* (2nd ed.). Englewood Cliffs, New Jersey: Prentice-Hall.

40. Gagne, R., Briggs, L. and Wager, W. (1992). *Principles of Instructional Design* (4th ed.). Fort Worth, Texas: HBJ College Publishers.

41. Glaser, B.G. and Strauss, A.L. (1967). *The discovery of grounded theory: Strategies for qualitative research*. Hawthorne New York: Aldine Publishing.

42. Hartwick, P. and Nowlan. N. S. (2019). Integrating Virtual Spaces: Connecting Affordances of 3D Virtual Learning Environments to Design for Twenty-First Century Learning. In I. Management Association (Ed.), *Virtual Reality in Education: Breakthroughs in Research and Practice* (pp. 124-150). Hershey, PA: IGI Global. Retrieved: https://www.igi-global.com/chapter/integrating-virtual-spaces/224694

43. Holstein, J. A., and Gubrium, J. F. (1995). *Qualitative Research Methods: The active interview*. Thousand Oaks, California: Sage Publications.

44. Honer, A. (2004). Life-world analysis in ethnography, in U. Flick (Ed.), *A Companion to Qualitative Research*. (pp. 113–17). London: Sage.

45. Hutton, M. (1980). Learning from action: a conceptual framework. In S. Warner Weil and M. McGill (Eds.) *Making Sense of Experiential Learning* (pp. 50–9). Milton Keynes: SRHE/Open University Press.

46. Itin, C. M. (1999). *Reasserting the Philosophy of Experiential Education as a Vehicle for Change in the 21st Century*. The Journal of Physical Education, 22(2), 91-98. Retrieved: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.835.7043&rep=rep1&type=pdf

47. Jo, J. (2017, February 2). E-Learning through Virtual Reality. *Techkno.net:Latest Technology Updates*. Retrieved from http://www.techknol.net/2017/02/e-learning-through-virtual-reality.html.

48. Johnson, R. B., and Onwuegbuzie, A. J. (2004). Mixed methods research: A paradigm whose time has come. *Educational Researcher*, 33(7), 239-271. http://dx.doi.org/10.3102/0013189X033007014.

49. Johnson, R. B., Onwuegbuzie, A. J., and Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of mixed methods research*, 1(2), 112-133. Retrieved: https://journals.sagepub.com/doi/abs/10.1177/1558689806298224.

50. Johnson-Laird, P. N. (1983). Mental models: *Towards a cognitive science of language, inference, and consciousness*. Cambridge, UK: Cambridge University Press.

51. Jonassen, D. H. (1991). Evaluating Constructivistic Learning. *Educational Technology*, 31(9), 28-33. Retrieved: https://www.learntechlib.org/p/170798/.

52. Jonassen, D. H., Mayes, T., and McAleese, R. (1993). A manifesto for a constructivist approach to uses of technology in higher education. In T.M. Duffy, J. Lowyck, and D.H. Jonassen (Eds.) *Designing environments for constructive learning*. NATO ASI Series (Series F: Computer and Systems Sciences), vol 105. Berlin, Heidelberg: Springer.

53. Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development (ETR&D)*, 48(4), 63–85. Retrieved: https://link.springer.com/article/10.1007/BF02300500.

54. Jonassen, D. H. (2004). *Learning to solve problems: An instructional design guide*. San Francisco, California: Pfeiffer/Jossey-Bass.

55. Jonassen, D. H. (2007). Toward a taxonomy of meaningful learning. *Educational Technology*, 47(5), 30–35. Retrieved: https://www.jstor.org/stable/44429440?seq=1.

56. Kapp, K. M., O'Driscoll, T. (2010). *Learning in 3-D: Adding a New Dimension to Enterprise Learning and Collaboration*. San Francisco, California: Pfeiffer.

57. Kapp, K. M. (2017, January 3). 3 Instructional Design Strategies for Virtual Reality Learning. *E-Learning Industry: Instructional Design*. Retrieved: https://elearningindustry.com/instructional-design-strategies-virtual-reality-learning.

58. Keating, D. P., and Clark, L. V. (1979). Development of physical and social reasoning in adolescence. *Developmental Psychology*, 16(1), 23–30. Retrieved: https://onlinelibrary.wiley.com/doi/epdf/10.1002/cd.23219790506;

59. Kirkwood, A., Price, L. (2013). Technology-enhanced learning and teaching in higher education: what is ‘enhanced’ and how do we know? A critical literature review. *Learning, Media and Technology,* 39(1), 6-36, Retrieved: https://www.tandfonline.com/doi/full/10.1080/17439884.2013.770404?scroll=top&needAccess=true"needAccess=true

60. Kirschner, P. A., and Van Merriënboer, J. J. G. (2008). Ten steps to complex learning: A new approach to instruction and instructional design. In T. L. Good (Ed.), *21st century education: A reference handbook*. (pp. 244-253). Thousand Oaks, California: Sage Publications.

61. Kolb, D. (1984). *Experiential Learning as the Science of Learning and Development*. Englewood Cliffs, New Jersey: Prentice Hall.

62. Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory into Practice*, 41 (4): 212–218. Routledge. Retrieved: https://www.tandfonline.com/doi/abs/10.1207/s15430421tip4104_2.

63. Kolasinski, E. M. (1995). *Simulator sickness in virtual environments* (Technical Report 1027). U.S. Army Research Institute for the Behavioral and Social Sciences. Retrieved: http://www.dtic.mil/dtic/tr/fulltext/u2/a295861.pdf

64. LaViola, J. J. Jr (2000). A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, 32: 47–56. Retrieved: https://dl.acm.org/doi/10.1145/333329.333344.

65. Mantovani, F. (2001). VR learning: Potential and challenges for the use of 3D environments in education and training. In G. Riva and C. Galimberti (Eds.) *Towards cyberpsychology: Mind, cognitions and society in the internet age*. (pp. 207-226). Amsterdam: IOS Press.

66. Markaridian Selverian, M. E. (2004). *Being there in the VLE: A pan-pedagogical model for enhanced learning through perceptual states of "presence"*. Ph.D. Thesis. Temple University, Philadelphia, Pennsylvania. Retrieved: https://www.learntechlib.org/p/121832/

67. Mathews, M. (2017, June 13). Full Bloom with Mixed Reality. *Talentquest*. Retrieved: http://www.talentquest.com/full-bloom-with-mixed-reality/.

68. McLellan, H. (1996). Virtual realities. In D. H. Jonassen (Ed.) *Handbook of research for educational communications and technology.* (pp. 457-487). New York: Macmillan Library Reference, USA.

69. McLellan, H. (2003). Virtual realities. In D. H. Jonassen and P. Harris (Eds.) *Handbook of research for educational communications and technology* (2nd ed.) (pp. 461-498). Mahwah, New Jersey: Lawrence Erlbaum.

70. Merriam, S. B., Caffarella, R. S., and Baumgartner, L. M. (2007). *Learning in adulthood: a comprehensive guide*. San Francisco: John Wiley & Sons, Inc.

71. Merrill, M. D.; Drake, L.; Lacy, M. J.; Pratt, J. (1996). Reclaiming instructional design. *Educational Technology*. 36(5), 5-7. Utah State University. Retrieved: https://mdavidmerrill.files.wordpress.com/2019/04/reclaiming.pdf

72. Merrill, D., (2002). First Principles of Instruction. *Educational Technology Research and Development*, 50(3), 43-59. Retrieved: https://mdavidmerrill.files.wordpress.com/2019/04/firstprinciplesbymerrill.pdf

73. Muhanna, A. Muhanna. (2013). Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions. *Journal of King Saud University - Computer and Information Sciences.* 27(3), 344-361. Retrieved: https://www.sciencedirect.com/science/article/pii/S1319157815000439.

74. National Research Council, Computer Science and Telecommunications Board, Committee on Virtual Reality Research and Development. (1995). In N.I. Durlach and Anne S. Mavor (Eds.) *Virtual Reality: Scientific and Technological Challeng*es. Washington: National Academies Press, Retrieved: https://www.nap.edu/read/4761/chapter/1.

75. Nielsen, J. (1992). Finding usability problems through heuristic evaluation. In *Proceedings of the ACM CHI '92 Conference* (pp. 373-380). New York: ACM.

76. OECD. (2015). Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development. *The Measurement of Scientific, Technological and Innovation Activities*. Paris: OECD Publishing. Retrieved: https://www.oecd-ilibrary.org/docserver/9789264239012-en.pdf?expires=1584302178&id=id&accname=guest&checksum=CEB73704105750D54171E0D0D39443C3.

77. Pantelidis, V. S. (1993). Virtual reality in the classroom. *Educational Technology*, 33(4), 23-27. Retrieved: https://www.learntechlib.org/p/170877/.

78. Pantelidis, V. S. (1995). *Reasons to use virtual reality in education. VR in the Schools, 1(1), 9.*

79. Pantelidis, V. S. (1996). Suggestions on when to use and when not to use virtual reality in education. *VR in the Schoo*ls, 2(1), 18. (Retrieved August 2018: http://vr.coe.ecu.edu/vrits/2-1Pante.htm).

80. Pantelidis, V. S., & Auld, L. (2002). Teaching virtual reality courses online. *CCAI, Journal for the Integrated Study of Artificial Intelligence Cognitive Science and Applied Epistemology,* 19(3-4).

81. Pantelidis, V. S. (2009). Reasons to Use Virtual Reality in Education and Training Courses and a Model to Determine When to Use Virtual Reality. *Themes in Science and Technology Education,* Special Issue, 59-70. Klidarithmos Computer Books. Retrieved: https://www.researchgate.net/publication/268002587_Reasons_to_Use_Virtual_Reality_in_Education_and_Training_Courses_and_a_Model_to_Determine_When_to_Use_Virtual_Reality.

82. Papert, S. (1980). *Mindstorms: Children, computers and powerful ideas*. New York: Basic Books.

83. Papert, S. (1993a). *The Children's Machine: Rethinking School in the Age of the Computer.* New York: Basic Books, Inc.

84. Papert, S. (1993b). *Mindstorms* (2nd ed.). New York: Basic Books, Inc.

85. Papert, S., and Harel, I. (1991). Situating constructionism. In I. Harel and S. Papert (Eds.) *Constructionism*. Norwood, New Jersey: Ablex Publishing Corporation. Retrieved: http://web.media.mit.edu/~calla/web_comunidad/Reading-En/situating_constructionism.pdf.

86. Felicia, P. (2011). *Handbook of research on improving learning and motivation through educational games: Multidisciplinary approaches*. Hershey PA: Information Science Reference.

87. Perkins, D. (1985). The Fingertip Effect: How Information-Processing Technology Shapes Thinking. *Educational Researcher*, 14(7), 11-17. Retrieved: http://www.jstor.org/stable/1174808

88. Piaget, J., & Cook, M. T. (1956). *The origins of intelligence in children (2nd ed.)*. New York: International Universities Press. Retrieved: https://www.pitt.edu/~strauss/origins_r.pdf.

89. Roussos, M., Johnson, A., Moher, T., Leigh, J., Vasilakis, C., & Barnes, C. (1999). Learning and building together in an immersive virtual world. *Presence: Teleoperators and Virtual Environments*, 8, 247-263. Retrieved: https://www.researchgate.net/publication/2372520_Learning_and_Building_Together_in_an_Immersive_Virtual_World.

90. Salomon, G. (1992). Effects with and of computers and the study of computer-based learning environments. In Dans E. DeCorte, M.C. Linn, H. Mandl et L. Verschaffel (Eds.), *Computer-based Learning Environments and Problem Solving* (p. 249-263). Berlin: Springer-Verlag.

91. Salomon, G. (1994). Differences in patterns: Studying computer enhanced learning environments. Dans S. Voniadou, E. De Corte et H. Mandl (Eds.), Technology-based learning environments: Psychological and educational foundations (pp. 79-85). Berlin: Springer-Verlag.

92. Salomon, G., & Perkins, D. N. (1996). Learning in wonderland: What computers really offer education. In S. Kerr (Ed.). *Technology and the future of education*. (pp. 111-130). NSSE Yearbook. Chicago: University of Chicago Press.

93. Salzman, M. C., Dede, C., Loftin, R. B., & Chen, J. (1999). A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments*, 8, 293-316. Retrieved: https://www.mitpressjournals.org/doi/pdf/10.1162/105474699566242.

94. Siraj-Blatchford, I., Sylva, K., Muttock, S., Gilden, R. and Bell, D. (2002). *Researching Effective Pedagogy in the Early Years (REPEY).* London: Department for Education and Skills / Institute of Education, University of London.

95. Slater, M. (2003). A note on presence terminology. *Presence Connect*, 3(3), 1-5. Retrieved: http://s3.amazonaws.com/publicationslist.org/data/melslater/ref-201/a%20note%20on%20presence%20terminology.pdf.

96. Stegemann, K. C., and Jaciw, A. P. (2018). Making it Logical: Implementation of Inclusive Education Using a Logic Model Framework. *Learning Disabilities - A Contemporary Journal*, 16(1), 3-18. Retrieved, September 2018: https://files.eric.ed.gov/fulltext/EJ1179944.pdf

97. UNESCO Office Bangkok. (2014). *2013 Asia-Pacific Education Research Institutes Network (ERI-Net) regional study on integrating transversal competencies in education policy & practice (Phase I): regional synthesis report*. Retrieved: http://www.unescobkk.org/fileadmin/user_upload/epr/ERI-Net_Seminar/2013/Transversal_16_Oct.pdf.

98. Tashakkori, A. and Teddlie, C. (1998). *Mixed Methodology: Combing Qualitative and Quantitative Approaches*. London: Sage.

99. Tashakkori, A. and Teddlie, C. (2003). *Handbook of Mixed Methods*. London: Sage.

100. Tashakkori, A., & Teddlie, C. (2009). *Sage Handbook of Mixed Methods in Social & Behavioural Research* (2nd ed.). London: Sage Publications Ltd.

101. The European Parliament and the Council of the European Union. (2006). *Recommendation of the European Parliament and of The Council of 18 December 2006 on*

Key Competences for Lifelong Learning. European Commission. Retrieved: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006H0962.

102. Tomka, B. (2013). *A Social History of Twentieth-Century Europe*. London and New York: Routledge. Retrieved: https://www.routledge.com/A-Social-History-of-Twentieth-Century-Europe-1st-Edition/Tomka/p/book/9780415628457 .

103. Turner, C.W., and Nielsen, J. (2002). Current Issues in the Determination of Usability Test Sample Size: How Many Users is Enough? *Current issues in the determination of usability test sample size: How many users is enough*. Retrieved: https://www.semanticscholar.org/paper/Current-Issues-in-the-Determination-of-Usability-%3A-Turner-Nielsen/68e4d61c3c8b1adf2c57b09250d47fcac03027cc)

104. Van Merriënboer, J. J., & Kirschner, P. A. (2012). *Ten steps to complex learning: A systematic approach to four-component instructional design*. London and New York: Routledge.

105. Virtual Reality Society. (2017). *Advantages of virtual reality in medicine.* Retrieved: https://www.vrs.org.uk/virtual-reality-healthcare/advantages.html.

106. Virtual Reality Society. *What is virtual reality*? Retrieved: https://www.vrs.org.uk/virtual-reality/what-is-virtual-reality.html

107. Virzi, R. A. (1992). Refining the Test Phase of Usability Evaluation: How Many Subjects Is Enough? *Human Factors*, 34(4), 457-468. Retrieved: https://journals.sagepub.com/doi/abs/10.1177/001872089203400407.

108. Virtual Reality Society. (2017) "Virtual Reality in the Military - Virtual Reality Society". (Retrieved May 2018: https://www.vrs.org.uk/virtual-reality-military/).

109. Vygotsky, L.S. (1962). *Thought and Language*. Cambridge, MA: MIT Press.

110. Vygotsky, L.S. (1978). *Mind in Society*. Cambridge, MA: Harvard University Press.

111. Wann, J. and Mon-Williams, M. (1996). What does virtual reality NEED?: Human factors issues in the design of three-dimensional computer environments. *International Journal of Human-Computer Studies*. 44. 829-847. Retrieved: https://www.sciencedirect.com/science/article/abs/pii/S107158199690035X?via%3Dihub.

112. Winn, W. (1993). *A conceptual basis for educational applications of virtual reality.* Seattle, Washington: Human Interface Technology Laboratory, University of Washington. Retrieved: http://www.hitl.washington.edu/research/learning_center/winn/winn-paper.html~

113. Whitelock, D., Brna, P. and Holland, S. (1996). What is the value of virtual reality for conceptual learning? Towards a theoretical framework. In P. Brna, A. Paiva and J. A. Self (Eds.), *Proceedings of the European Conference on Artificial Intelligence in Education* (pp. 136–141). Lisbon: Edicões Colibri.

114. Youngblut, C. (1998). Educational uses of virtual reality technology. *Executive report. Reprinted from Educational uses of virtual reality technology (IDA Document Report Number D-2128)*. Alexandria, VA: Institute for Defense Analyses, 1998. VR in the Schools, 3(1). Retrieved: http://papers.cumincad.org/data/works/att/94ea.content.pdf.

Appendices

Appendix 1 – Evaluation tool

Macro-criteria	Criteria	Sub-criteria	*Title of the learning experience*
1. Purpose	1) Type of Experience	Activity Lesson Experience Interactive simulation Experience + activity Experience + lesson Immersive virtual world	
	2) Problem	Learning problem that has to be addressed	
	3) Goal	Single	
		Multiple / interdisciplinary	
		Adjustable	
	4) Fields of Science according to the OECD classification	Natural Sciences Engineering and Technology Medical and Health Sciences Agricultural Sciences Social Sciences Humanities	
		Primary FOS	
		Secondary FOS (interdisciplinary)	
	5) Solution	Presented learning solution	

2. Instructional strategy	6) What are the pedagogical perspectives that inform instruction?	Single		
		Multiple		
		Mixed		
		Behaviourism		
		Cognitivism		
		Constructivism		
		Connectivism		
	7) Learning Objectives	Single		
		Multiple		
	8) Chosen task design	Sequential		
		Interrelated		
	9) Possible competition element involved	Individual	Team	
		Ranking Score	Time-count	
		Adjustable	Other	
	10) Learner's role	Passive explorer – learner absorbs the experience, yet has no additional control over the environment in the speed or mode of interaction		
		Reactive – learner is actively responding and interacting with the learning environment		
		Pro-active – learner drives and controls the learning environment		
	11) Cognitive knowledge dimensions	Factual		
		Conceptual		
		Procedural		
		Meta-cognitive		

<table>
<tr><td rowspan="19"></td><td rowspan="6" colspan="2">12) Cognitive process dimension</td><td>Remember</td><td></td></tr>
<tr><td>Understand</td><td></td></tr>
<tr><td>Apply</td><td></td></tr>
<tr><td>Analyse</td><td></td></tr>
<tr><td>Evaluate</td><td></td></tr>
<tr><td>Create</td><td></td></tr>
<tr><td rowspan="7">13) Competences developed</td><td rowspan="3">Knowledge</td><td>Disciplinary knowledge</td><td></td></tr>
<tr><td>Interdisciplinary knowledge</td><td></td></tr>
<tr><td>Practical knowledge</td><td></td></tr>
<tr><td rowspan="3">Skills developed</td><td>Cognitive and meta-cognitive skills</td><td></td></tr>
<tr><td>Social and emotional</td><td></td></tr>
<tr><td>Physical and practical skills</td><td></td></tr>
<tr><td>Attitudes and values</td><td>Attitudes and values</td><td></td></tr>
<tr><td rowspan="4" colspan="2">14) Monitoring and assessment</td><td>Learner is assessed in real-time (right or wrong signals, score, points, levels, number of errors, completion time, other real-time metrics)</td><td></td></tr>
<tr><td>Learner is assessed after completing several sessions</td><td></td></tr>
<tr><td>Self-assessment</td><td rowspan="2"></td></tr>
<tr><td>No assessment is incorporated into the experience</td></tr>
</table>

3. VR learning experience design	15) Chosen technologies	High compatibility (a range of headsets devices / platforms)	
		Low compatibility	
		Web VR friendly	
		VR / AR / MR mode	
	16) Tracking analytics (e.g. attention, eye-movement, facial expressions, EEG, ECG, EMG, EDA)[19]	Engagement, interaction	
		Eye-tracking, viewpoint monitoring	
		Sensory tracking (facial expressions, EEG, ECG, EMG, EDA)	
		Haptic interaction	
	17) Type of VLE strategy	Individual	
		Group	
		Adjustable (real-time, multi-user, synchronous)	
		Avatar persona	
		Role play	
		Scavenger hunt	
		Guided tour	
		Operational application	
		Conceptual orienteering	
		Critical incident	
		Co-creation	
		Small group work	

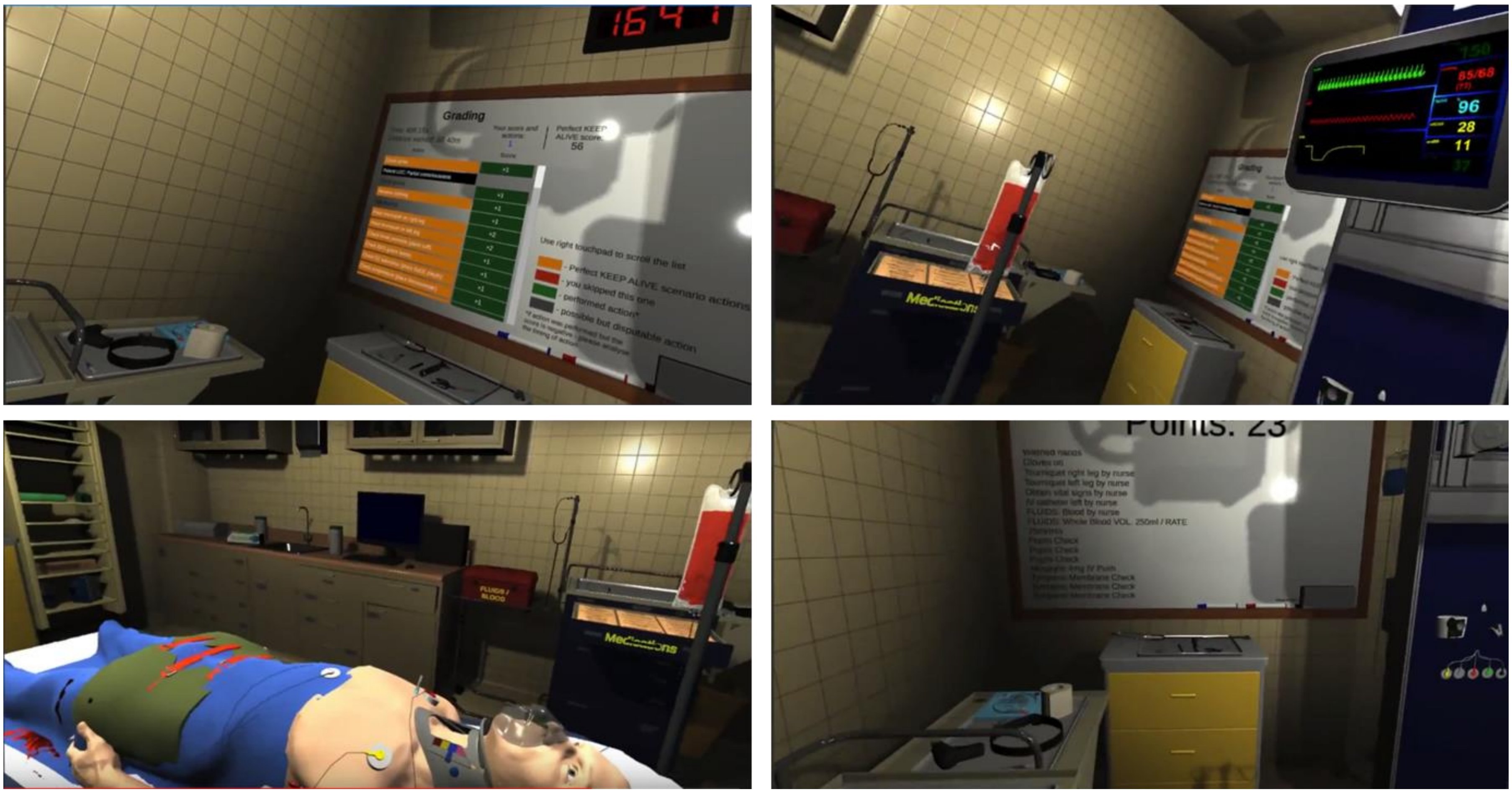
[19] EEG (electroencephalogram) – detects electrical activity of the brain; ECG (electrocardiogram) – measures electrical activity of the heart; EDA (electrodermal activity) – detects skin response to emotional stimuli; EMG (electromyography) – detects facial muscle movement.

		Group forums	
		Social networking	
	18) Role of VR space (including artefacts within the space) in achieving learning objectives	Primary significance – learning occurs from interaction with the space	
		Important – not a primary driver of learning experience, yet important in conveying contextual knowledge and cues	
		Supportive / entertaining	
	19) Characteristics of VR learning environment utilised	Representational fidelity	
		Learner interaction	
		Social fidelity (including social familiarity and social reality)	
		Social presence	
		Immediacy of discourse	
	20) Availability of instructor or feedback	Yes	
		No	
		Correct / incorrect guide, success rate, progress	
		Test or quiz	
	21) Learning affordances of VR space	Spatial knowledge representation	
		Experiential learning	
		Engagement	
		Contextual learning	
		Collaborative learning	

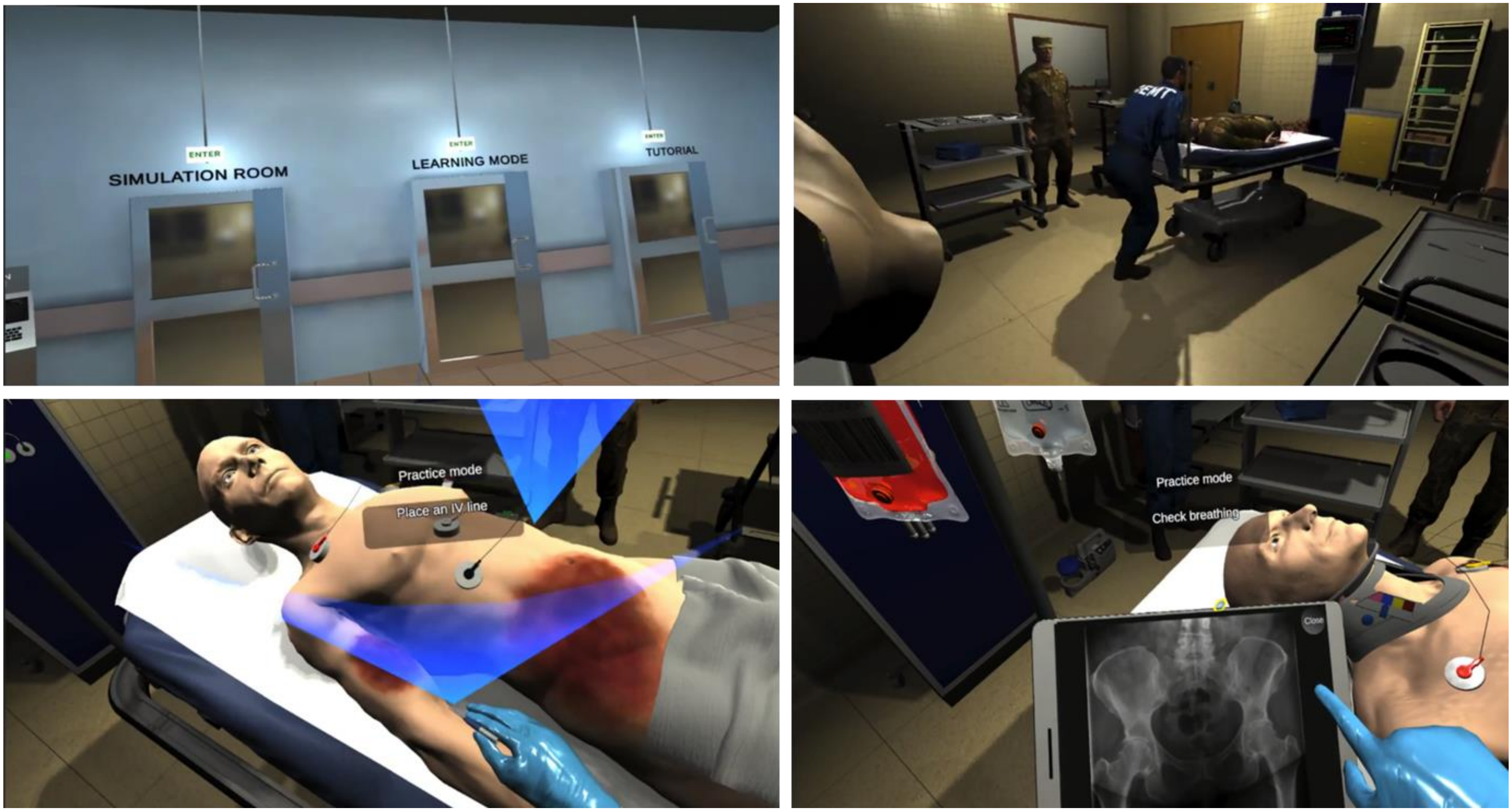
Appendix 2 – Screen Captures of VR learning experiences

"Life" medical care for a new-born infant by Oxford University (ENGAGE)

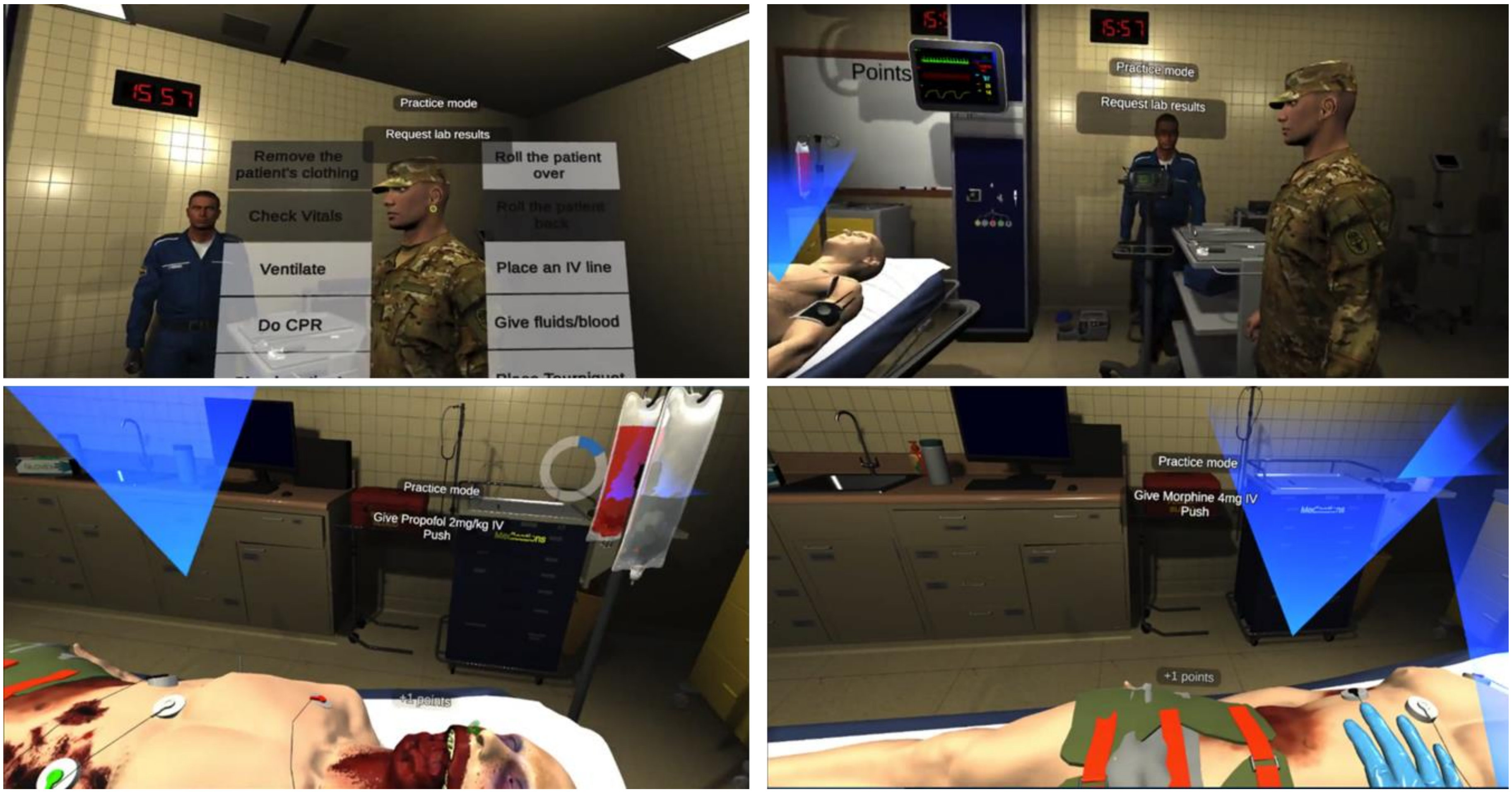
Trauma simulator by Exonicus



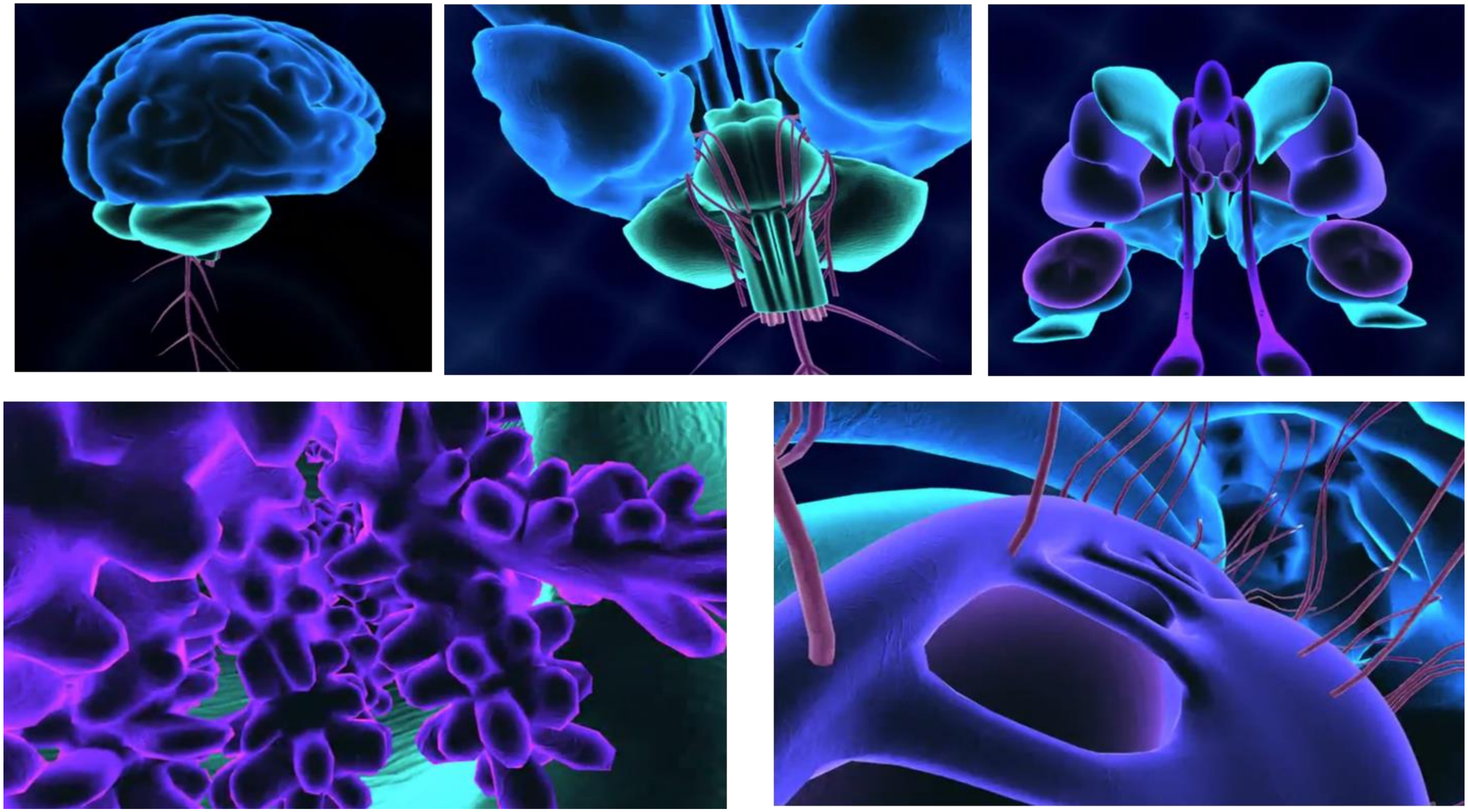

Give medications
Lab results
Imaging
Disposition
Nurse commands
Ask patient
Remove the patient's clothing
Check Vitals
Do CPR
Shock patient
Roll the patient over
Roll the patient back
Place an IV line
Place Tourniquet
Give blood
Give IV fluids
Give fresh frozen plasma
Give platelets
Give red blood cells
FLUIDS / BLOOD


ENTER
SIMULATION ROOM
LEARNING MODE
TUTORIAL
Practice mode
Place an IV line
Practice mode
Check breathing

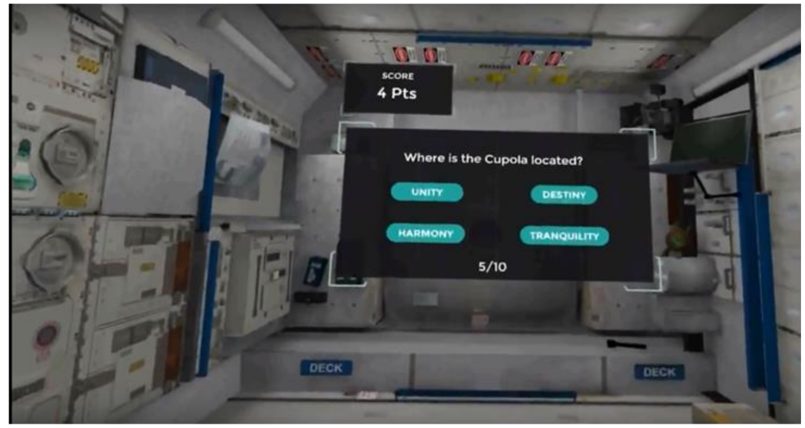

Practice mode
Give Morphine 4mg IV Push
Practice mode
Place pelvic binder
Practice mode
Give Whole blood 1000ml 100ml/min
Practice mode
Request lab results

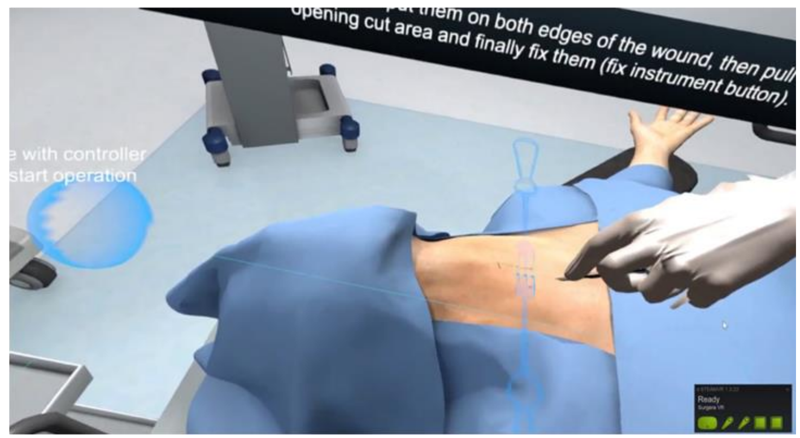

Practice mode
Request lab results
Remove the patient's clothing
Check Vitals
Ventilate
Do CPR
Roll the patient over
Place an IV line
Give fluids/blood
Points
Practice mode
Request lab results
Practice mode
Give Propofol 2mg/kg IV Push
Practice mode
Give Morphine 4mg IV Push
+1 points

Unimersiv "A Journey into the Brain"



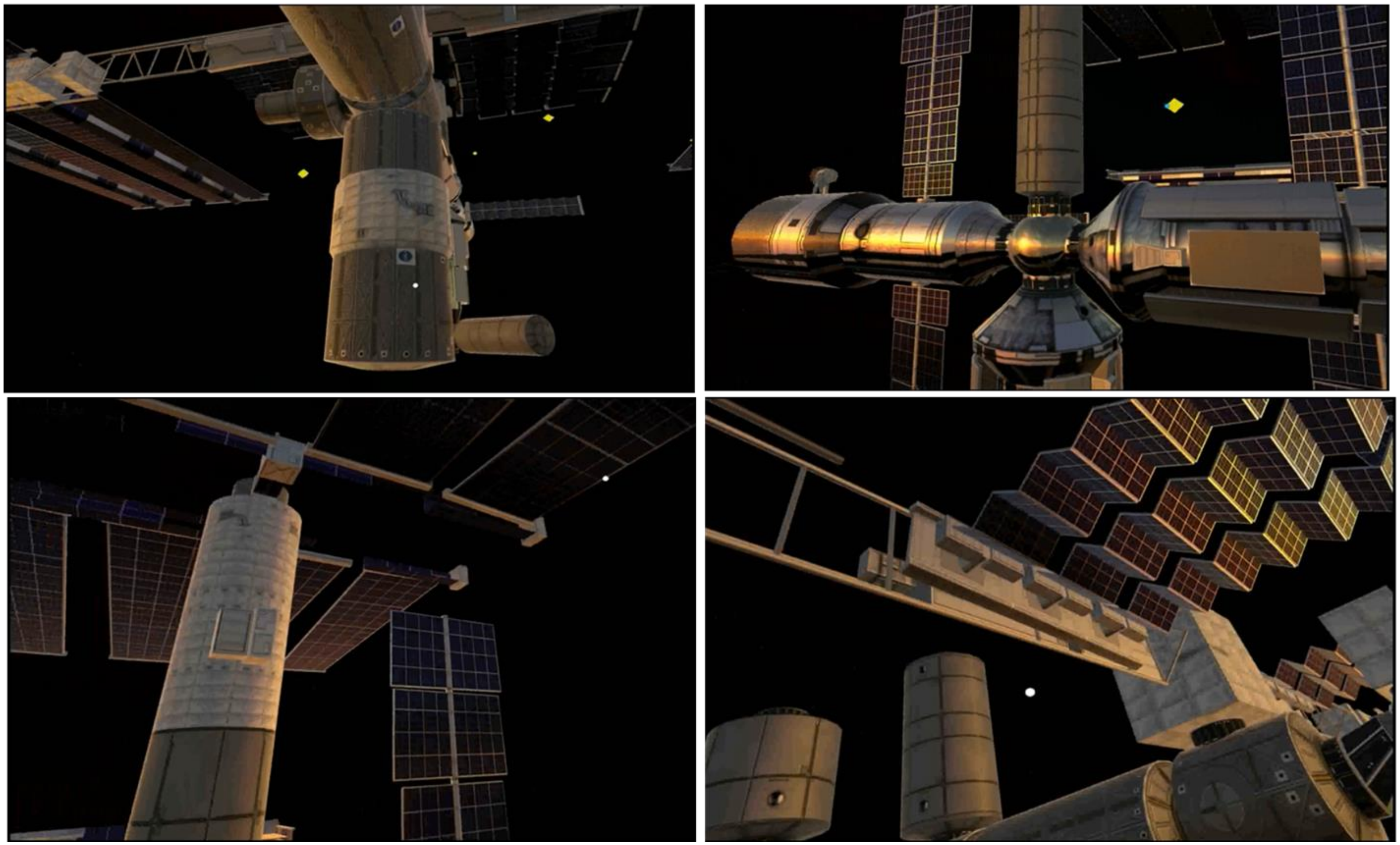
Unimersiv "International Space Station (Units)"



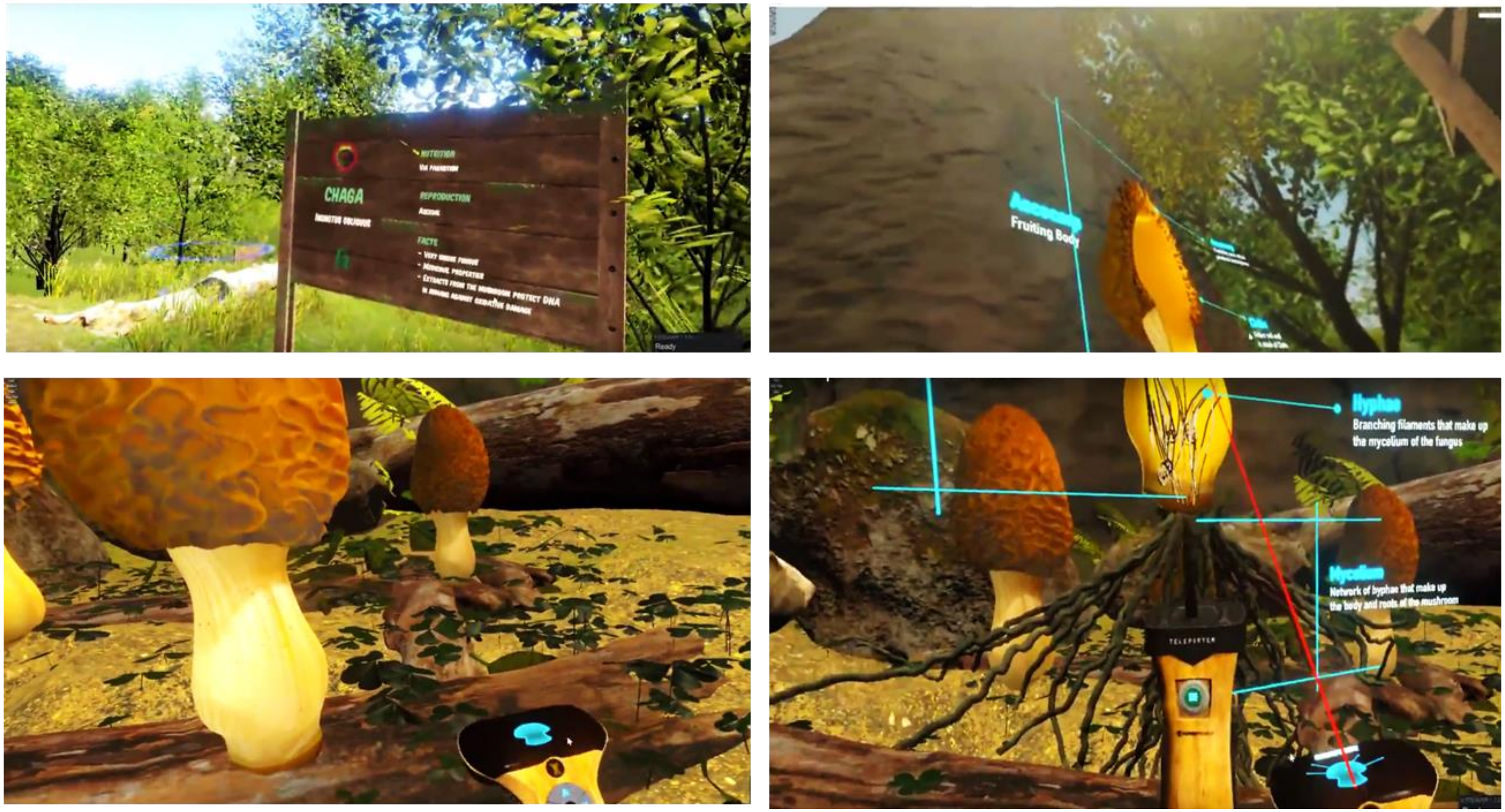


Surgera VR

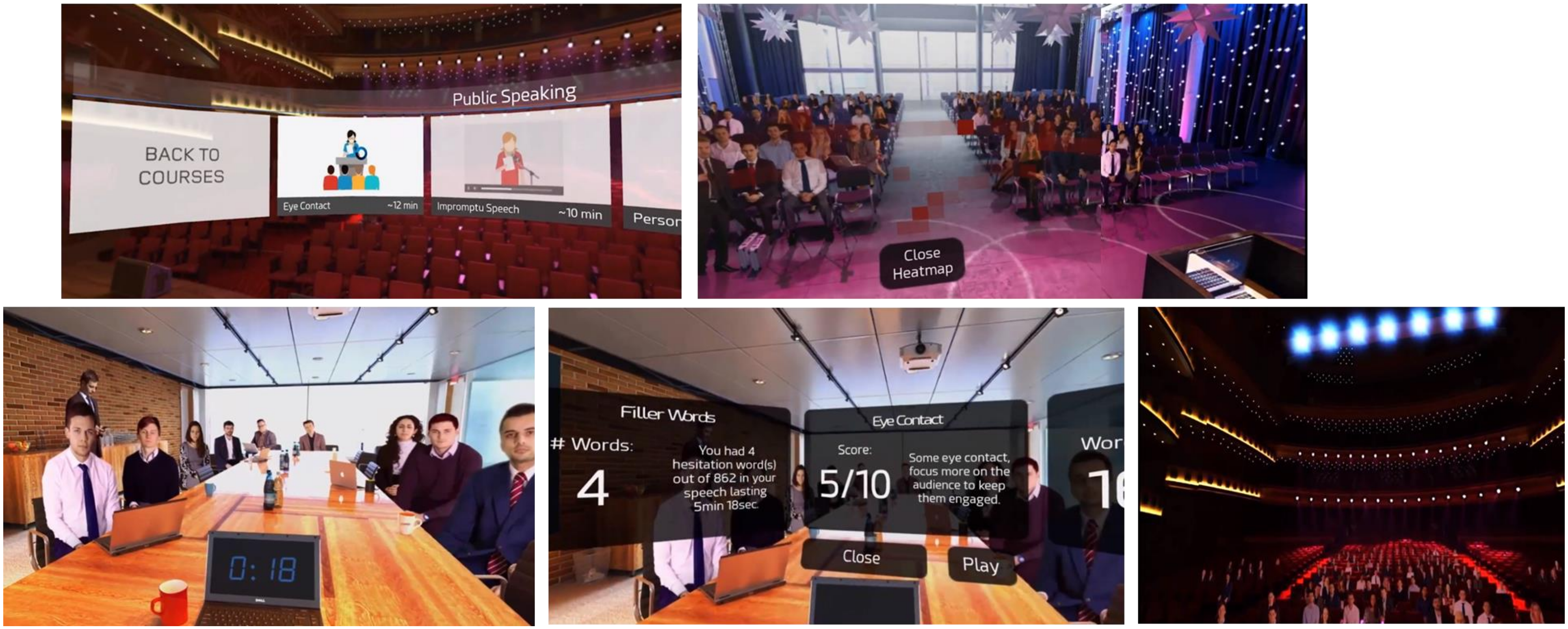
Explore the International Space Station by Unimersiv



Xennial - Fungi World

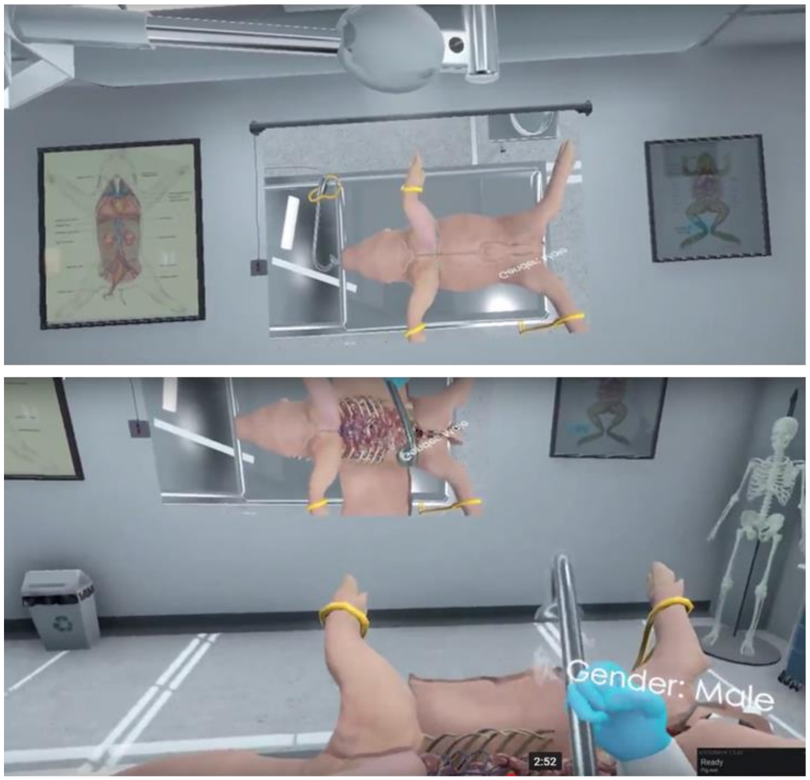


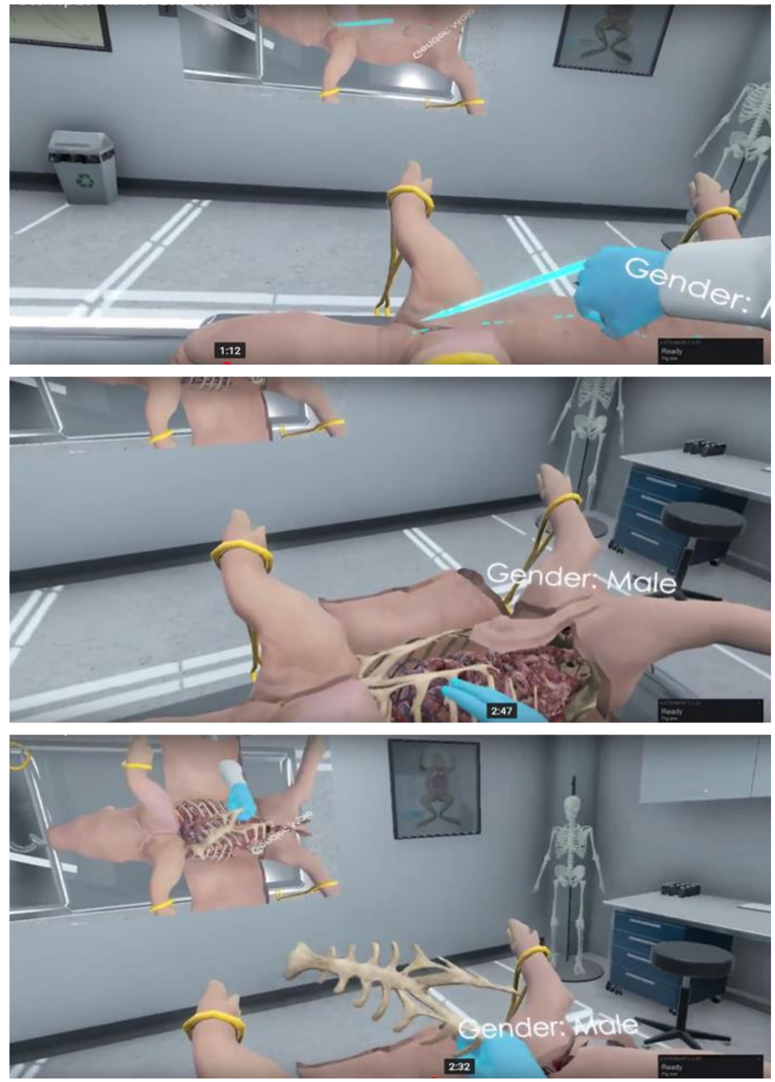
Virtual Speech (Public Speaking course)



Exploring Venus by Oxford University (ENGAGE)

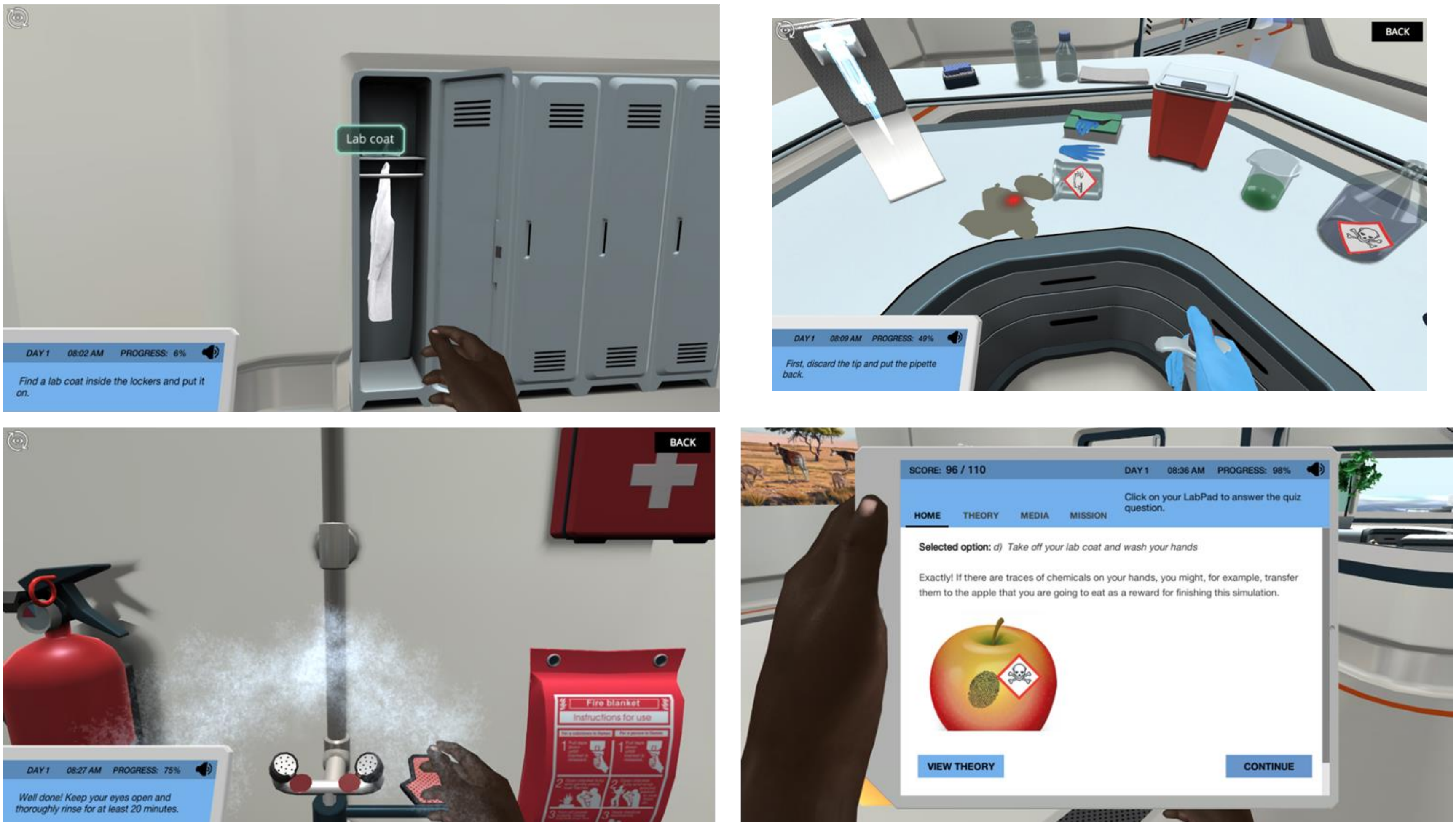
Xennial – Pig Dissection





Xennial – Chemistry reactions

Lab safety simulation (Labster)



Syrinx – Viking Village (Second Life)