Virtual Reality-Based Learning Environments: Recent Developments and Ongoing Challenges

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Abstract. Virtual Reality (VR) technologies bring new opportunities and challenges to teaching and learning. Virtual Reality Learning Environment (VRLE), a VR-based interactive environment incorporating instructional design for educational purposes, nowadays draws great attention of interdisciplinary scholars. In this paper, we first introduce the current status of VRLE-based research studies from various perspectives and then summarise the on-going challenges based on previous research studies and our own experience in this research area.

Keywords: Virtual reality · Virtual reality learning environment · Human-computer interaction · Special education

1 Introduction

The proliferation of Virtual Environments (VEs) developed for entertainment, game-play and education in recent years is driven partly by advances in and the reducing costs of the enabling technologies for immersive multimedia and natural multimodal interfaces. These technologies enable a user to interact with objects and/or characters within a virtual scenario designed to stimulate certain affects which in turn gives rise to a user experience that may not be possible to acquire easily or safely in the physical world. Due to these unique advantages of VEs, in the past decade, many VEs have been developed for serious applications in psycho-therapy [39], skill-based training [42] and education [29]. A recent survey of educational virtual environments defined a Virtual Reality based Learning Environment (VRLE) as "a virtual environment that is based on a certain pedagogical model, incorporates or implies one or more didactic objectives, provides users with experiences they would otherwise not be able to experience in the physical world and redounds specific learning outcomes" [29]. This definition puts emphasis on the pedagogical approach and the intended learning outcomes that underlay the design of the VRLE and the associated learning content, in which way it distinguishes VRLE from other types of VEs and interactive contents such as those designed purely for gaming or entertainment purposes.

From a pedagogical perspective, although in traditional learning environments (e.g., classroom, laboratory or fieldwork settings) learners have the opportunities to try and explore as part of the learning process, teacher-guided linear learning still

S.K.S. Cheung et al. (Eds.): ICHL 2015, LNCS 9167, pp. 3–14, 2015.
DOI: 10.1007/978-3-319-20621-9_1

dominates for most of the time. Furthermore, physical constraints frequently limit what can be simulated or what kind of authentic experience can be acquired in a classroom or laboratory setting. On the other hand, by virtue of its immersiveness and natural interaction with the learning content and using the pedagogical approach of constructivism, VRLEs motivate the learners to freely explore within the virtual space to achieve the learning outcomes, and provide unprecedented learning experience within a safe and controlled environment.

The learning cycle in VRLEs typically follows that of the Experiential Learning model [18] and begins with a learner being encouraged to explore a virtual scenery and to carry out a set of learning tasks within the environment. The VRLEs are programmed to react appropriately to the learner's action or behavior via providing multisensory feedbacks, which prompt the learner to react upon his/her actions and to formulate new ideas or solutions to the tasks at hand that s/he can then try or test out in the environment. This learning process can be repeated at almost no cost, through which learners will gradually build their own knowledge or skills on specific learning domains.

Comparing to the enabling technologies for VRLEs ten years ago, the three main areas oftechnologies that supporting VRLE-based teaching and learning, saying immersive virtual realitytechnologies, multimodal interface technologies, and development tools for VR contents, aremore accessible. Some commercially available VR-enabling products (e.g., Oculus Rift, Microsoft Kinect, Unity 3D game engine, etc.) further lower the cost of tailor-made VRLE development and deployment.

In this paper, we will briefly review the recent developments of VRLE and particularly we will focus on some representative VRLEs developed between the five years period of 2010 to 2014. These VRLEs will be discussed with reference to their underlying pedagogies and theories, learning domains, contents, and interactive design.

2 Learning Theories for VRLEs

Cognitive Load Theory (CLT) and constructivism (as a learning theory) are the two dominant learning theories that are predominant in guiding the design of VRLE and the associated training protocols. In this section, we will briefly introduce both of the theories and discuss how they are applied to guide the design of VRLEs.

2.1 Cognitive Load Theory

The Cognitive Load Theory (CLT) was proposed based upon the concept of Working Memory (WM) (a.k.a., short-term memory). Short-term memory is very limited in terms of capacity and persistence [30]. On the contrary, modern cognitive science research suggests that Long-Term Memory (LTM) appears to have an unlimited capacity, and information is stored and organized in LTM as schemas, and postulated that learning mechanism in human is based upon the interplay between WM and LTM (See Fig. 1.) [31].

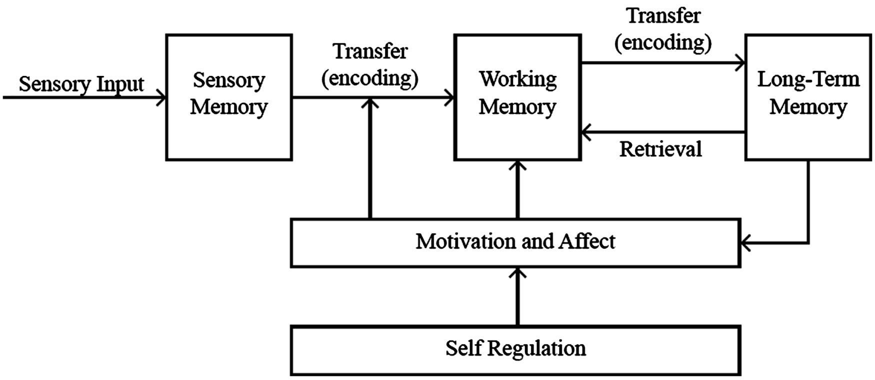

Fig. 1. Cognitive-affective theory of learning with media [31]. The diagram shows not only the interaction between Working Memory and Long-Term Memory during cognitive processes, but also the effects of motivation and affect on the processes

Specifically, three types of cognitive load have been identified in previous research studies [46, 33]; they are (1) extraneous cognitive load, (2) intrinsic cognitive load, and (3) germane cognitive load. CLT suggests that, when designing learning contents, we need to minimize extraneous cognitive load [34], appropriately manipulate intrinsic cognitive load (e.g., [45] incorporates Intelligent Tutoring System (ITS) approaches to VRLE), and maximize germane cognitive load [6].

2.2 Constructivism (as Learning Theory)

Constructivism admits that the external world is real and objective but everyone may interpret the external world in his/her own way based on personal experience and knowledge [19].

The major challenge of applying constructivism approaches either in VRLEs or other types of learning environments, from the pedagogical perspective, is how the environment or facilitators can support learners in an efficient and appropriate way. Previous research studies question that VRLE-based learning programs without appropriate guidance and feedbacks, especially in the early stage of learning or at the point where the learner encounters great difficulty, may be inefficient [48, 2, 47]. For example, learners may need extra time to get used to the learner-scenario interactions or the immersive VR displays in order to avoid disorientation.

There are also concerns on unexpected learning outcomes if insufficient support (e.g., scaffolding, debriefing, etc.) is provided to learners [21].

Hauptman [13] suggests using self-regulating questions to scaffold learning when applyingconstructivism. The study investigates whether self-regulating questions can improve learning effectiveness via a self-designed and self-develop program called Virtual Space. The experiment conducted on a population of 194 using factorial design reveals evidences showing that self-regulating questions make VRLE-based learning more efficient, in terms of enhancing learners' spatial thinking. Besides, other studies had also suggested introducing collaborative learning as a supportive tool of applyingconstructivism [3, 25, 14]. In those collaborative VRLEs, learners proactively provided support to their peers who encountered difficulties. Huang and Hu [14] evaluated and analyzed the peer learning behavior in a self-designed collaborative mathematics learning virtual environment. Results show that the students were more active in the collaborative environment and “not only solved the (geometry) problem on their own tables and white boards, but also criticized peers’ solutions and helped.. . to get answers”.

In summary, researchers and scholars are aware of the shortcomings of constructivist approaches when applied to VRLEs (e.g., problem-based learning, experiential learning, discovery learning, case-based learning, etc.), and have attempted to overcome them by introducing self-regulation, peer support or support from instructors as part of the learning process. However, Fowler [9] points out that although many studies have adopted various approaches based on constructivism, few of them had “a clear (theoretical) pedagogical model” to guide and inform the design and use of the VRLEs.

3 Learning Domains for VRLEs

VRLEs have been applied in various learning domains (e.g., biology and ecology, language learning, mathematics, chemistry, history, art, etc.) in previous research studies. Most of these learning and training programs benefit from two advantages of VRLEs. First, VRLEs help spatial cognition training; and second, simulations and simulated situations can be easily recreated, presented, and repeated in the virtual reality setting.

3.1 Spatial Cognition Training

Since spatial cognition has been shown to be the foundation of many other learning topics, VRLE has been developed and used extensively for spatial cognition training.

For example, [37] and [23] are two novel studies using VRLEs on visually impaired people for spatial cognition training. In conventional VRLEs, visual stimulation dominates the sensory inputs. However, visually impaired people can hardly been visually stimulated. In both studies, the authors successfully recreated virtual indoor environments with automatic speech guidance according to real indoor environments, so that learners can sense the environments via auditory and haptic stimulations. [13] and [50], on the other hand, use VRLE for spatial cognition training in a more conventional way. Traditional spatial cognition training requires learners to mentally manipulate two-dimensional shapes or three-dimensional objects. This supposes to be a challenging task because there are no direct visual feedbacks during mental manipulation. VRLEs are ideal for this kind of training, because any kind of manipulation can be instantly visualized.

Besides the four studies mentioned here, the use of VRLEs as a tool for spatial cognition training can also be found in [22, 28, 27, 24, 22] investigates the possibility of using spatial memory to help students remember history chronology. Merchant et al.

[28] and Merchant and Goetz [27] use VRLE to help students learn Valence-shell Electron Pair Repulsion theory (VSEPR) in chemistry. According to all the authors of these mentioned publications, achieving the intended learning outcomes requires spatial thinking ability either directly or indirectly.

3.2 Learn by Simulation

VR environments are designed to make users sense presence [44]. Hence, the technology must be able to simulate the real world in terms of visual fidelity, laws of physics, and sometimes even social interactions. In such simulated and highly interactive environments, students are free to experience and explore. Most of the topics in science and engineering learning indeed encourage and require students to test hypothesizes via controlled experiments and precise measurements. We see some of the studies using VRLEs directly as a tool for laboratory sessions in, for example, [40, 32]; or fieldwork sessions in [10, 38].

In the Hummingbird Survival learning scenarios [16] developed based on the SAMAL Model for affective learning proposed by Ip et al. [15, 18], we not only simulate and model the hummingbird flying physics and surviving criteria in the scenario but also implement the learner-scenario interaction based on motion and pressure sensors (Wii remote and balance board), so that learners can experience the simulated learning content in a much more immersive and intuitive way.

VRLEs can also be programmed to simulate social situations. For example, [5, 26] aim to help learners with special education needs. These studies make very good use of VRLEs as tools to recreate and simulate social situations. Those social situations allow learners, especially learners with Autism Spectrum Disorders (ASD) or Autistic Syndrome Conditions (ASC), to practice their social skills and social functioning in a safe and private environment without the risk of embarrassing themselves or others. We will further address several examples in Sect. 5.1.

4 Education Activities for VRLEs

Various educational activities have been applied in recent VRLE-based research studies (e.g., problem-based learning, inquiry-based learning, discovery learning, role playing, collaborative learning, virtual laboratories, virtual fieldwork, etc.) with the characteristics of VRLEs in mind. According to previous surveys (e.g., [29, 8, 49]) and our study, problem-based learning, inquiry-based learning (a.k.a., discovery learning) and collaborative learning are the three most widely adopted education activities for VRLEs.

4.1 Problem-Based Learning

Problem-based learning is the education activity in which learning is driven by solving problems. Specifically, learners are first given an authentic problem, and during learning, learners are expected to solve this particular problem in the virtual environment via solving a series of sub-problems. There are many VRLE-based studies explicitly state the adoption of problem-based learning (e.g., [13, 28, 14, 50], etc.). The two major issues of problem-based learning are that (1) at the very early stages of learning, when learners are not familiar with the environment enough, they could possibly lost their interests and motivation; and (2) in the later stages, misconcepts could form if there is not enough support or guidance. Hence, several studies suggested that after the VRLE-based training, instructors should help students clarify any misconcepts via post-learning activities (e.g., debriefing, and consolidation, etc.) [41].

4.2 Inquiry-Based Learning

Inquiry-based learning typically started with a topic or a task. The learners were required to observe, pose their own research questions, design research methods, collect data, analyze data, draw conclusions, and present the findings. VRLEs provided the ideal environments for this type of education activity; in the virtual environment, learners are free to explore unfamiliar or even hostile and inhabitable environments (e.g., underwater world, disaster scenes, Mars surface, the VEL science project[1] [38]) without worrying about their safety or the accuracy of their virtual data collection tools.

4.3 Collaborative Learning

Collaborative learning is a constructivism approach that can invoke and practice collaboration skills among learners. In practice, collaborative learning is recommended and adopted by many modern VRLE-based learning and training programs based on constructivism. The reasons are quite simple: (1) large scale collaborative learning cannot be easily realized in conventional learning environments due to physical and geographical constraints [7, 35]; and (2) the peer-based activities (e.g., peer review, peer sharing, etc.) are proved to be pedagogically beneficial, especially when incorporating with other constructivism approaches [3, 25, 14].

As the development of high speed network connections and in-browser VR technology (e.g., WebGL), two major open collaboration VR platforms, Second Life[2] and Open Wonderland,[3] have been widely used in VRLE research studies adopting the paradigm of collaborative learning (e.g., [10, 28, 27, 12, 4], etc.). These latest research studies on applying collaborative learning in VRLE-based training programs focused on investigating the very fundamental question; that is compared to real world settings (e.g., classroom, lecture hall, etc.) which allow collaborative learning, how VRLEs influence collaborative learning. To answer this question via psycho-educational experiments, most of the latest research studies we mentioned above simulate and recreate the real world settings in the VR for the intervention, so that only the medium of learning content delivery will be changed while the basic environment settings are

[1] http://www.velscience.com/

[2] http://secondlife.com/

[3] http://openwonderland.org/

kept the same (i.e., basic environment setting, as an independent variable, is controlled). From the psycho-educational experiment point of view, those studies are well designed and give concrete and solid evidences showing that VRLEs encourage peer activities [28, 27, 12]. However, we see that most of these studies do not fully benefit from the adoption of VR technologies. Specifically, the recreation of real world settings without introducing or exploiting the unique features of VR (e.g., the ability of simulating complex processes purely based on learner-scenario interaction, etc.) seems to be done mainly for the purpose of psycho-educational experiments and did not take the full advantages of VR-based collaborative learning.

5 VRLEs for Special Education

Because of the characteristics and uniqueness of VRLEs mentioned above, several pioneering studies investigate the possibility and pedagogical guidelines of applying VR technologies for special education. In this section, we discuss the use of VRLEs for learners with Autism Spectrum Disorder (ASD) or Autistic Syndrome Conditions (ASC) and for learners with intellectual disabilities.

5.1 VRLEs for Leaners with ASD or ASC

According to [1], individuals with ASD have "neurodevelopment disorders characterized by deficits in social perception and cognition, subtle impairment of verbal and non-verbal communication, presence of idiosyncratic isolated interests, and repetitive behaviors". The major objective of using VRLEs for learners with ASD or autistic features is to help them improve their social competence via practicing in simulated real-world social situations. By applying VR-based learning rather than real-world situated learning, embarrassment and potential danger can be avoided.

For example, the collaborative VRLE proposed in [5] aims to help learners with ASD or ASC understand empathy, which is considered as a wider definition than "theory of mind". The authors recreate a restaurant setting and script four social scenes in which the learner may utilize empathy. Because the virtual setting and learning content are replicated from daily life, the learners are expect to generalize and transfer what they have learned in the VRLE to their daily life. As expected, during training and post-training maintenance sessions, the learners all exhibit improvements in terms of understanding of empathy comparing to their baseline performance. However, the experiment was conducted on only three participants with ASD. The results are therefore not particularly conclusive unless the effects could be demonstrated on more individuals.

Lorenzo et al. [26] help learners with Asperger Syndrome (a.k.a., high functioning ASD) using similar technologies but for different purposes. The study aims to improve learners' executive functioning via organizing, planning and executing tasks with persistent attention in the VRLE. Specifically, the authors design 16 tasks (e.g., preparing materials for the following school day, asking the teacher questions, inviting a friend to play at home, etc.) to be executed in the VRLE. Each of the 16 tasks will be carried out for 5 times. The training will last for almost one school year excluding school holidays. It seems the excessive and highly repeated training is necessary for learners with ASD, because by interpreting the collected data, we can observe cases of relapse in terms of executive performance after summer holidays. However, if relapse does exist, there is lack of evidence to show the program's long-term effects.

Although the above studies as well as other relevant studies, which use VRLEs to help learners with ASD or ASC, indeed show some promising results, the effectiveness, especially long-term effectiveness and knowledge or skill transferring rate which are quite critical for learners with ASD or ASC, needs to be further investigated [36].

5.2 VRLEs for Learners with Intellectual Disabilities

The learning difficulties that teenage and adolescent learners with intellectual disabilities are facing during every day learning are severe. These learners need simultaneous repetitions to develop cognitive awareness and to acquire and practice generic skills [43]. VRLEs provide such safe and highly repeatable environments for them to learn.

Based on the SAMAL Model [15, 18], Ip et al. [17] further extended the use of VRLEs for severe intellectually disabled (SID) learners. The novel programme consists of 8 specially designed virtual reality learning scenarios to help SID learners in 4 learning domains (see Fig. 2). They are (1) safety awareness domain, (2) cause and effects domain, (3) balance and coordination domain, and (4) sensational experience learning domain. Preliminary quantitative evaluation shows that both in school setting and in off-campus settings, most of the SID participants are more engaged and motivated. Interviews with the teachers and the parents indicate that knowledge and skills SID participants learnt in the VRLE can be successfully transferred to real life.

The major challenge of designing VRLEs for learners with intellectual disabilities is how to make the learning contents adaptive to the learners' ability. Because of the variety of their intellectual disabilities, intrinsic cognitive load of the same learning content could be dramatically different from individual to individual. Also, intellectual disabilities, especially severe intellectual disabilities, could possibly be accompanied by physical disabilities, which limit the interaction between learners and the environment. Hence, the content design and instructional design should consider the learners' special needs as much as possible.

6 On-going Challenges and Open Issues of VRLEs

VRLE is a relatively new medium for teaching and learning. Questions on the learning effectiveness of using VRLEs have been raised since the emergence of this medium.

Traditional evaluation approaches require rigorous psycho-education experiments. For example, to apply the most commonly used ANCOVA approach, each learner needs to be assigned to either the control group or the intervention (treatment) group randomly [20]. Even this is very difficult to achieve for most of the school-based VRLE research studies, because the randomness requirement of ANCOVA approach and

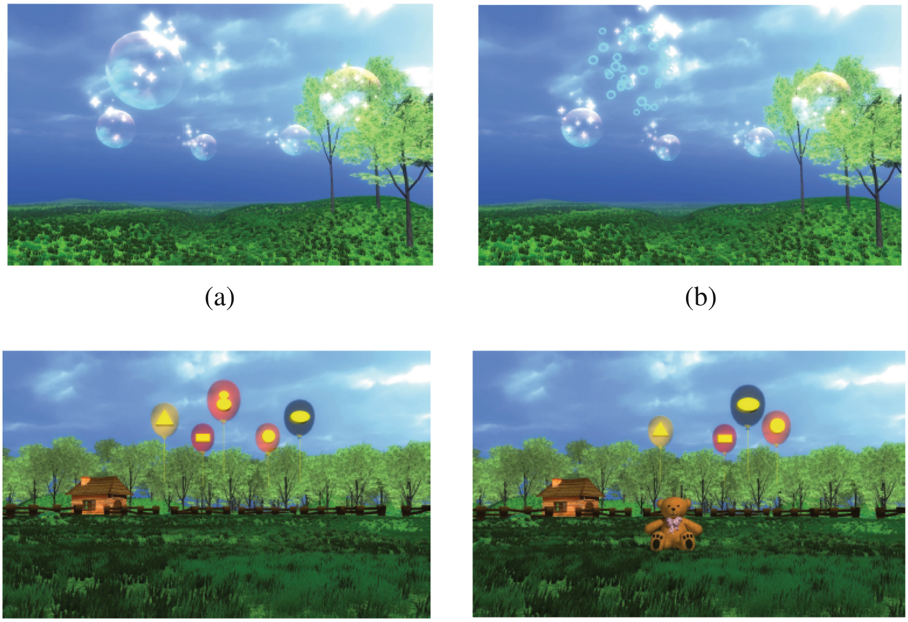

Fig. 2. Screenshots of InSPAL learning scenario "Touch-to-Change" and "Coloured Balloon Sculpture" [17]. The learning scenario "Touch-to-Change" ((a) and (b)) is designed to be visually less complex than "Coloured Balloon Sculpture" ((c) and (d)) is, in order to lower the cognitive load of learners during their very first exposures to the VRLE.

other experimental designs makes the research hard to be integrated into school curriculum and could cause potential logistic issues.

Besides challenges on the practical adoption of experimental designs, unlike psychological experiments which are usually carried out in laboratory settings in a relatively short time, education programmes usually last for months in unstructured open settings. Hence, even if the evaluation results appear to be promising, it may not be possible to tell whether it is due to the programme or other uncontrolled variables. Similar concerns have been reported in [11].

Another major concern on the effectiveness of VRLE-based education programmes is that most research studies failed to assess long-term knowledge and skills transferring. Although many previous research studies favor VRLE as a tool enabling harmless simulation of physical or social situations, how to guarantee the transferring of knowledge and skills learners acquired in VRLEs needs to be further investigated via long-term observation and assessment.

Acknowledgement. We would like to thank our colleagues, Ms. Julia Byrne and Ms. Kate S Y Lau, of Centre for Innovative Applications of Internet and Multimedia Technologies (AIMtech Centre) and Department of Computer Science, City University of Hong Kong, for their contribution to our research studies on VRLEs for general and special education.

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