



Educational virtual environments: A ten-year review of empirical research (1999–2009)

Tassos A. Mikropoulos*, Antonis Natsis¹

The Educational Approaches to Virtual Reality Technologies Lab, Department of Primary Education, The University of Ioannina, Ioannina 45110, Greece

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ABSTRACT

This study is a ten-year critical review of empirical research on the educational applications of Virtual Reality (VR). Results show that although the majority of the 53 reviewed articles refer to science and mathematics, researchers from social sciences also seem to appreciate the educational value of VR and incorporate their learning goals in Educational Virtual Environments (EVEs). Although VR supports multisensory interaction channels, visual representations predominate. Few are the studies that incorporate intuitive interactivity, indicating a research trend in this direction. Few are the settings that use immersive EVEs reporting positive results on users' attitudes and learning outcomes, indicating that there is a need for further research on the capabilities of such systems. Features of VR that contribute to learning such as first order experiences, natural semantics, size, transduction, reification, autonomy and presence are exploited according to the educational context and content. Presence seems to play an important role in learning and it is a subject needing further and intensive studies. Constructivism seems to be the theoretical model the majority of the EVEs are based on. The studies present real world, authentic tasks that enable context and content dependent knowledge construction. They also provide multiple representations of reality by representing the natural complexity of the world. Findings show that collaboration and social negotiation are not only limited to the participants of an EVE, but exist between participants and avatars, offering a new dimension to computer assisted learning. Little can yet be concluded regarding the retention of the knowledge acquired in EVEs. Longitudinal studies are necessary, and we believe that the main outcome of this study is the future research perspectives it brings to light.

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1. Introduction

Information and Communication Technologies (ICT) are considered to be one of the most powerful tools for the support of the learning process (Jonassen, 1999; Smeets, 2005). Their contribution mainly comes from their technological characteristics, the ways they record, manage, represent and communicate data and information. These characteristics concern the management of a high volume of data and information in a short time, information presentation through dynamic interactive and multiple representations, and communication. However, the essential contribution of ICT to the learning process comes indirectly through their pedagogical exploitation and certain features that arise from the above technological characteristics. This contribution mainly involves tasks for the active participation in the learning process for students and teachers, action and feedback through educational scenarios and interactive meaningful learning activities based on a certain theoretical model, as well as processes that support the creation of mental models. Our view is in concurrence with Dalgarno's and Lee's conception that "technologies themselves do not directly cause learning to occur but can afford certain tasks that themselves may result in learning" (2010).

Virtual Reality (VR) technologies seem to have become a powerful and promising tool in education because of their unique technological characteristics that differentiate them from the other ICT applications. VR can be described as a mosaic of technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments that represent real or non-real situations. This

* Corresponding author. Tel.: +30 2651005697; fax: +30 2651005484.

E-mail addresses: amikrop@uoi.gr (T.A. Mikropoulos), anatsis@cc.uoi.gr (A. Natsis).

¹ Tel.: +30 2651005655; fax: +30 2651005484.

description shows that VR can be pedagogically exploited through its unique technological characteristics that can be compiled as follows (Mikropoulos & Bellou, 2006):

- creation of 3D spatial representations, namely virtual environments (VE)
- multisensory channels for user interaction
- immersion of the user in the VE
- intuitive interaction through natural manipulations in real time.

An Educational Virtual Environment (EVE) or Virtual Learning Environment (VLE) can be defined 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.

Virtual reality is usually described in terms of a “collection of technological hardware” (Steuer, 1992), thus having a technological focus. However, this technological approach fails to provide a conceptual framework for the educational uses of virtual reality. Learning using virtual environments has been proposed since 1990 when Bricken specified natural semantics and cognitive presence as the main features of virtual environments and constructivism as the theoretical model supporting EVEs. In 1992 Helsel proposes a conceptual and not technological orientation to VR concerning educational applications, describing VR as “a process that enables users to become participants in abstract spaces where the physical machine and physical viewer do not exist”. Pantelidis (1993) provides a number of reasons for the use of VR in the classroom reporting active participation, high interactivity and individualisation as the main features for learning outcomes. Winn (1993) argues on a conceptual basis for educational applications of VR stating that immersive systems involve first-person experience and non-symbolic interaction, and support the construction of knowledge under a social constructivist point of view. Later Winn and Windschitl (2000) extend his theoretical approach to desktop VR environments, reporting that the sense of presence that students feel in the virtual environments is of major importance in the learning process. This is because the sense of presence enhances “first hand” experiences (Winn & Windschitl, 2000) and “first-person psychological activity occurring when people interact directly with worlds, whether real or virtual” (Winn, 1993). Researchers in these first steps of VR educational applications argue on the usefulness of VR as an educational tool, although evaluations of certain EVEs do not exist yet.

Since then, a number of research articles have appeared reporting on the design, development and evaluation of EVEs concerning a variety of disciplines and different educational levels. There are many technological approaches that the EVEs follow, but few pedagogical ones. In general, only a minority of studies report on specific VR features that EVEs exploit and on evaluations based on these. The unique features that designate VR as a promising and powerful educational tool are not yet so clear.

Learning is a complex process and the features of a learning environment do not act in isolation, but they all play a role in the learning process and outcomes (Salzman, Dede, Loftin, & Chen, 1999). However, defining and studying the main features that arise from the VR characteristics is an important step in understanding the contribution of virtual environments to learning outcomes.

Spatial representations allow the user complete at will navigation in the 3D virtual space, as well as a first-person user point of view. Virtual environments allow the use of natural semantics, thus avoiding the use of difficult to learn and remember symbolisms (Mikropoulos, Chalkidis, Katsikis, & Emvalotis, 1998). Winn (1993) has proposed ‘size’, ‘transduction’ and ‘reification’ as features for educational VR applications. Changes of size are significant for the learning process. The virtual environment gives the users the ability to ‘change’ their physical size, so that they can navigate and interact in macro and micro worlds, such as inside an atom (Kontogeorgiou, Bellou, & Mikropoulos, 2008) or in the solar system (Bakas & Mikropoulos, 2003). A VE as a transducer extends the user’s capability to feel data that would normally be beyond the range of their senses or experiences. Reification implies the transformation of abstract ideas into perceptible representations, something that can be realized by virtual objects. These features seem to be exploited by Salzman et al. (1999) in the design of EVEs concerning conceptual learning in physics teaching. Virtual environments are autonomous worlds. For example, in a virtual environment, the earth rotates around its axis and revolves around the sun, independently of the students’ actions (Bakas & Mikropoulos, 2003). All the above features, together with the technological characteristics of multisensory interaction channels, intuitive interactivity and immersion, contribute to another feature, that of presence which has psychological origins. Presence is described as the user’s “sense of being there”, in the virtual environment as a separate entity. Although there is not much research in the educational domain, presence seems to play an important role in EVEs (Mikropoulos & Strouboulis, 2004). The feature of presence transforms the users of a VE into participants in an alternative world.

To summarize, we propose that the features that arise from the technological characteristics of virtual reality and contribute to positive learning outcomes, are first-order experiences, natural semantics, size, transduction, reification, autonomy, and presence. The questions that arise are whether researchers take into account the above features for the design of EVEs and whether these features do contribute to positive learning outcomes. In 1994 Hedberg and Alexander propose immersion, fidelity and active learner participation as the characteristics of virtual environments for “a superior learning experience”. Later, Whitelock, Brna, and Holland (1996) propose representational fidelity, immediacy of control and presence as the characteristics for conceptual learning using virtual environments. Whitelock’s et al. framework is in agreement with Hedberg’s and Alexander’s model. It seems that researchers start shifting from technological to conceptual models as far as virtual reality and learning are concerned, despite the lack of empirical evidence. Salzman et al. (1999) consider that the VR technological characteristics of 3D immersion, frames of reference and multisensory cues are promising features for conceptual learning. But their conclusions on science learning using immersive EVEs are that VR affordances have to be studied in a context together with other factors such as the concepts to be learned, learner characteristics, learning and students’ interaction experience. In a recent article, Lee, Wong, and Fung (2010) propose a conceptual framework of the outcomes in a desktop EVE, based on Salzman’s model (1999). Lee et al. claim that VR characteristics like representational fidelity and immediacy of control “influence learning outcomes indirectly through the mediation of usability and psychological factors of learning experience such as presence, motivation, cognitive benefits, control and active learning, and reflective thinking”.

The purpose of this article is to review empirical research studies and contribute toward an understanding of the research approaches that characterize research on educational virtual environments. Our aim is to investigate the educational context EVEs are used in, the

exploitation of the characteristics and features of VR in the learning process, the contribution of EVEs to positive learning outcomes, as well as the pedagogical approaches followed in the EVEs.

2. Methodology

The research axes of this review are the study of:

- the educational context the research studies are conducted in
- the characteristics and features of VR exploited by the EVEs
- the learning theory authors follow and apply in their research studies.

This article reviews peer-reviewed empirical research studies published as full length articles written in English in scientific journals, proceedings of international conferences, symposia and workshops, as well as book chapters during the last decade (1999–2009).

The relevant literature reviewed was found through a search in electronic databases of academic resources, organizations and publishers. ERIC, JSTOR, PapersFirst, IEEE, WilsonWeb, Elsevier, InformaWorld, Mary Ann Liebert, SpringerLink, Wiley Interscience, and MIT press are the databases we have used. As a first step in our search, we used the keywords “educational virtual environment” and “virtual learning environment”. As a second step we used the keywords “virtual environment” and “virtual reality” and then we did a within results search using the terms “education” and “learning”. Finally, we searched for articles that are cited in the papers we have read.

In our review we have included EVEs that only refer to formal and mainstream education. One study (Adamo-Villani & Wilbur, 2008) that concerns deaf students is included in the review since it concerns hearing students as well. From the review we have excluded all the articles that do not present empirical data from evaluations of EVEs or describe only pilot studies (Bailey & Moar, 2001; Cheung et al., 2008; Dede, Ketelhut, & Nelson, 2004; Mpouta, Paraskeva, & Retalis, 2007; Richard, Tijou, Richard, & Ferrier, 2006; Tijou, Richard, & Richard, 2006), as well as short papers presented at conferences, symposia and workshops. Furthermore, augmented (mixed) reality environments and virtual classrooms have been excluded. Mixed realities are differentiated from the virtual environments by combining virtual with real situations. Virtual schools often refer to technologies different from virtual reality, such as systems for synchronous and asynchronous distance learning.

Finally, a total of fifty three (53) studies published between 1999 and 2009 are included in the review. One article is published as a book chapter (Dede, Salzman, Loftin, & Sprague, 1999), six are presented at international conferences (Goncalves, 2005; Hokanson et al., 2008; Mikropoulos & Bellou, 2006; Sato, Liu, Murayama, Akahane, & Isshiki, 2008; Winn, Windschitl, Fruland, & Lee, 2002; Yun, Xi, & Li, 2006), one is presented at a symposium (Adamo-Villani & Wilbur, 2008), and three in workshops (Cooper, 2007; Ni, Krzeminski, & Tuer, 2006; Ye, Fang, Liu, Chang, & Dinh, 2007). We have included articles published in conference proceedings, following Randolph's et al. investigation in computer science (Randolph, Julnes, Bednarik, & Sutinen, 2007), which reported that “there were no practically or statistically significant differences between the articles published in journals and those published in conference proceedings on any of the indicators of methodological quality”.

The 42 journal articles found are published in 22 different journals. All but five articles are published in computer related journals. These five articles appear in journals related to specific disciplines such as engineering (International Journal of Continuing Engineering Education and Life-Long Learning), biology (Journal of Biological Education) and science education (International Journal of Science Education, Journal of Research in Science Teaching).

All but six journals are indexing/abstracting in databases such as ACM Guide to Computing Literature, British Education Index, Computer Science Index, Contents Pages in Education, Current Abstracts, Educational Research Abstracts, ERIC, Google Scholar, MEDLINE, PsycINFO, Scopus, and Social Sciences Citation Index. The remaining six journals are published by non-profit professional societies, namely AACE (AACE journal, Journal of Computers in Mathematics and Science Teaching, Journal of Interactive Learning Research), Institute of Biology (Journal of Biological Education), IEEE (IEEE Computer Graphics and Applications), and ISLS (International Journal of Computer-Supported Collaborative Learning).

Twelve journals have an impact factor between 0.400 and 2.190 (Thomson Reuters 2008–2009 Journal Citation Reports). It is worth noting that not all the journals have an impact factor. We believe that the reason is that educational technology is a relatively new field, with many new journals. Moreover, many researchers, especially in the fields of human and social sciences, believe that the impact factor is not the only measure for the relative importance of a scientific journal.

In order to study the educational context of the reviewed studies, the following categories were applied: research discipline and topic, research method, learner characteristics, attitudes towards VR and learning outcomes. These will help researchers, educators, designers and practitioners to easily review the potential benefits and research perspectives regarding how VR is applied in education.

Regarding the technological characteristics of VR, we are looking for multisensory interaction channels, intuitive interactivity and immersion. The features of VR that contribute to learning and which we study in this article are: free navigation, first-person point of view, first-order experiences, natural semantics, size, transduction, reification, autonomy and presence.

The above characteristics and features contribute to the design of constructive learning environments, as reported by many authors (Bricken, 1990; Neale, Brown, Cobb, & Wilson, 1999; Salzman et al., 1999; Winn, 1993; Winn & Windschitl, 2000). Constructivism in its various types is the theoretical approach the majority of EVEs is based on. In this review we do not only record each study's theoretical basis, but we also study if authors follow the main principles of constructivism. Although many researchers have proposed such principles (Boyle, 1997; Cunningham, 1993; Merrill, 1992), in this study we apply the seven principles as presented by Jonassen (1994):

1. Provide multiple representations of reality – avoid oversimplification of instruction by representing the natural complexity of the world
2. Focus on knowledge construction not reproduction
3. Present authentic tasks (contextualizing rather than abstracting instruction)
4. Provide real world, case based learning environments, rather than predetermined instructional sequences
5. Foster reflective practice

6. Enable context, and content, dependent knowledge construction
7. Support collaborative construction of knowledge through social negotiation, not competition among learners for recognition.

We believe that the seven principles for constructive learning stated above, compile all the similar classifications. Moreover, as far as it concerns the study of EVEs, these principles have been used successfully for the evaluation of virtual environments (Neale et al., 1999).

3. Results and discussion

Forty one (41) different VEs have been used in the studies we include in this review, as some of the VEs are used in more than one study with different research objectives.

3.1. The educational context

Forty (40) out of the 53 empirical studies refer to science, technology and mathematics. The preponderance of science and mathematics over the social sciences topics is rather predictable. In most of the cases, science and mathematics concern space and time scales far from everyday experience, unobservable phenomena, abstract concepts, difficult to understand physical laws and magnitudes. Such topics also have an experimental nature and require spatial abilities and high order thinking skills. All the above make the construction of mental models difficult. Computer-based learning environments and especially dynamic models, simulations and visualizations contribute to conceptual change, development of thinking skills, promotion of cognitive development (Webb, 2005). All the educational subjects of the reviewed articles are based on the difficulties presented above, where VR seems to be a strong educational tool. On the other hand, social sciences are a challenge to the design of computer-based learning environments, since they refer to abstract ideas and situations. Most of the reviewed articles concerning social sciences again exploit inaccessible time and space scales and incorporate their topic in spatial representations. History and culture are popular topics, where authors represent ancient cities and buildings (Bowman, Hodges, Allison, & Wineman, 1999; Di Blas & Poggi, 2007; Goncalves, 2005; Hokanson et al., 2008; Ligorio & Van Veen, 2006; Mikropoulos, 2006; Mikropoulos & Strouboulis, 2004). Narration, writing, educational drama and various topics are also subjects where spatial representations support the learning environments (Machado, Brna, & Paiva, 2005; Marshall, Rogers, & Scaife, 2005; Patera, Draper, & Naef, 2008; Robertson & Despa, 2002; Robertson & Good, 2003; Winn et al., 1999).

Most of the EVEs are designed and developed by interdisciplinary groups which are composed of educational technologists, computer scientists, educators and teachers of the relevant disciplines. The selection of the subject under study is not explicitly mentioned in all the studies. Only five studies are in accordance with the curriculum requirements for a specific discipline (Bakas & Mikropoulos, 2003; Johnson, Moher, Cho, Edelson, & Russell, 2004; Minogue, Jones, Broadwell, & Oppewall, 2006; Pasqualotti & Freitas, 2002; Patera et al., 2008). The number of EVEs where the learning problem is chosen in collaboration with teachers is even smaller (Crosier, Cobb, & Wilson, 2000; Lim, Nonis, & Hedberg, 2006; Winn et al., 1999). In nine studies the topic under study is based on previous research on students' misconceptions (Barab et al., 2000; Barnett, Yamagata-Lynch, Keating, Barab, & Hay, 2005; Chen, Yang, Shen, & Jeng, 2007; Gazit, Yair, & Chen, 2005, 2006; Holmes, 2007; Keating, Barnett, Barab, & Hay, 2002; Roussou, Oliver, & Slater, 2006; Trindade, Fiolhais, & Almeida, 2002), while only in two studies (Bakas & Mikropoulos, 2003; Kontogeorgiou et al., 2008) the EVE is based on the results of empirical studies that were conducted by the researchers themselves in order to investigate students' misconceptions. Almost all the empirical studies follow Johnson, Moher, Ohlsson, and Gillingham's (1999) statement that the learning goal must be important, hard and plausibly enhanced by the introduction of VR technologies.

The sample in the 53 empirical studies ranges from elementary school pupils to university students and teachers. There are seven studies involving teachers in their sample. Six of them report on teachers' attitudes and evaluations on the use of EVEs as educational tools (Di Blas & Poggi, 2007; Goncalves, 2005; Kameas, Pintelas, Mikropoulos, Katsikis, & Emvalotis, 2000; Ligorio & Van Veen, 2006; Ni et al., 2006; Sardone & Devlin-Scherer, 2008), and only one reports on teachers' learning outcomes (Mikropoulos, Katsikis, Nikolou, & Tsakalis, 2003).

Fifteen (15) studies have been conducted in research laboratories and 33 in schools and colleges. One study involves some students in schools and some others in labs, while four studies do not mention where the study took place.

The type of research method applied in an empirical study is an important issue in educational research, especially when interventions such as computer-based environments are involved. Among the 53 reviewed articles, two main types of research methods have been found, descriptive and experimental. According to Ross and Morrison (1997, 2004), descriptive research depicts conditions as they exist in a particular setting, and experimental research typically involves an experimental group and a control group to test hypotheses regarding certain treatments or interventions.

We have found 28 descriptive and 25 experimental studies. Among the experimental methods, we have classified six as within-subjects experiments and six as quasi-experiments.

The descriptive research method is followed by the majority of the reviewed articles. This probably indicates that the researchers are interested in getting information about the intervention with EVEs, focus on variables that could be used to study cause and effect, and then proceed to experimental studies. This finding is consistent with Hew and Cheung (2010), who have found 14 out of 15 descriptive settings reviewing the use of 3D immersive worlds in K-12 and higher education. However, there are some researchers who start a descriptive study and continue with experiments. This is the case of Judy Robertson and her associates with the Ghostwriter, an EVE for writing activities. Their first article is a descriptive study investigating pupils' social presence in the EVE (Robertson & Despa, 2002) and their second article is an experiment studying the effect of the EVE on the characterization in stories written by the pupils (Robertson & Good, 2003).

The authors of the reviewed articles use a variety of data collection methods, independent of the research method used. Most of the studies use more than one method for data collection. There are questionnaires with close, open and multiple choice questions (35 studies), interviews (23 studies), observations (10 studies), various types of recordings (14 studies), log files (six studies), and completion of tasks in the EVEs (seven studies). Questionnaires seem to be the most common method as in the case of Hew and Cheung (2010). Concerning knowledge assessment methods, there are 24 studies using questionnaires, seven interviews, seven task completion in the EVE, and nine studies where the researchers review students' submissions (papers, pictures, stories, quests, etc.).

Although all the studies mention characteristics of their samples such as gender, age and computer experience, only a few of them relate learners' characteristics with the virtual experience. Gender is studied in six articles. Concerning task performance in the EVE, three studies have found no gender differences (Ketelhut, 2007; Nelson, 2007; Roussou et al., 2006), while two others report that boys perform better than girls (Adamo-Villani & Wilbur, 2008; Hokanson et al., 2008). Crosier et al. (2000) just report that girls have better computer attitudes, and the virtual experience has not affected them. Roussos et al. (1999) have found that females were slightly better than males in orienting themselves in the environment, and Yun et al. (2006) report improvement in girls' mental rotation ability. Gender also played an important role in the level of embedded guidance of the subjects in Nelson (2007) and Nelson and Ketelhut (2008) studies. Girls accessed more guidance messages and outperformed boys in overall learning outcomes. Spatial ability in relation to conceptual understanding was examined in the study conducted by Trindade et al. (2002). Students with high spatial abilities showed an increased conceptual understanding of some contents according to the researchers. Moreover, Goncalves (2005) concludes that prior computer knowledge may decrease the feeling of presence in the EVE. In Virvou and Katsionis' (2008) experiment regarding usability and likeability, the results showed that the less experienced players faced two kinds of usability problems (user interface acquaintance and navigational effort). On the other hand, the more experienced users were affected most by the third kind of usability problem (virtual reality distractions). Crosier et al.'s (2000) results indicate that both ability level and the order in which the conditions were completed significantly affected the attitude scores.

Although all the 53 reviewed empirical studies investigate the educational aided value and especially the learning outcomes gained by the virtual environments, only 17 comment on students or teachers attitudes towards the use of VR in the learning process. These studies report on the usability (three studies) (Adamo-Villani & Wilbur, 2008; Dede et al., 1999; Virvou & Katsionis, 2008), enjoyment (two studies) (Adamo-Villani & Wilbur, 2008; Winn et al., 1999), enthusiasm (five studies) (Bakas & Mikropoulos, 2003; Johnson et al., 2004, 1999; Pasqualotti & Freitas, 2002; Robertson & Despa, 2002), motivation (five studies) (Dede et al., 1999; Gazit et al., 2006; Limniou, Roberts, & Papadopoulos, 2008; Tuzun, Yilmaz-Soylu, Karaku, Inal, & Kizilkaya, 2009; Virvou, Katsionis, & Manos, 2005), interest (three studies) (Johnson et al., 2004; Limniou et al., 2008; Minogue et al., 2006), and willingness to use (one study) (Goncalves, 2005). Students' positive attitude towards EVEs has been reported in different studies (Lim et al., 2006; Minogue et al., 2006; Ni et al., 2006; Robertson & Good, 2003; Sato et al., 2008; Shim et al., 2003; Virvou et al., 2005). Teachers' attitudes towards EVEs are also positive (Goncalves, 2005; Kameas et al., 2000; Mikropoulos et al., 2003; Ni et al., 2006; Sardone & Devlin-Scherer, 2008). Despite teachers' positive attitudes to history learning, they described difficulties in implementing the technology in their classes (Goncalves, 2005). Minogue et al. (2006) reports that the addition of haptic feedback has been shown to have a positive impact on the users' interest in, attitudes towards, and ability to navigate in 3D virtual environment.

Concerning engagement, most of the studies claim that subjects remained engaged throughout their interaction with the EVE (Johnson et al., 2004, 1999; Marshall et al., 2005; Patera et al., 2008; Sato et al., 2008). Conversely in NICE project (Roussos et al., 1999), only the student who had the role of the leader of the group who simultaneously experienced the EVE remained engaged. The level of engagement of students was low in the study of Lim et al. (2006). Distractions in the virtual environment, the students' difficulty with language used in the environment, their lack of computer competency for the tasks they were asked to perform, and/or their inability to complete the quests' section on reflections are believed to be the reasons for this. However, the same researchers believe that "a student could be engaged in the 3D MUVE by exploring the different worlds, avatars, and quests but fail to engage in the learning tasks".

Learning outcomes are usually classified into cognitive, psychomotor and affective outcomes (Sharda et al., 2004). In the present study, we focus on cognitive outcomes, such as comprehension, knowledge, application and analysis (Sharda et al., 2004). The learning outcomes found in almost all the reviewed studies are positive. Two studies do not report on learning outcomes. Adamo-Villani and Wilbur (2008) state that this is the aim of a future work, while Goncalves (2005) studies the learnability of a virtual castle with teachers and comments that their satisfaction scored higher than learnability. Only three studies present negative learning outcomes. Crosier et al. (2000) has not found obvious benefits for the use of VR over traditional teaching methods. Minogue et al. (2006) have not found any cognitive impact with the addition of haptics in a virtual animal cell task. Finally, Patera et al. (2008) state that "there seems no real indication of a benefit in any of the measures (motivation and creativity) we used".

3.2. Technological characteristics of VR

Although one might expect that research involving VR technologies would exploit more than one VR technological characteristic, things are rather conventional. Of course all the studies use visual representations, but few are those that are extended to multisensory interaction channels. Twelve (12) studies combine the visual with the auditory channel, aiming at better user performance and learning outcomes. Four of the studies use haptic systems, all concerning science topics. It seems that the authors are looking for an additional way to enhance the users' experiences and mental models in topics far from everyday experience. Multimodal interaction in these four studies has shown positive results. Dede et al. (1999) claim that immersive 3D multisensory representations may facilitate the students' development of more complete mental models than 2D representations. Teachers and administrators believe that multisensory environments help students to better understand and have more fun in learning (Ni et al., 2006; Sato et al., 2008). Positive results are reported by Minogue et al. (2006) regarding the users' interest, attitudes and ability to navigate in virtual environments. As far as learning is concerned, haptic interaction has not promoted a greater degree of integration and internalization of "the salient aspects of the complex cell concepts presented" (Minogue et al., 2006) such as the recognition, molecular structure and function of cell organelles.

VR technology offers a variety of specialized peripherals aiming at intuitive interactivity, such as special joysticks, 3D spheres and space mouse, data gloves, styluses, wands, and head trackers. The majority of the studies use mouse and keyboard as interaction devices. Mikropoulos and Strouboulis (2004) research focuses on the different input devices regarding the sense of presence and pupils' preference. They report that the combination of the keyboard and mouse and the keyboard on its own are preferred by the pupils, giving at the same time a sense of presence. This might be because of the age of the pupils who have great experience in game playing using the mouse and the keyboard. Only one study reports on the use of a data glove for navigation and manipulation of virtual objects (Mikropoulos & Bellou, 2006). While the data glove is considered to be the proper peripheral for interaction in three dimensional synthetic spaces, the students reported that they had a sense of presence using the combination of mouse and keyboard, although they had a more natural feeling manipulating the virtual objects with the glove. The use of the glove was tedious and the students proposed the use of exoskeleton systems for interaction. It

seems that carefully designed learning activities are more important than an exotic interface that contributes to intuitive interaction in an EVE.

Most of the reviewed studies use desktop systems for the display of the EVEs. Although immersion is a typical characteristic of VR, only 16 empirical studies use immersive or semi-immersive systems, four of them being *Cave Automatic Virtual Environments* (CAVEs). The main reason for researchers to use desktop systems is their low cost which makes the induction of VR technology in schools easier. This is facilitated by the development of Web3D technologies (e.g. VRML, X3D Graphics, Java3D, Shockwave 3D) that allow the delivery of interactive 3D applications over the Internet and the ever increasing use of Multi-user Virtual Environments (MUVES), such as SecondLife and Active Worlds which can also be used for educational purposes.

Three studies compare the different level of immersion. Adamo-Villani and Wilbur (2008), Mikropoulos (2006) and Winn et al. (2002) have concluded that immersion compared to a desktop system has a great advantage only when the content to be learned is complex, 3D and dynamic, on the condition that students do not need to communicate with the “outside” world. Mikropoulos (2006) reports that pupils completed their learning tasks more easily and successfully using a head mounted display in combination with their egocentric representation model than interacting through a wall projection system. Adamo-Villani and Wilbur (2008) have found that the virtual object construction took longer in the immersive system, while the travel task took longer on the desktop. Stereoscopy has been used as a variable in only one study conducted by Trindade et al. (2002) and according to the authors, it does not seem to play an important role in conceptual understanding. Immersive systems are combined with intuitive interaction by the use of head trackers, styluses and wands, in order to maximize positive learning outcomes (Adamo-Villani & Wilbur, 2008; Bowman et al., 1999; Dede et al., 1999; Johnson et al., 1999; Mikropoulos, 2006; Mikropoulos & Strouboulis, 2004; Roussos et al., 1999; Roussou et al., 2006; Sato et al., 2008; Winn et al., 2006; Winn et al., 2002).

3.3. Unique features of EVEs

There are no EVEs that exploit all the unique features of VR. We assume that this happens because of the educational context and the didactic goals of each application.

Almost all of the EVEs exploit free navigation and first person point of view, features that mainly lead to first order experiences. This finding indicates that during the last decade researchers have understood the differences between VR and other 3D graphic environments.

Natural semantics is mainly used in EVEs where symbolic representations might cause misconceptions. The quantum atom (Kontogeorgiou et al., 2008) is a characteristic example. In order to represent the shape of the hydrogen atom, the authors have solved the corresponding Schrödinger equations for the ground and excited atom states. Besides the educational context which gave positive learning outcomes, these representations “are” natural semantics, since it is rather the first time where an atom shape is represented according to modern physics theory, thus giving a tool for scientific visualization. These representations might also be helpful in physics research where scientists usually study the atom by solving the appropriate equations without giving any information about its shape.

The other EVEs that study atoms and molecules represent them by balls and sticks, the usual method in science education (Dede et al., 1999; Limniou et al., 2008; Sato et al., 2008; Trindade et al., 2002). Natural semantics is also used for the presentation of organelles in plant and animal cells (Mikropoulos et al., 2003; Minogue et al., 2006), laser (Mikropoulos & Bellou, 2006) and radiation laboratories (Crosier et al., 2000). The rest of the reviewed EVEs use natural semantics to represent the macrocosm in virtual solar systems, cities, etc.

The features of size, transduction, reification and autonomy appear in environments that demand them and predominate in science topics that deal with abstract concepts and phenomena beyond everyday experience. Large scales of size are used in environments like astronomy (Barab et al., 2000; Barnett et al., 2005; Keating et al., 2002), while small size scales are mainly used in environments of the microcosm such as the study of laser physics (Mikropoulos & Bellou, 2006) or biology (Shim et al., 2003). Transduction and reification are exploited for the study of molecules (Limniou et al., 2008) and cells (Minogue et al., 2006). Autonomy appears in ten virtual environments, justified by the type of the discipline and the didactic goals.

The sense of presence is considered to be a key feature of EVEs (Mikropoulos & Strouboulis, 2004). There are 19 studies where authors report that their sample had the feeling of “being there” and this might contribute to positive results. In three studies (Kontogeorgiou et al., 2008; Mikropoulos, 2006; Winn et al., 1999) presence has contributed to positive learning outcomes. In the above three studies, students had a high sense of presence interacting with the EVEs and that helped them perform their learning tasks successfully. In GhostWriter (Robertson & Despa, 2002; Robertson & Good, 2003) students stayed focused during their exposure to the virtual environment because of their sense of presence. As it is noted by Mikropoulos and Strouboulis (2004), a high degree of presence can be induced both by an immersion system and by the projection on a wall. The sense of presence shows the need for educational environments where the students prefer to behave like they do in the real world and “be” inside the learning environment, indicating the necessity for learner-centered environments.

3.4. Theoretical approach

The prerequisite for an effective learning environment is its pedagogical approach, the learning theory that follows in order to fulfil the educational goals and reach the desirable learning outcomes.

Only a few of the reviewed empirical studies clearly state the theoretical model their authors follow for both the design and use of the EVEs. Among these, all but one (Bowman et al., 1999) report constructivism as their theoretical approach (Gazit et al., 2005, 2006; Kameas et al., 2000; Mikropoulos & Bellou, 2006; Mikropoulos et al., 2003; Roussou et al., 2006; Winn et al., 1999) and its various types such as social constructivism (Dede et al., 1999; Kontogeorgiou et al., 2008), situated learning (Ligorio & Van Veen, 2006), and constructionism (Roussos et al., 1999).

Some other studies imply constructivism, as shown by the terminology they use. Barab, Sadler, Heiselt, Hickey, and Zuiker (2007), Lim et al. (2006), Tuzun et al. (2009) refer to experiential learning, inquiry-based learning and collaborative learning. Chen et al. (2007) propose guided discovery learning. Hokanson et al. (2008) follow learning by doing. Collaborative learning is followed by Holmes (2007), Johnson et al. (1999), Ketelhut (2007), Machado et al. (2005), Nelson (2007), Nelson and Ketelhut (2008), Sardone and Devlin-Scherer (2008). All the

above articles have been published by research groups where educational technologists, educators, cognitive scientists or psychologists participate. This is probably a reason why these articles follow a specific theoretical approach and try to incorporate the EVEs into an integrated educational context.

All the other reviewed articles do not refer explicitly to a learning theory. By studying the descriptions of their educational tasks and procedure, it seems that they also imply constructivism.

In the real world that is closely connected with specific activities, tasks are carried out through direct manipulation (Brown, 1989). Virtual environments can replicate this relationship, using realistic tasks that require skills similar to those which would be used to complete those tasks in the real world.

All the reviewed articles provide real world, authentic tasks and case based learning EVEs that enable context and content dependent knowledge construction. In EVEs developed for scientific inquiry, students have to collect data by exploring the environment or interviewing people represented as avatars, they have to analyze these data and propose solutions for a given problem (Barab et al., 2007; Hokanson et al., 2008; Holmes, 2007; Johnson et al., 2004; Lim et al., 2006; Nelson, 2007; Nelson & Ketelhut, 2008; Sardone & Devlin-Scherer, 2008; Tuzun et al., 2009). In Roussos et al. (1999) children can plant seeds, be responsible for their growing and learn about simple biological concepts. In Dede et al. (1999) students manipulate virtual objects to perform virtual physics experiments. In Crosier et al. (2000), pupils learn about radioactivity by making experiments in a virtual laboratory which resembles a real one. The buildings and the virtual city of Pasqualotti and Freitas (2002) are modelled in a way to show to the students that the 'real' objects with which they interact can be represented by mathematical models. In two EVEs for astronomy education (Bakas & Mikropoulos, 2003; Johnson et al., 1999), students become astronauts and perform tasks in space. In Mikropoulos et al. (2003), students have to 'create' the chemical reactions to complete the process of photosynthesis inside a virtual plant cell. In Mikropoulos (2006) and Mikropoulos and Strouboulis (2004), students perform tasks analogous to those in a real ancient city. In Roussos et al. (2006) children learn about fractions by picking blocks and covering a selected area. In Ye et al. (2007) the student serves as the user of a stream bank, and must invest money in developing the stream bank in order to maximize both economic and environmental benefits from the investment. In Hokanson et al. (2008) pupils have to learn about the culture of the Mandan people by engaging in tasks in an ancient village.

Multiple representations as well as the representation of the natural complexity of the world are key features of constructivism. Virtual reality adds to modelling with multiple 3D representations and frames of reference, allowing to represent "many aspects of the complex scientific models" (Dede et al., 1999). These features are also exploited in EVEs concerning astronomy (Bakas & Mikropoulos, 2003; Chen et al., 2007; Gazit et al., 2005, 2006; Ni et al., 2006), biology (Mikropoulos et al., 2003; Minogue et al., 2006; Shim et al., 2003), physics and chemistry (Dede et al., 1999; Limniou et al., 2008; Trindade et al., 2002). Hokanson et al. (2008) exploit various non-linguistic representations to help students construct new knowledge.

The different viewpoints in an EVE are another way for multiple representations to contribute to knowledge construction. This feature that arises from technological characteristics seems to help students to understand the structure and function of the eye (Shim et al., 2003), planetary phenomena (Bakas & Mikropoulos, 2003; Gazit et al., 2005, 2006), as well as to balance scientific and socio-economic factors (Barab et al., 2007).

Multimedia content is also a method for multiple representations presenting the natural complexity of the world, giving multiple representations in the EVE for agricultural technology (Kameas et al., 2000). Multiple representations are given in the form of 2D and 3D chemical animations helping students to comprehend molecules' structure and chemical reactions (Limniou et al., 2008).

Students understanding of the natural world's complexity is enhanced in Minogue et al.'s (2006) virtual animal cell by adding haptic augmentation to their EVE, though they did not find any positive cognitive impact, perhaps because of the written paper and pencil assessment tasks as authors report. Force feedback in a haptic EVE is also exploited by Ni et al. (2006) to control gravity wells in the solar system, as well as by Sato et al. (2008) for molecular chemistry education. In the above two studies, evaluation was conducted by students and teachers showing that virtual reality with haptics can help students better understand the concepts under study and make learning more interesting and interactive.

Collaboration is another strategy for achieving multiple perspectives (Bednar, Cunningham, Duffy, & Perry, 1992). Students collaborate on the design of the EVE (Barab et al., 2000; Barnett et al., 2005; Keating et al., 2002; Winn et al., 1999), during the process of scientific inquiry in order to propose a solution to a problem (Holmes, 2007; Johnson et al., 2004; Lim et al., 2006; Nelson, 2007; Nelson & Ketelhut, 2008; Sardone & Devlin-Scherer, 2008; Tuzun et al., 2009), to construct virtual 'cultural' houses (Ligorio & Van Veen, 2006), to complete learning tasks (Johnson et al., 1999; Roussos et al., 1999). Students also collaborate with educators on exploring EVEs (Chen et al., 2007; Kontogeorgiou et al., 2008).

The characteristics of current VR technology allow not only collaboration among participants, but also the "social negotiation" for collaborative knowledge construction between participants and avatars. In Adamo-Villani and Wilbur's (2008) EVE, avatars communicate with the participant in written and spoken English or in American Sign Language in order to perform their tasks. In Barab et al.'s (2007) EVE, the students' avatars share information with the virtual characters to save the fish population. Avatars also help students to interact with the EVE and perform various tasks (Hokanson et al., 2008). In the MUVE River City, students communicate with "computerized residents" in order to gather useful clues for their research (Ketelhut, 2007; Nelson, 2007; Nelson & Ketelhut, 2008). In the PUPPET world children and animal – avatars play the roles of protagonist and antagonist respectively, in order for the children – farmers to have their "farmyard in its proper place" (Marshall et al., 2005). In Mikropoulos' (2006) and Mikropoulos and Strouboulis' (2004) ancient city, participants collaborate with avatars in order to navigate correctly and perform their tasks in an ancient house. In a recent article of Tuzun et al. (2009), students talk to the virtual agents, gathering data about geographic characteristics.

Collaboration among participants inside the virtual environment for knowledge construction is exploited in all the studies that exploit MUEs (Barab et al., 2007; Di Blas & Poggi, 2007; Holmes, 2007; Ketelhut, 2007; Lim et al., 2006; Nelson, 2007; Nelson & Ketelhut, 2008; Sardone & Devlin-Scherer, 2008; Tuzun et al., 2009). In these EVEs, students work collaboratively in order to find out the solution to problems presented by the respective storylines. Students communicate with each other by using the chat window or in the real world, whenever this is possible. In Euroland (Ligorio & Van Veen, 2006) students and teachers from Holland and Italy use the chat tool of Active Worlds in order to construct cultural houses in a multi-disciplinary content. Students also collaborate successfully on understanding molecules and chemical reactions (Limniou et al., 2008).

In two cases students collaborate with their teachers (Chen et al., 2007; Kontogeorgiou et al., 2008). In Chen et al. (2007) the teacher asks questions and students explore the EVE in order to find the answers. Students are encouraged to discuss with their classmates, to share their findings and to demonstrate the operations of the system to classmates. In Kontogeorgiou et al. (2008) students collaborate with the researcher in order to reveal their mental images, construct the virtual quantum atomic model of hydrogen and interact with it.

In Roussos et al. (1999) a group of students visit the EVE NICE and collaborate with the avatar of one of the students who has the role of the group leader. Authors report that only the leader remained engaged with the EVE, whereas the other children were distracted and unfocused. Based on these observations, a group of the same researchers followed a different approach regarding collaboration (Johnson et al., 2004, 1999), giving the role of the leader to all the children alternatively. An important positive outcome is that these studies engaged children who were less willing to participate.

Children also collaborate successfully in order to be motivated to imaginative writing (Patera et al., 2008), as well as to create stories (Machado et al., 2005). In Ghostwriter, a virtual role-play environment, children control an avatar and communicate with each other by sending and receiving typed messages. As authors report, surprise, suspense, decision making as well as the ease of use of the virtual environment motivated even low achieving children to write messages and stories (Robertson & Despa, 2002; Robertson & Good, 2003). In Winn et al. (1999) students cooperate to make decisions about how an EVE should look and behave, by choosing the content, finding ways to show objects and making metaphors about invisible objects and procedures. Likewise, in Barnett et al.'s (2005) EVE, students work in dyads and triads to build models of different aspects of the solar system. In On-A-Slant (Hokanson et al., 2008), students collaborate by combining their knowledge and by teaching each other.

Reflection on existing mental models, another principle of constructivism, is used to infer, explain, and predict a new situation (Jonassen, 1994). In Bakas and Mikropoulos (2003) the representation of the Earth–Sun system and the characteristics of the EVE give the opportunity to students to create cognitive conflicts. In Barnett et al. (2005) “the students are given a range of opportunities to reflect on the model-construction process and the astronomy concepts demonstrated”. In Kontogeorgiou et al. (2008) students reflect on their mental models by discussing them with the researcher during their interaction with the virtual quantum atom. In the MUVes Quest Atlantis (Barab et al., 2007; Lim et al., 2006; Tuzun et al., 2009) and River City (Ketelhut, 2007; Nelson, 2007; Nelson & Ketelhut, 2008; Sardone & Devlin-Scherer, 2008) pupils, through exploration and interaction with virtual objects or avatars, collect and analyze data to develop a hypothesis about a given problem. This process requires “a continual reflection and revision” of students’ understanding (Barab et al., 2007). Similarly in the single player game Appalachian Tycoon (Ye et al., 2007) the students must maximize both economic and environmental benefits, requiring reflection of their actions by encountering the situation, acting on it, and thinking about what they did (Jonassen, 1999). In Cooper (2007) the EVE simulates food choices, and the player can see the effects the different food choices have on their health. Ackermann (1996) argues that in order to learn from experience, it is necessary to step back from it momentarily and to reflect upon it in objective terms. Ackermann’s statement is clearly used by Marshall et al. (2005). Using the recording and editing facilities in PUPPET pupils are allowed to “offload cognitive effort onto the system” (Marshall et al., 2005), thereby having the chance to iteratively improve upon the dialogue they had created. Similarly in NICE (Roussos et al., 1999), all the actions of the children are recorded, producing a narrative which can be studied any time in order for them to understand the consequences their actions had on the growing of the plants.

4. Conclusions

This study is a ten-year review of empirical research on the educational applications of virtual reality. It is noteworthy that it is based on 53 research studies found by using specific search criteria. It is an attempt to explore the status of the research on virtual reality in education, to indicate some research perspectives, and cannot be a complete overview.

The findings of the review provide insights for researchers into the technological characteristics and unique features of VR technology that contribute to learning, as well as the educational context and the theoretical approach followed in the studies. The VR characteristics and features, as well as constructivism as the preferred learning theory this review has been brought out, are in agreement with those recently proposed (Dalgarno & Lee, 2010; Lee et al., 2010).

As far as the educational context is concerned, the majority of the empirical studies (33) have been conducted in schools and colleges. It seems that at the end of the decade, virtual reality is a mature technology appropriate for pedagogical use. Forty (40) of the 53 reviewed empirical studies refer to science and mathematics topics. This is rather to be expected, since teaching and learning science incorporates a number of issues that can be exploited by VR technology. These mainly concern information and knowledge organization, concepts and notions out of the everyday experiences, experimental nature of phenomena, spatial perception and orientation, visual perception. Things are different with social sciences. Researchers in this field are not usually keen to use ICT for teaching and learning, and the topics under study are quite different from those in science. Even in this case, this review has brought out that researchers from social sciences have appreciated the educational value of VR and 13 references have been found where authors have incorporated their learning goals in single or multi-user virtual environments by designing proper spatial representations. It seems that researchers in social sciences exploit virtual environments in order to contextualize rather than abstract instruction, provide real world case based environments, and enable context and content dependent knowledge construction.

The main technological characteristics of VR can be defined as multisensory interaction channels, intuitive interactivity and immersion. Although VR systems support multisensory interaction channels, visual representations predominate. Less than a quarter of the studies (12) add the auditory channel, especially those exploiting MUVes. Haptic systems are still expensive and awkward and are used only in four studies concerning science topics. The experimental character of scientific topics and the need for direct and physical manipulation of objects promote the use of haptic systems. Although such systems are used in other VR applications like surgery and engineering, we believe that it is early to think of using them in mainstream education. The same holds for olfactory systems that Richard et al. (2006) and Tijou et al. (2006) present in their pilot studies in EVEs concerning chemistry education. Multisensory channels “can be used to direct students’ attention and enhance the quality of the learning and interaction experiences”, “but we need to know when and how to use them for supporting different learning tasks and various learner needs” (Salzman et al., 1999).

Intuitive interactivity is a desirable characteristic for every educational environment, especially for those referring to science. VR is claimed to be the only technology up to now, that supports intuitive interactivity through the use of specialized peripheral devices and

systems. The results of the last decade's empirical research in EVEs have not shown clear positive results. Of course, few are the studies that incorporate systems promoting intuitive interactivity, and much research is needed. Our findings are consistent with Papastergiou's (2009) recent review on the potential of computer and video games for health and physical education. Her conclusions are that games with standard interfaces such as keyboard, mouse and joysticks are effective in favouring knowledge acquisition, whereas games with exertion interfaces such as motion platforms, motion tracking cameras and haptic devices are appealing, motivational and effective in producing fitness and health benefits.

Immersion, another key characteristic of VR systems appears as a result of the involvement of more than one perceptual channel such as visual, auditory, haptic and olfactory, by using specific peripheral devices. Although some immersive systems are now affordable and practical even for schools, only 16 of the reviewed empirical studies use immersive EVEs. Their results are positive concerning both users' attitudes and learning. Chris Dede in his recent article in the *SCIENCE* journal (2009) supports such findings and mentions that immersion "can enhance education in at least three ways: by allowing multiple perspectives, situating learning, and transfer". This statement also indicates that constructivism is the preferred pedagogical approach of EVEs. Dede, in the same article, also recommends that "further studies are needed on the capabilities of immersive media for learning, on the instructional designs best suited to each type of immersive medium, and on the learning strengths and preferences these media develop in users". This statement also implies that users' characteristics such as learning styles, gender and age play an important role in learning with EVEs, a topic not sufficiently studied in the last decade, as our review has shown. Moreover, the need for new methodologies for the assessment of learning outcomes in EVEs emerges. We believe that one approach to this could be evaluations inside the EVE, such as task performance.

Features of VR that contribute to learning and which we report in this article, are first order experiences mainly coming from free navigation and first-person point of view, natural semantics, size, transduction, reification, autonomy and presence.

The basic feature of first order experiences is followed by all the reviewed articles. It seems that researchers exploit this feature for the design of student-centered learning activities. This is an indication that VR might be the technology that offers environments that promote knowledge construction. Natural semantics also plays an important role in this direction by avoiding the use of symbols. Natural semantics allows the representation of the "invisible" like an atom or the electric field, as well as the "impossible" like an ancient city. First order experiences and natural semantics are two of the features that contribute to a sense of presence inside an EVE.

Size, transduction, reification and autonomy are exploited where needed and allow learners to experience phenomena and situations out of everyday experience that contribute to the creation or enhancement of mental models for knowledge construction. Autonomy seems to play a particularly positive role in MUVES where the educational environments have to "work" even if not all the participants are present at the same time in the same place.

The sense of presence seems to play a role in EVEs. The results of this review show that presence might contribute to positive learning outcomes, but things are not so clear. Whitelock, Romano, Jelfs, and Brna (2000) in their early experiments on perfect presence in virtual learning environments suggest that a high degree of presence "is very motivating but could well take up too much of the users' attention and produce a cognitive overload when it comes to understanding conceptual notions". In the same article the authors note that social presence enhances a feeling of team work. In 2003, Selverian and Hwang in their review on presence and learning (17 research studies), report that "most of the research has failed to associate spatial and social presence with levels of learning objectives and learning achievement" (Selverian & Hwang, 2003). Our findings show that at least 12 out of the 53 last decade's studies reviewed positively connect presence with learning.

In the literature, the terms presence and immersion are often used as having the same meaning and origin. We believe that immersion is a result of the involvement of more than one perceptual channel and not only a subjective impression, as Dede (2009) notes. We think that presence is a subjective experience, and the reason that learners can feel more psychologically present in an EVE (Bailenson et al., 2008). Our small difference with Bailenson et al.'s (2008) definition that "an immersive virtual environment is one that perceptually surrounds the user, increasing his or her sense of presence or actually being within it", is that an immersive virtual environment is one that perceptually surrounds the user, and could increase his or her sense of presence. We believe that both technological characteristics like immersion and individual factors like age, gender, computer experience, psychological factors, cognitive and learning styles affecting presence need to be studied in relation to learning outcomes. According to the findings of this kind of research we could then turn to adaptive EVEs where each student might decide about the factors affecting their sense of presence, set their personal learning goals, the type of the learning task to complete, in a constructivist context.

The pedagogical model an educational environment is based on, determines the learning tasks and the roles of teachers and learners. Constructivism is the contemporary theoretical model most of the computer-based educational environments follow. This happens with almost all of the reviewed empirical studies. Some of the articles clearly state their theoretical model, and this is confirmed by the principles they follow for the EVE design, as well as from the learning tasks they involve. The majority of the studies seem to follow constructivism, as is shown by their characteristics. Of course not all the EVEs incorporate all the constructivism principles, but most of them combine more than one.

All the reviewed EVEs present real world, authentic tasks that enable context and content dependent knowledge construction. It seems that 3D spatial representations and first order experiences provide the suitable environments that foster such tasks.

Almost all the EVEs also provide multiple representations of reality. VR technology gives the background for implementing the multiple representations in a variety of ways such as different viewpoints, haptic augmentation and force feedback, multimedia content, collaborative strategies, thus supporting different learning styles.

For example, different viewpoints contribute to multiple representations in Bakas and Mikropoulos (2003) by allowing students to observe planetary phenomena from spaceship and Sun. In Johnson et al. (1999) each child acts both as an astronaut and mission control during the interaction with the EVE to see both views in order to understand that the Earth is spherical and the implications of that fact. In NewtonWorld (Dede et al., 1999), students can change their viewpoint by becoming a ball moving along the corridor or an observer thus providing multiple representations of the phenomena under study. Moreover, students' multiple representations are enriched by sensing potential energy through tactile feedback. This is also achieved in Sato et al.'s (2008) EVE, where students sense Van der Waals energy in water molecules. Multimedia content helps users of the EIKON EVE to combine information gathered from both the virtual objects and the database for understanding how agricultural technology evolves and works (Kameas et al., 2000).

EVEs also support collaborative knowledge construction through social negotiation, and foster reflective practices. Reflective thinking is beneficial in the learning process, but much research is needed in the context of EVEs (Lee et al., 2010). Collaboration is not only limited to the participants of an EVE, but VR technology through MUEs offers a new dimension to it, the collaboration and social negotiation among participants and avatars. Avatars may be other participants' representations as well as computerized residents, giving new perspectives to synthetic educational environments. The positive results shown by this review agree with Bailenson et al.'s (2008) remark that the presence of virtual others, among other factors, have an impact on learning.

The findings of this review and our view concur with Dalgarno's and Lee's (2010) model of learning in 3D virtual learning environments, incorporating unique characteristics and learning affordances. Taking into account technological characteristics and features of VR, the authors propose five learning affordances of such environments: spatial knowledge representation, experiential learning, engagement, contextual learning and collaborative learning. We believe that these affordances imply the seven principles of constructivism followed more or less by the researchers of the reviewed articles.

The question that arises from the constructivist principles found in the reviewed articles is whether authors integrate them in a constructivist model or they exploit the characteristics and features of the technology in order to implement learning tasks in their EVEs. We believe that the conclusion of this review is similar to that of Higgins and Spitulnik (2008) review on teachers' use of technology in science instruction. "Despite the promise of technology for instruction, research to date has indicated that teachers tend to use new technologies to support existing practices, rather than developing methodologies more suited to the unique affordances of educational technology".

Our findings show that both students and teachers share a positive attitude towards the use of virtual reality in educational settings, EVEs have shown their potential in the understanding of concepts and in rejecting students' misconceptions. But the main outcome of this study is the future research perspectives it brings to light. VR systems with all their characteristics may not be easily acquired in the classroom, but EVEs "became common place, and it is important to understand how this digital technology will aid the basic learning process" (Bailenson et al., 2008).

Little can be yet concluded as regards the retention of the knowledge acquired in the EVEs. Longitudinal studies conducted at schools with large samples and in different disciplines are necessary in order to prove that, as also suggested by the relevant review of Hew and Cheung (2010).

Characteristics of VR such as immersion and features, especially the sense of presence, are also important factors that contribute to learning and need further exploration. Factors connected with presence such as perceptual features, individual factors, content characteristics, interpersonal, social and cultural context seem to be essential to learning and have not been studied extensively since 2003 (Mantovani & Castelnuovo, 2003).

This review shows that MUEs or otherwise collaborative virtual environments (CVEs) find their place in education and collaboration happens between participants and between participants and computerized residents. So, the use of avatars in educational settings is an area needing further study, as also noted by Hew and Cheung (2010). Avatars reproducing users' facial expressions and body movements, as well as developing intellectually along with the users, are proposed in recent studies (Holmes, 2007; Vrellis, Papachristos, Bellou, Avouris, & Mikropoulos, 2010).

Methodology of educational research in EVEs also is a topic for further study. Probably, the "paper and pencil" methods are not proper for the assessment of knowledge gained through the exposure to an EVE (Minogue et al., 2006; Roussos et al., 1999). Evaluation methodologies during the interaction with the EVEs should be developed, as Minogue et al. (2006) and Sato et al. (2008) propose, in order the added value of virtual reality in education to be brought out.

Concluding, we agree with Dalgarno's and Lee's (2010) statement that a systematic effort and more empirical studies are needed in order to show how the characteristics and features of EVEs can be pedagogically exploited.

Finally, we believe that independently of the above topics, the most important research perspective of this review is that every EVE has to be incorporated in a well designed educational context that follows a theoretical approach and specific didactic goals. The need for a "goal-based scenario approach" in EVEs was proposed in 2003 by Mantovani and Castelnuovo and still remains a demand in 2009 (Dede, 2009).

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