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Virtual Reality for Training and Lifelong Learning

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Abstract

This article covers the application of virtual reality (VR) to training and lifelong learning. A number of considerations concerning the design of VR applications are included. The introduction is dedicated to the more general aspects of applying VR to training. From multiple perspectives, we will provide an overview of existing applications with their main purposes and go into more depth on certain learning areas. Recent developments of virtual environments for training and lifelong learning are analyzed, followed by an analytical viewpoint on design, advocating more explicit paradigmatic considerations and development of generic design methods. These approaches and proposals are aimed at better exploiting the uniqueness of VR and designing more effective virtual environments. Finally, a number of conclusions will be drawn for future technology-enhanced training and for lifelong learning using VR.

Introduction

This article focuses on adult learning in relation to the needs of both training and lifelong learning. Learning is regarded as an ongoing process that engages human beings from the day they are born. This process continues with their childhood education, into their adolescence, and finally adulthood. Some characteristics of this process change over time. On the one hand, individuals mature and age, and, on the other hand, they are influenced by their social and occupational contexts.

Learning is highly context-dependent; that is, formal and informal learning are quite different activities, as are on and off-the-job learning. Adults often encounter strong outer constraints such as time or occupation. For this reason, the use of virtual reality to support adult learning requires taking into account the above external constraints, in addition to the type of learning being considered, learner characteristics, the learning context and how the learning will be used. Designers will also have to consider the aspects and paradoxes generated by social principles and characteristics of public market needs such as developing cheap applications for fast and efficient learning. A number of adult learning characteristics are illustrated below.

1) While childhood and youth are times to discover the world and to learn about its rules, adulthood is the time to become efficient. Therefore, adult learning needs to be more specific and more contextualized. Training will often be skill-oriented, using hands-on methods such as learning by doing, experiential learning or on-the-job learning. Because of both its financial and learning retention efficiency, e-learning has become a regular component of lifelong learning.
2) Any new acquisition is supported *de facto* by pre-acquired knowledge and pre-existing conceptions. The more robust and the more valid pre-acquired knowledge and pre-existing concepts are, the better and the more consistent will be future learning acquisitions. In academic contexts, when errors occur, it is not easy to find out which pre-existing misconceptions were responsible for the error (Winn & Windschitl, 2001); heterogeneity of cultural backgrounds, knowledge and acquired lifelong experiences make it even more difficult with an adult.
3) Formal training learning situations have to be fast, safe, cheap, and efficient. Therefore, they have to be directly focused on what is required by the targeted results. At first sight, learning situations as similar as possible to real occupational circumstances may seem to be the most likely to support learning. This cliché is often encountered in virtual reality for training as a justification for realistic virtual environments, resulting in a solid tradition of using full-scale simulators in several industries. Later, we will consider how the concept of realism can be left aside when focusing on learning efficiency.

Being conscious of the social and economical constraints of adult training permits us to take such constraints into consideration when focusing on learning, which is the core-issue of virtual reality both for education and training. This article is aimed at providing complementary information and specifications concerning adult learning.

General interest of VR for training and lifelong learning

Virtual reality (VR) for training and lifelong learning is a recent innovation. It started on the research side, and since has followed two different paths: on one hand, experiments have focused on realism in order to substitute a real environment by a virtual one; on the other hand, some experiments have focused on researching unique characteristics and assets of VR for learning.

The first path was inherited from full-scale simulation, which found more flexibility and easier generalization with VR technologies. The principle consists basically in duplicating a real object and its context of use by an artifact. It is efficient and provides valuable added value, but it does not always take into consideration the related learning aspects. These aspects are left to be considered later on by trainers and instructors.

Researchers following the second path, for example, explorations started at the University of Washington in the early 90's (Bricken, 1991; Winn, 1993, 2003a, 2003b, 2005), at George Mason University (Dede, 1995), and at East Carolina University (Pantelidis, 1996), tend to consider this approach inadequate to attain the possibilities that VR can offer to support learning.

In this article, we pay more attention to this second path: the quest for identifying and exploiting the unique characteristics of VR. The objective is to examine how new technologies can generate new uses, support brand new practices, and permit what has not been possible to realize up to now. We will work to contribute to this quest of knowledge what is unique with virtual reality and what new opportunities it represents for learning. First, we will review a series of questions about what virtual reality can provide to adult learning.

Can virtual reality facilitate learning?

As learning has always been a difficult activity for human beings, history shows that nearly all available means and technologies (from printed documents to educational software) have been exploited to create learning resources. It also shows that real situations have always been preferred for adult learning, even if they are not always efficient, nor usable. In reality, real situations often do not provide learners with accurate support, because what would really be supportive might not be perceptible to the human senses.

In order to circumvent this type of snag, classically educational answers consist in using complementary approaches (e.g., mock-ups, schemes, formal models, abstract concepts). The learner can find it difficult to link these complementary approaches to their related real situations. What is new with virtual reality is that it allows making perceptible anything that is needed to be perceived by the learner while removing anything that could make learning unnecessarily complicated or confused. VR technologies offer this important possibility of creating alternative realities. In a later stage, we will examine some of the different attempts that have been made so far.

The first question is the relevance of VR as a support for learning. This issue was being discussed in the early 90's. At that time, the potential and the challenges were clearly identified (e.g., Bricken, 1991). Sometime later, it became a highly debated issue. Kozak, Hancock, Arthur, and Chrysler (1993) describe the failure of VR as a support for training as they observed a poor transfer from the VR environment to the real situation. The experiment consisted in object manipulating in virtual and in real environments. Psotka's resumption paper in 1995 reopened the discussions, criticized Kozak-et-al.'s experiment, which poorly supported kinesthetic-gesture because of technological limitations (Psotka, 1995).

More optimistic views re-emerged. Regian (1997) developed a new approach for the transfer of VR-based acquisitions. Since then, it has become obvious that learners can benefit from VR applications. Let us now examine how effective benefits can occur.

Can virtual reality support abstract concept learning?

The early research approach showed the unique characteristics of virtual reality for learning were rapidly successful (Dede, 1995, Winn, 1993), and showed how abstract concepts could be learned in virtual environments. Most of those experiments were dedicated to academic learning (Chen, Yang, Shen, & Jeng, 2007; Dede, Salzman, Loftin, & Ash, 2000; Loftin, Engelberg, & Benedetti, 1993; Salzman, Dede, Loftin, & Chen, 1999; Winn & Windschitl, 2001). Later, explorations were made to see how theoretical concepts supporting industrial skills could be acquired in a virtual environment (VE). For instance, the Virtual Technical Trainer (Crison et al., 2005; Mellet-d'Huart et al., 2004) examines how body experiences may contribute to the acquisition of fundamental concepts of metal machining. It uses a force feedback interface combined with *pseudo-haptics* principles (Lecuyer,Coquillart, Kheddar, Richard, & Coiffet, 2000) to make a learner feel how much force is required to proceed depending on multiple variables. However, the correction of existing misconceptions remains a difficult topic (Dede et al., 2000; Winn & Windschitl, 2001).

Can virtual learning environments implement paradigms and learning theories?

Educationalists are used to making reference to paradigms as basic frames of reference in which learning takes place (usually Behaviorism, Cognitivism, Connectionism, Constructivism, Constructionism or Enactivism) (Dimitropoulos, Manitsaris, & Mavridi, 2008; Mellet-d'Huart, 2006; Roussos et al., 1997; Winn, 2003a). Thus, there were a number of attempts to apply Constructivist or Constructionist paradigms to the design of virtual environments especially for education (e.g., Virtual Reality Roving Vehicle (Winn, 1995); NICE (Roussos et al., 1999).

Although the implementations were successful, the learning benefits were not so straightforward. Such virtual environments could have provided the learner with insufficient guidance. In archaeology, the concept of discovery learning has been developed and experimented. Once more, no clear evidence has been produced on the effectiveness of this approach in terms of learning (e.g., Pujol-Tost, 2005). There were few explorations on the training side, where an educational hypothesis often remains implicit.

Nevertheless, an important experiment took place at the University of Southern California (Los Angeles). Following Newell (1990)'s unified theories of cognition, based on a Cognitivist paradigm, SOAR programming language was developed to support AI applications. The STEVE virtual pedagogical agent, which was providing educational tutoring in a virtual environment, was developed with SAOR. The result was that important paradigmatic coherence was reached.

Clear references to a Constructivist paradigm were made in simulation design (e.g., problem solving simulations, which is supported by vocational didactics – an approach based on job analysis to support the design of problem-solving simulations for training (Pastré, 2006). More recently, approaches have been developed which incorporate the Enactivist paradigm for learning virtual environments (Mellet-d'Huart, 2006). Even if it opens the way to new perspectives in regard to the understanding of learning processes, the exploitation of unique VR possibilities and design methods, no controlled experimental validation has been implemented yet.

Can virtual reality support vocational training?

After years of benefits from full-scale simulation, the first real success of VR for training occurred in the context of the NASA's Hubble space telescope mission (Loftin & Kenney, 1995). Effective training was required for a 100-person team without the possibility of using the real telescope which was in area of the full-scale mock-up reserved for the core-team of astronauts.

The design was supported both by a task analysis method and an explicit definition of learning scenarios using an intelligent tutoring system. In this live situation; the whole team supporting the astronauts was trained using this virtual environment. Evaluation showed this approach to be effective. It also taught us about how important analysis is. Further experiments like the virtual pedagogical agent STEVE see Figure 1 & 2 below), were developed in the Virtual Environment for Training on this basis (Rickel & Johnson, 1999).

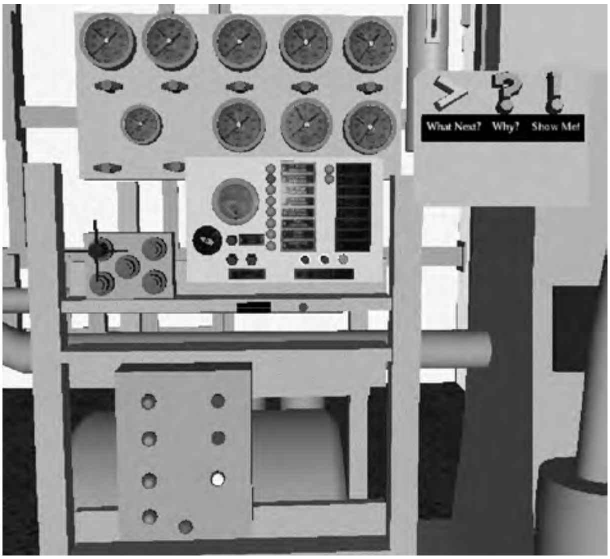

Figure 1. Restitution of the job environment in Virtual Environment for Training (Copyright University of Southern California).

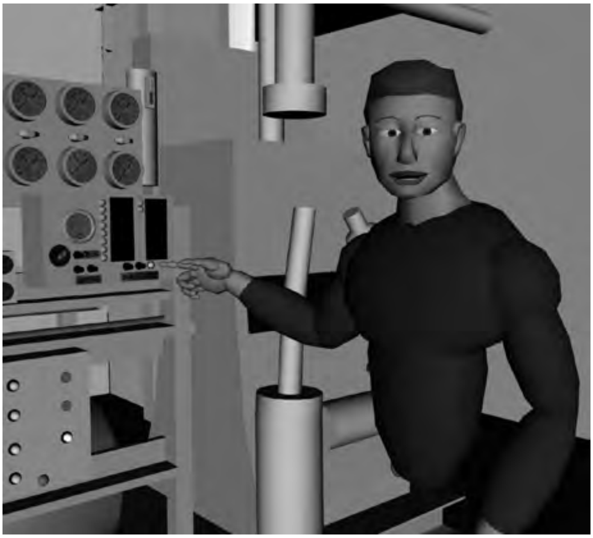

Figure 2. STEVE pointing at a Gauge in Virtual Environment for Training (Copyright University of Southern California).

In the late 90s, more applications for training were developed both on the industrial side (e.g., Virtual Industrial Faucet; Frejus, Drouin, Thibault, & Schmid, 1997) and on the research side (e.g., Virtual Environment for Training with STEVE agent). In the early 2000s, more mature applications were designed and have been fully used in industrial contexts (e.g., FIACRE trains train-drivers on railways as shown Figure 3

Figure 3. The Virtual Hand, Avatar of the Learner, acting in FIACRE (Copyright SNCF).

(David & Lourdeaux, 2001), CS WAVE is a welding training system (Da Dalto, Steib, Mellet-d'Huart, & Balet, 2007).) All those developments confirmed what Loftin and Kenney (1995) showed earlier: in order to achieve a certain degree of effectiveness, the design approach to the virtual environments for learning (VEL) has to be supported by job analysis and by instructional design methods.

In addition, VR has also improved simulation practices (e.g., Thurman & Mattoon, 1994), for instance the medical domain frequently uses VR simulations for surgeons' training (e.g., Ota, Loftin, Saito, Lea, & Keller, 1995).

Can virtual reality-based learning overpass learning in real situations?

In order to be efficient and avoid wasting time, on-the-job learning has often been regarded as a paragon for vocational learning. For a long time, simulators simply used to duplicate real situations. Progressively, the additional advantages of the virtual solution have been considered. However, the difficulties that learners encounter in a real situation are often underestimated or neglected. A major problem found in real situations is that not all relevant objects or phenomena can be perceived (e.g., the welding bead for the welders). This becomes more and more dramatic as computerized systems are interfaced with machines. Thereby, operators become more and more distant from the process. Because of the growing number of numeric interfaces, work situations have become more and more dematerialized.

It is not surprising that VR has been used since the mid-90s to teach computerized numerical control machining [CNC] (e.g., CNC milling machine; Lin, Hon, & Su, 1996; Liu & Qiu, 2002; Mellet-d'Huart et al., 2004). It becomes impossible for new users to have on-the-job training experience on CNC machines because of both the risks from accidents and damaging tools, as well as the impossibility of having sensorial feedback using the trial and error method. The paradox is that, because of work activity dematerialization, VR can provide more tangible and direct contacts with processes than can real situations. Moreover, additional cues and data can be added to facilitate the realization of an activity or to support learning.

Global outcomes, assets and conflicting results

Classical advantages of VR are well-known: creating safe situations; supporting rehearsals for emergency situations (e.g., on industrial hazardous sites by SecuRéVi as shown in Figure 4; Querrec, Buche, Maffre, & Chevaillier, 2003), enabling skill acquisition for hazardous tasks, learning to operate, maintain or repair unavailable machines and equipment (e.g., NASA's Hubble space telescope mission; Loftin & Kenney, 1995); SIMURAT in the railway industry; see Figure 5). Obviously, virtual reality can make up for training situations that cannot be set in real situations, because they are too dangerous, too expensive or simply unachievable.

Figure 4. Securévi: Firefighters fighting a fire in an Harbour (Copyright CERV/INOVADYS).

Figure 5. SIMURAT: Controlling Freight Cars before Departure (copyright SNCF).

However, it can also be used to enhance training situations even when feasible in the real world in order to have easier and more efficient learning. VR learning environments can provide different feedbacks and replay functions, multiple scenarios, close adaptation to learners' activities, etc. These aspects are not really unique; they are broadly shared with simulation. Nonetheless, it has also been demonstrated that VR can help accelerate learning processes (Frejus et al., 1997; Seidel, 1997), propose new educational potentials (didactics, pedagogy and learning process) (Burkhardt, Lourdeaux, & Mellet-d'Huart, 2006; Mantovani, 2003; Winn, 1997; Winn, Windschitl, Fruland, & Lee, 2002), and includes new possibilities for perception and action (Mellet-d'Huart, 2006), that can be specific to VR.

Unfortunately, experimental results about using VR for learning are not all so straightforward (Winn, 2003a; 2005); they may sometimes be conflicting, even disappointing or confusing as Kozak-et-al.'s experiment was. How can this be explained? Although technical limitations still exist, we should not simply incriminate technology but rather consider the short time such practices have been used and the lack of design methods. Three types of explanations can be envisaged:

1) dependence on existing clichés (e.g., the claim for realism; Tinker, 1992) rather than exploring new educational paths;
2) application design based upon virtual reality concepts (e.g., immersion, interaction) instead of learning concepts;
3) lack of design method and/or lack of job analysis. We will return to this point when discussing the design of virtual environments for training.

State of the art and analysis of current applications

Rather than presenting an exhaustive list of state of the art of virtual environments for learning, we will focus on illustrating VR assets using a small range of applications. We will point out a number of characteristics making VR unique as a learning support. At the same time, it is important to remind ourselves that other information technologies also have unique and complementary contributions to learning (e.g., artificial intelligence enabling the development of Intelligent Tutoring Systems; e-learning supporting distant learning and the organization of learning contents, thanks to Learning Content Management Systems; knowledge management and ontologies supporting the organization of large amounts of data).

Therefore and unsurprisingly, there is an increasing technical mix of technologies (e.g., e-learning, multimedia, serious games, simulation, virtual reality) and broader concepts such as Technology Enhanced Learning (TEL) or Technology-Assisted Education used. In fact, pure virtual reality-based applications are rare and probably not relevant. Technological blending may generate interesting added-facilities in global and integrated learning systems. Meanwhile, in the context of this chapter, we will limit our purposes and focus on virtual reality applications. A large part of such applications integrate *de facto* complementary technologies.

A general survey

VR applications for training and lifelong learning are numerous and various. The field is heterogeneous whether regarding the forms of the applications, their contents or the technologies they use. Rather than presenting those applications in a jumble, we will consider successively: technical aspects; occupational fields; types of public; contents then pedagogy. In a later stage, we will stress learning aspects more specifically.

A technically-oriented approach

General characteristics of virtual reality are covered elsewhere in this issue. Specific interfaces (e.g., generic real-time interfaces; highly immersive interfaces) enable the elimination of dedicated mock-ups and provide a broader range of possibilities for users. Based on the technological opportunities that are provided by VR, Kalawsky (1996) explored the applications that could be supported by VR in higher education. A typology was proposed, mainly based on visual immersion technologies.

Nowadays, higher immersion is no longer regarded as being automatically the most appropriate, but it still remains a criterion to establish categories among applications (e.g., immersive vs non-immersive applications). Mixed with pragmatic and economic considerations, desktop virtual reality becomes a standard for learning applications. Concerning training and based on technical possibilities, we find numerous VR-based simulations (e.g., for surgery) ranging from highly immersive systems using sophisticated force-feedback devices to mouse and keyboard desktops. Emphasizing VR software characteristics (e.g., real-time, 3D models, and autonomous agent-based software), Tisseau (2004) shows how complexity may be approached in VR applications and how the possibilities to reach un-anticipated results are characteristic of VR.

A field-oriented approach

Rather than drawing up a long and unorganized list of fields using VR technologies for training, we have chosen to distinguish three categories.

The first category comprises fields favoring virtual environments that look alike to real occupational situations. It includes training on industrial machine and power-plant operation, vehicle driving, piloting, traffic-control, maintenance simulators, medical procedures and military operations (Wasfy, Wasfy, & Noor, 2004). In these fields, simulation, realism and fidelity are regarded as crucial concepts (e.g., safe, “near-natural” synthetic environments (Wasfy et al., 2004).) The main asset of virtual reality is the development of cheaper, more flexible and portable resources (e.g., ASSIMIL, an approach to flight training using case-based reasoning on desktops (Aka & Frasson 2002). It facilitates technological blending (e.g., integration to Internet distant learning systems), can involve more educational resources (e.g., a classical full-scale truck driving simulator) and can be connected, for instance, to Learning Content Management Systems. This category encompasses areas such as the aerospace industry, maintenance, the army, firefighters and surgery. Applications are often called virtual reality-based training simulators.

The second category comprises fields in which the objective is to (re)present aspects of the real world that cannot be perceived as such (e.g., in architecture; Smith, 1995), or aspects that need to be modified in order to better support learning activities. This category brings together fields such as cultural heritage (e. g., visiting ancient sites, learning about old civilizations; Di Blas, Gobbo, & Paolini, 2005; Patel, Walczak, Giorgini, & White, 2004), architecture (developing projects with no mock-ups, presenting different stages of building (Sampolo & Henriques, 2006) or presenting the invisible (e.g., in architecture; Kieferle & Wossner, 2001), nuclear industry, firefighters (e.g., firefighting when dealing with specific risks as industrial gas containers; Querrec, et al., 2003), medicine (Mantovani, Gaggiolo, & Riva, 2003; Riva, 2003; Szekely & Satava, 1999; Waterworth, 1999), industrial design, biology and physics (from virtual experiments to learning supports), and so forth. What is remarkable in these fields is that VR resources can be used in an almost identical manner for work or for training purposes (e.g., industrial design, tele-operations in surgery, etc.).

The third category presents activities which are not pure training situations, but which involve cognitive activities that might require a number of implicit learning actions (e.g., behavioral therapy, team training, leadership development, etc.). This can be found in fields such as the army, industry, and medical rehabilitation. The range of such developments is becoming larger and larger.

A public-oriented approach

Every individual is different; every learner is different. When considering sensory or motor abilities, a virtual environment should be adapted to his/her user (Maillard, Gapenne, Gaussier, & Hafemeister, 2005; O’Regan & Noe, 2000; Philipona, O’Regan, Nadal, & Coenen, 2004). In this perspective, training resources can benefit from supplemental interfaces which (re)interpret perceptive data that has been missed by the individual in a way that becomes particularly significant for disabled persons. When considering learning styles, cognitive abilities or pre-acquisitions, a virtual environment for learning should be adapted to his/her learner. These characteristics can either be embedded in the virtual environment, managed thanks to artificial intelligence as in intelligent tutoring systems, or constitute the main purpose of the virtual environment (e.g., delivering learning facilities to target publics). Specific target publics (e.g., tall vs small persons, cognitive impaired (Pugnetti et al., 1995), disabled persons; Cobb & Sharkey 2007) may benefit largely from VR adjustable interfaces. Such specific interfaces can be used for training purposes but can also be used for rehabilitation or to tune a workplace to its users.

A content-oriented approach

Regarding the contents that are primarily developed in virtual environments for training, we can either develop a non-exhaustive list, naming the nature of the content and based on current developments or use a typology which describes particular characteristics of the content. One main difficulty in building typologies consists in choosing an accurate frame of reference.

We propose to focus on the relation between the embodied human being and the real world. Therefore, we distinguish two aspects: (a.) the actual existence of an object, and (b.) and the possibility for that object to be directly perceived by a human being in full possession of his/her senses. In this context, an object can designate nearly anything, be it concrete, animated, living, immaterial, or conceptual. Each aspect can be valued depending on its truth:

a) On one hand, an object can be
   1) Actual;
   2) Likely or probable (e.g., resulting in unproved theories; existence of cues or uncertain signs of the object presence); or
   3) Definitely non-existent.
b) On the other hand, the human being
   1) Has a clear perception and directly perceives the object (direct perception);
   2) Identifies the presence of the object based on perceptive clues (indirect perception);
   3) Cannot perceive the object (non-perception).

From those two aspects, we have created the following table (Table 1, which provides indications on qualities of the content and examples of virtual environments.

Table 1. A two-aspect characterization of contents

X.0 Actuality of an Object 0.Y Perceptibility of the object	**1.0 Actual**	**2.0 Likely**	**3.0 Non-existent**
0.1 Direct Perception	1.1 Direct perception of an actual object *VR can be used for duplicating or simulating what cannot be currently perceived (e.g,. Hubble telescope); what is too hazardous or expensive to use for learning purposes (e.g., full-scale simulators and realistic VR-based simulator.*	2.1 Direct perception of a maybe-existing object, which means that the perception is uncertain: it might either be a correct or an incorrect perception (e.g., a misinterpretation of sensitive data. *VR can be used to learn how to interpret clues and signs (e.g.,. facial signs of anger (Gratch et al., 2001.*	3.1 Direct perception of a non-existing object, which means that it is a perceptive illusion or a projection of the mind. *VR can be used to educate perception or the correct development of the mind. It can also be used to create and make perceptible objects that do not exist (e.g., creation of new realities as SecondLife).*
0.2 Indirect Perception	1.2 Perception of clues that indicate the existence of an object, which does exist without being perceptible. *VR can be used to develop tangible representations of what is numerically referred to in regular working situations -e.g., VTT (Mellet-d'Huart et al., 2004.*	2.2 Perception of clues that might be interpreted as signs of existence of an object, which might also be a misinterpretation because the existence of the object is uncertain. *VR can be used to teach how to analyze and interpret significant clues in order to determine what does exist or not in a particular situation -e.g., breakdown diagnose on industrial faucet (Frejus et al., 1997.* Knowing individual minds *Behavioral therapy (e.g., Rizzo, Buckwalter, & Neumann, 1997).*	3.2 Perception of clues that are wrongly interpreted as signs of existence of an object, which does not exist. *VR can be used to educate perception or the correct development of the mind. It can also be used to create clues and establish correct connections between actual clues and real objects -e.g., presentation of the actual appearance of a default following welding errors in CS WAVE (Da Dalto et al., 2007).*

continued

Table 2. ***continue***

0.3 Non-Perception	1.3 No perception of an existing object; from a sensory viewpoint, it is as if this object does not exist. *VR can enlarge objects that are too small; reduce objects that are too large; shorten the distance between objects that are too far away; apply transduction on non-perceptible phenomena, reification on conceptual data (Winn, 1993) -e.g., showing attraction forces between molecules (Loftin et al., 1995); making dangerous gas perceptible in fire-fighting application (Querrec et al., 2003.*	2.3 No perception of any maybe-existing object; from a sensory viewpoint it is as if this object does not exist at all, although it might exist. *VR can be used to make perceptible uncertain objects or theoretical laws, which potential existence has better been taken into account - e.g., zone of high risk on railways (Lourdeaux, Fuchs & Burkhardt, 2001); Newton Laws (Dede*, Salzman, & Loftin, *1996)*.] *Conceptual data, procedures are object in the mind that can be approached as maybe-existing objects, depending on the fact that the operator is aware of them and support them appliance* (e.g., *procedural training GVT (Gerbaud, Mollet, & Arnaldi, 2007).*	3.3 Non-perception of a currently non-existing object, which is correct. *VR can be used to make perceptible objects that no longer exist -e.g., paleontology, cultural heritage (Wojciechowski, Walczak, & Cellary, 2005) or that do not exist yet -e.g., industrial design or architecture (Sampolo & Henriques, 2006) or support the creation of imaginary worlds.*

A pedagogically oriented approach

Another trend consists in choosing to use virtual reality to support new or specific educational or pedagogical methods: e.g., implementing specific learning theories, developing learning resources fitting with specific paradigms (e.g., Constructivism (Dimitropoulos et al., 2008; Roussos et al., 1997; Winn, 1995), Enactivism (Mellet-d'Huart, 2006; Winn, 2003a)) overcoming specific learning difficulties (Michel, 2004). This approach rejects the "realistic a priori" and is in quest of what might be unique with virtual reality (Burkhardt et al., 2006; Dede et al., 2000; Mellet-d'Huart, 2006; Winn 1997, 2003b, 2005). This had clearly been a major trend in the field of education, in the mid-90s in the United States. It has also been an approach used for training (e.g., welding, metal machining, etc.; Mellet d'Huart et al., 2005), although the requirement for realism could be stronger. Nowadays, the constructivism paradigm is often being taken as evidence among learning professionals, but it is not always well understood and sometimes lacks the guidance required to support efficient learning. As William Winn claimed in the early 2000s, it is time to return to sciences in order to refresh learning theories (recently, a number of multidisciplinary research teams have been formed under the label "Learning Sciences", e.g., Singapore Institute for Learning Sciences; Looi, Hung, Bopry, & Koh, 2004).

Another pedagogical approach consists of providing real-time support to teachers and learners in their interrelations. Bailenson, Blascovich, Beall, Lundblad, and Jin (2008) experimented with the introduction of additional data in a virtual environment in order to orient teachers' attention on particular students, especially on neglected students. They transformed the perception of the spatial relations between teachers and students in a virtual classroom, depending on how each individual felt considered and on the teachers' attention. Although the educational model remains classical, the use of VR technology supports dynamic enhancements of the teaching situation.

The next paragraphs will illustrate an attempt to refine the educational criteria for breaking-up an activity based on an Enactive paradigm and a meta-model of action (for more details, see Mellet-d'Huart, 2006). The developments result from the study of different scientific fields such as biology of cognition (Maturana & Varela, 1980), neurophysiology of action (Berthoz, 1997), and can be defined as a learning science approach. Thus, we will explore a number of specific virtual reality characteristics.

Specific support for learning science-oriented approach

As seen previously, the basic approach in order to properly understand an application is to explain the paradigm to which it refers (e.g., Cognitivist paradigm for STEVE). The following framework which is used for splitting up learning activities refers to the paradigm of enaction and is based on a meta-model of action (Mellet-d'Huart, 2006). This framework identifies three learning categories that will be presented along with three different applications illustrating these categories. The interest of this framework is twofold:

1) it helps organize learning activities in a clear and progressive approach;
2) it facilitates the design of virtual environments by taking into consideration specific characteristics of each category. Thereby, we distinguish between learning activities that either focus on understanding, on decision-making, or on realizing body action.

Supporting understanding

The first learning category refers to a range of learning activities identified as *understanding activities*. This range of cognitive activities consists of producing and planning anticipations for future actions, analyzing their possible consequences on the environment and, recursively, on the living being. It simulates the interplay between an individual and his/her environment, and looks to understand the processes involved. Simulating implies spatiotemporal projections, searching for causation in the past and projecting consequences in the future. It requires the development of space and time references, using what has been memorized and simulating the possible results of an action over time based on the current situation. Moreover, in order to use the experience results for future advances or predictions, experience has to be transformed into concepts, rules, beliefs or knowledge. It therefore produces distinctions, categories, generalizations and causations by observing, experiencing, abstracting, and "languaging" (e.g., using concepts). Those cognitive functions aim at explaining results that have been achieved and at the possible foreseeable consequences of future actions. Learning about basics models (theoretical, technological and scientific models) underlies our understanding of the real world. This dimension is broadly shared with education. Thus, the virtual environment will tend to be generic and non-contextual. It will tend to make explicit and perceptible causation/cause-effect relations that are relevant to understanding what is to be learned.

A VEL developed during the late 90s illustrates this approach accurately. A *Virtual Faucet* (Frejus et al., 1997) was developed by EDF (France) to support the learning of a diagnostic method and to apply this diagnostic method to diagnosing and fixing breakdowns in electric power stations (see Figures 6 and 7). This 1996-1997 experiment was engaged in order to evaluate virtual reality added value on technical trainings. Up to now, no further developments or industrial applications have followed.

The case-study approach used presents a virtual faucet. It can present different breakdowns on the faucet. The accurate application of the diagnostic method presupposes that the learners know and understand how a faucet works. They have to use mental simulations of the processes and to anticipate the consequences of any particular breakdown.

Figure 6. Virtual Faucet: *As Built* Virtual Copy of the Context of the Operation (produced from a 3D laser survey including photo texturing) (Copyright EDF).

The virtual faucet thus illustrates a situation where understanding a system and learning to anticipate and simulate a process constitute a major topic. The learner has to acquire a conceptual model of the faucet and the processes involved when working normally. He/she must be able to detect and figure out possible causes for any breakdown. This means that the activity requires learners to master a conceptual approach to the problem-solving situation. Therefore, the application presents a generic model of a faucet, highlights concepts and names of parts, and provides a transduction representation of fluid circulation, pressure and temperature.

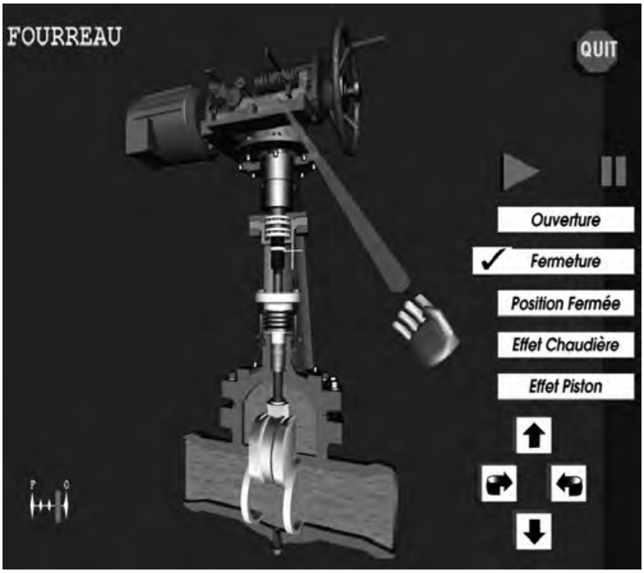

Figure 7. Virtual Faucet with User Interface and Virtual Hand (Copyright EDF).

The faucet may be dismantled when working, thus offering see-through facilities. Trainees can make the circulation of fluids, temperatures and pressures, and so forth, visible. There is no background, no detail and no singularity. In order to compare the virtual environment to the related real situation, the frame of reference is used to characterize the content. Thus, we will see how virtual environment characteristics can intentionally differ from the real world. The relation object/perceptibility is modified according to particular rules in order to facilitate learning activities see] Table 2).

Supporting decision-making

Another aspect of human activity, which has to be learned as well, deals with decision-making and mobilizing and engaging the vital energy required to carry out an action. The decision concerning what is to be realized will result from a synthesis of elements stemming from inner and outer evaluations. Therefore, human beings make

Table 3. The Industrial Faucet: Differences Real/Virtual environments

X.0 Actuality of an Object / 0.Y Perceptibility of the object	1.0 Actual		2.0 Likely		3.0 Non-existent	
0.1 Direct Perception	*1.1 Direct perception of an actual object*		*2.1 Direct perception of a maybe-existing object.*		*3.1 Direct perception of a non-existing object.*	
	Real environment	Virtual environment	Real environment	Virtual environment	Real environment	Virtual environment
	Outside appearance and context	Inside processes		Breakdown causes and breakdown consequences		
0.2 Indirect Perception	*1.2 Perception of clues that indicate the existence of an object.*		*2.2 Perception of clues that might be interpreted or misinterpreted as signs of existence of an object*		*3.2 Perception of clues that are wrongly interpreted as signs of existence of an object.*	
	Real environment	Virtual environment	Real environment	Virtual environment	Real environment	Virtual environment
	Some cues of the faucet working or not working	Some cues of working	Breakdown consequences			
0.3 Non-Perception	1.3 No perception of an existing object.		2.3 No perception of any maybe-existing object.		3.3 Non-perception of a currently non-existing object.	
	Real environment	Virtual environment	Real environment	Virtual environment	Real environment	Virtual environment
	Inside processes	Outside appearance	Breakdown causes			

evaluations of internal states, lacks and potentials, and external risks and sources of satisfaction with regard to the simulations of anticipated action. From a biological viewpoint, any decision-making has to do with making the right decisions in order to secure the continuation of *autopoietic processes* (process that insures that an organism remains alive; Maturana & Varela, 1980).

An inner evaluation process provides data about needs and existing means. It supports knowledge on the energy available to undertake any perceptual and motor activity of the body in the environment. The energy's availability has to be checked and mobilized, in order to have it ready to be engaged if the decision is to carry out the simulated action. Another duty is to track down any outside threat and detect all existing risks in order to protect the autopoietic process (e.g., prey avoiding predators). The emotional state (e.g., fear, despair, hope) of the organism will play a part in deciding whether a simulated action is to be engaged or inhibited. It is well-known that when real world conditions have safety trade-offs and industrial performance under pressure from the workplace, people may choose higher risk behavior (Rundmo, 1997).

Contextual elements prevail when learning decision-making. Therefore, the virtual environment will emphasize all contextual elements and minimize elements that are proper to the main process. "However, it is believed that in order to gain a better understanding of decision-making performance provided by virtual reality-based industrial training systems, it is important to better understand perception in the virtual environment" (Duffy, Ng, & Ramakrishnan, 2004). The learner has to develop a large and encompassing perception.

A VEL developed in the early 2000's by the University of Southern California Institute for Creative Technologies (USC-ICT) USA to train military personnel in peace-keeping operations illustrates this category. In this case, priority is given to human factors and emotional interactions. Role-playing has been widely used for this purpose, but it has major limitations –for both organizational and educational reasons. It may mobilize numerous actors and large-scale resources, with hazardous results. *Mission Rehearsal Exercise* (MRE) is a virtual environment for learning based on an interactive story; the outcome depends on decisions and actions that participants make during the simulation see (Figure 8).

Figure 8. A Learner in Action in MRE (image courtesy of University of Southern California's Institute for Creative Technologies).

The goal is to prepare decision-makers who need to think efficiently and accurately, while facing realistically bewildering and stressful circumstances (Gratch & Marsella, 2001). This application focuses on the acquisition of high-level competences for decision-making. This means that the activity requires learners to master a complex and social-based dilemma through languaging and decision-making. MRE illustrates a situation where decision-making is the key point and where major risks of failure exist see Figure 9). The learner is confronted with a danger and with his/her emotional states.

Figure 9. MRE: A Complex and Hazardous Situation in Bosnia (image courtesy of University of Southern California's Institute for Creative Technologies).

Because danger and risks in real situations seldom result from unique and intrinsic causes (e.g., auto-generated default in the main process), but are connected with contextual hazards and unexpected events, several details have to be considered and represented in the virtual environment. Details are clues which help to anticipate future possible dangers. The learner's emotions also constitute a main issue of the application. He or she not only faces his/her own emotions, which can be affected by stress, but also other humans, who can develop irrational behaviors due to their own fears, anger or various emotional states.

A software component deals with the direct linkage between emotion and decision-making in connection with narrative (Gratch & Marsella, 2001). The VEL incorporates realistic and believable virtual humans with motor skills, problem solving abilities, emotions, and language skills (Rickel et al., 2002). Interactions take place in natural languaging. A virtual human, who acts as a trainer in the immersive learning environment, supports training functions. The notion of dilemma is the keystone of the application.

Using our frame of reference, we can see that the characteristics of the real world and the virtual environment are so close that they have been presented in one and alone table see Table 3).

Table 4. Mission Rehearsal Exercise: Differences Real/Virtual environments

X.0 Actuality of an Object / 0.Y Perceptibility of the object	1.0 Actual		2.0 Likely		3.0 Non-existent	
0.1 Direct Perception	*1.1 Direct perception of an actual object*		*2.1 Direct perception of a maybe-existing object.*		*3.1 Direct perception of a non-existing object.*	
	Real environment	Virtual environment	Real environment	Virtual environment	Real environment	Virtual environment
	External watchers' behaviors, cars, sergeant and soldiers	Emphasizing contextual elements (External watchers' behaviors, cars, sergeant and soldiers, etc).	Real child injuries	Minimizing the representation of child injuries		
0.2 Indirect Perception	*1.2 Perception of clues that indicate the existence of an object.*		*2.2 Perception of clues that might be interpreted or misinterpreted as signs of existence of an object*		*3.2 Perception of clues that are wrongly interpreted as signs of existence of an object.*	
	Real environment	Virtual environment	Real environment	Virtual environ ment	Real environment	Virtual environment
	Humor and temper of protagonists	Emphasizing humor and temper of protagonists.	Particular emotion of the mother and other inhabitants External risks (e.g., smoke).	Emphasizing details (e.g., smoke)		
0.3 Non-Perception	*1.3 No perception of an existing object.*		*2.3 No perception of any maybe-existing object.*		*3.3 Non-perception of a currently non-existing object.*	
	Real environment	Virtual environment	Real environment	Virtual environment	Real environment	Virtual environment
	Activities of other squad members	Idem				

Following the same trend, the Stability and Support Operations—Simulation and Training (SASO-ST) project trains military commanders in negotiation skills with more sophisticated models of human engagement and social and cultural interrelations between individuals (Traum, Swartout, Marsella, & Gratch, 2005) (see Figure 10). This model combines emotional data involved in decision-making with plans and rational anticipations produced by a good understanding of the situations.

Figure 10. SASO-ST: A Partner for Negotiation in his Context (image courtesy of University of Southern California's Institute for Creative Technologies).

Supporting realization

Realization deals with learning about skills and making actions more efficient in order to achieve appropriate effects in the real world. More basically, realization deals with efforts made by an embodied living being to modify its own environment in order to exist in this environment. It focuses on realizing, in a relevant manner, targeted forecasted actions in order to produce expected changes or effects within the environment. It aims at achieving intentional environmental modifications as simulated by the domain of virtualization, but they may also induce unintended effects.

In any case, environment is modified by action. The human being has to face the consequences of doing something in an environment and the impact of an environment on him/her. Thereby, executing an action involves continuous sensory-effector activity in order to correlate body states and activity with target elements of the environment and changes occurring in the environment. In order to organize body-movements in space, the domain of actualization attempts to articulate learned landmarks with significant environmental changes. It is therefore supported by perception, with its external sensors.

Perception, at this stage, supports the definition of spatial and temporal landmarks required for the embodied execution of the action. Perception and motor activity are deeply inter-dependent. Indeed, sensors require motion if they are to be effective: "… the sensors activity stage is brought about most typically by the organism's motions" (Varela, 1994). Actualizing an action requires energy to engage body movements within a material and spatial world that offers resistance in the form of gravity, inertia and so on. A virtual environment which supports body-action realization will integrate a high fidelity level regarding spatial organization and spatiotemporal ratios. When oculomotor activity prevails, accurate landmarks will be provided.

The archetypal virtual environment that will be considered here supports learning basic sensory-motor skills for welding, which are very difficult to learn in the real world. Classical training by doing requires long and repetitive rehearsal situations with very few visual clues (although oculomotor activity prevails) and hardly any direct feedback.

Because of such major learning difficulties, the focal point of the VR application is to enable learners to learn how to use and move the torch. AFPA and CS (France) developed CS WAVE, a virtual environment directed at the acquisition of welding sensory-motor skills. It is based on two principles. First, it is based on a breakdown of sensory-motor activity. It supports a step-by-step course, which begins by single factors with low levels of expectation, moving up to complicated handling of the torch, where levels of expectation are high. Second, it provides visual guides and real-time feedback to support the psychomotor activity. Different welding techniques, different welding positions and different parts and assembling situations are implemented (Da Dalto et al., 2007).

The curriculum is synchronized between the virtual environment and the real situation so that the learner faces identical situations and exercises in the two environments (Mellet-d'Huart et al., 2004). Visual guides have been introduced in order to provide clues about the correct movements expected of the torch and the learner's hands. A visual spot can guide the learner's movements through the welding process. Moreover, visual feedback is given about specific requirements for variables currently involved in a particular exercise. The variables correspond to different components of skilled action (e.g., advancing speed, angles formed between the nozzle and the cord – See Figure 11).

Anything that could prevent correct movements from being performed is removed. For this reason, in the virtual environment there are none of the lights or sparks that pollute the visual scene and the representation of the cord is average because at this

Figure 11. CS WAVE and its parameters (CS & AFPA 2007).

stage, the accuracy of the physicochemical process is not the purpose of the learning process. The comparison between what can be perceived in the real world with the virtual environment shows an inversion of several factors (see Table 4).

Those particular changes introduced in the virtual environment aim at facilitating the learning process (see Figure 12). The transfer in the real situation occurs progressively and continuously as exactly the same exercises are realized in the two environments following the same steps.

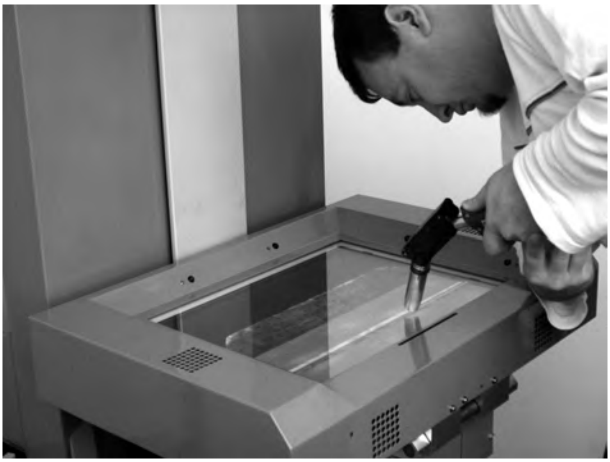

Figure 12. CS WAVE: A Learner in Action (CS & AFPA 2007).

Table 5. CS WAVE: Differences Real/Virtual environments

<table>
<tr><td>X.0 Actuality of an Object</td><td colspan="2" rowspan="2">1.0 Actual</td><td colspan="2" rowspan="2">2.0 Likely</td><td colspan="2" rowspan="2">3.0 Non-existent</td></tr>
<tr><td>0.Y Perceptibility of the object</td></tr>
<tr><td rowspan="3">0.1 Direct Perception</td><td colspan="2">1.1 Direct perception of an actual object</td><td colspan="2">2.1 Direct perception of a maybe-existing object.</td><td colspan="2">3.1 Direct perception of a non-existing object.</td></tr>
<tr><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td></tr>
<tr><td>Shadows (context), light and sparkles</td><td>Molten pool Cord</td><td></td><td>External defaults (as afterwards feedback)</td><td></td><td>Spots used as gesture guidelines
Real-time quality indicators</td></tr>
<tr><td rowspan="3">0.2 Indirect Perception</td><td colspan="2">1.2 Perception of clues that indicate the existence of an object.</td><td colspan="2">2.2 Perception of clues that might be interpreted or misinterpreted as signs of existence of an object</td><td colspan="2">3.2 Perception of clues that are wrongly interpreted as signs of existence of an object.</td></tr>
<tr><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td></tr>
<tr><td>Cord</td><td></td><td>External defaults</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">0.3 Non-Perception</td><td colspan="2">1.3 No perception of an existing object.</td><td colspan="2">2.3 No perception of any maybe-existing object.</td><td colspan="2">3.3 Non-perception of a currently non-existing object.</td></tr>
<tr><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td><td>Real environment</td><td>Virtual environment</td></tr>
<tr><td>Molten pool</td><td>Light and sparkles
Context (nor in shadows neither in clear)</td><td>Internal quality of the welding Internal defaults</td><td>Internal defaults</td><td></td><td></td></tr>
</table>

Design of virtual environments for training and lifelong learning

In the following paragraphs, we will consider the design of virtual environments for training and lifelong learning. We will present a number of remarks and an analysis of current difficulties encountered by designers, and make proposals in order to better understand and exploit the uniqueness of VR applied to learning. Up to now, there are very few rules or guidelines for designing virtual learning environments, mostly basic usability criteria which are common to all virtual environments (Dimitropoulos et al., 2008). The fact is that, when designing virtual environments for learning, experts encounter different kinds of difficulties due to technical, educational or socio-economic limitations.

Although designing VELs does require trans-disciplinary collaboration, difficulties arise as soon as experts coming from different fields with different backgrounds start working together. Neither shared references nor shared vocabulary are available to facilitate communication. As a result, misunderstandings occur and time-consuming regulation processes become necessary. As noted by Tchounikine et al. (2004), in order to become a scientific discipline *per se* and to develop engineering methods, it is necessary to develop a specific vocabulary aimed for all contributors to the design of technically-enhanced learning environments.

In addition, computer scientists, educationalists, and content experts need to share a common frame of reference in order to jointly supervise the design process and to fully communicate together. There is a clear need of explicit paradigms, shared concepts, trans-disciplinary references, design engineering and evaluation methods. This is the designated condition for trans-disciplinary collaboration, and for the production of knowledge in the context of a specific scientific field (Tchounikine et al., 2004).

Most importantly, there still is, at the present stage, a lack of engineering methods for VEL design. There are only limited and local methods directed at particular aspects or components of the VEL (e.g., $3I^2$ proposed by Fuchs (2006) to support the definition of interactions and the choice of interfaces) or generic method for software development (e.g., Boehm, 1986). Current design approaches are either based on trial-and-error processes, on the inheritance of existing features or components from a former application used in a new one (e.g., from the design of STEVE virtual agent (see Figure 2), from STEVE to Mission Rehearsal Exercise (Hill et al., 2003; Rickel, Gratch, Hill, Marsella, & Swartout, 2001) (see Figure 9), from Mission Rehearsal Exercise to SASO-ST (see Figure 10), and so on, or they refer to theories that can only be applied to limited aspects of the application. The process often becomes unbalanced due to the fact that while each of these groups has its own respective competences, they neither overlap nor cover the entire complexity of the application. Neither global frames of reference, nor meta-tools are available to deal with various aspects of complexity encountered when designing VELs. Very few research teams have completed developments on every type of component that constitutes a complete VEL as ICT did (Swartout et al., 2001).

Tackling complexity

If VELs present all characteristics of complex systems that have to ensure their own coherence and dynamic, they are also embedded in a threefold complexity that can be broken down into (1) complexity of learning (human dimension); (2) complexity of virtual environments (VEs) and their interfaces (artificial dimension); (3) complexity in initiating contextual uses (social and economic dimension).

Human complexity

To tackle the complexity of human learning requires operating knowledge about learning processes, didactics and pedagogy. In existing VELs, educational theories are often insufficiently integrated into a coherent virtual reality-learning sector. This is probably one of the main reasons why some experiments may either show insufficient evidence of effectiveness, or produce conflicting or contradictory results.

Moreover, because of the differences between individuals (e.g., prior learning, learning styles), we need to develop multiple and complex possible paths instead of a single, simple model of the knowledge approach from the expert's viewpoint. In addition, few VELs propose real guidance or monitoring tools for learners, which could make a real difference with more conventional learning environments. In order to provide more efficient guidance, we need to better understand the difficulties encountered by learners. Therefore, methods aimed at identifying and analyzing learning difficulties, for example, the approach developed by Michel (2004), are well appreciated and should be used as soon as the design project is engaged. This will help in understanding what is required to really support and facilitate the learning activity in VELs.

Artificial complexity

VEs are complex artificial systems. By using the term artificial systems, we tend to emphasize that it cannot be reduced to technological questions, even if there are several and difficult technical issues. Naturally, technological outcomes need to be taken into consideration: modeling, software programming, real-time calculation constraints, choice of interfaces, inter-compatibility of components, respect of international norms, development of intelligent tutoring systems, and so forth. Artificial complexity also encompasses qualitative issues such as computer graphic developments, defining characters, elaborating narrative, personalization of the environment, and, even introducing some humor.

Socio-economic complexity

Formal learning universes are complex and require a difficult equilibrium between human factors, methods, curricula, rhythms, duration, pedagogy, training resources, material means, rooms, and so forth. Changing any element may break down the coherence of the system and unbalance the whole situation. Therefore, introducing a VEL in an existing training context is not neutral and has to be foreseen from the very beginning of its design process. Important issues such as redefining the role of trainers are engaged.

Unfortunately, only a few VELs have reached their end-users in their own contexts, and have been experienced from the viewpoint of their integration into a professional context for everyday use. Important issues have to be addressed about how VELs are to be used, how pedagogy has to be adapted, how the role of trainers is modified, and so forth. Generalizing the use of a VEL on a large scale generates new difficulties and very few experiments have reached this level of analysis. Moreover, the overall coherence of VEL tuning to public and environment of use is yet to be studied. The real outcomes of using VELs in institutional, social and human contexts are still difficult to evaluate.

Complex dynamics

Building a system requires developing proper dynamic articulations between the three spheres of complexity: 1) Ergonomics and usability approaches deal with the interdependence between human complexity and artificial complexity 2) Economics directly influences the artificial sphere (e.g., in training applications, very few CAVE™ or head-mounted devices are used, but there are numerous desktop applications) 3) Pedagogy interfaces the socio-economic sphere with the human sphere.

Such a dynamic approach will influence the project recursively. Despite the current lack of specific methods, the usual way to deal with such dynamic aspects is to adopt an iterative approach and to involve end-users (real learners and trainers) at a very early stage of the process.

Overall complexity

Dealing with VELs is not just an addition of three complexities and their dynamic interrelations. The overall object has its own identity and its own levels of complexity. At this stage of our knowledge, it remains difficult to master the different factors involved, and to determine how they contribute to enhancing or lowering the performance or the system efficiency.

Therefore, a lack of overall or multifactor evaluation tools and means hinders the presentation of concrete evidence for the intuitive observations of effectiveness encountered in industry. Closer collaboration between research and industry is therefore required (Mellet-d'Huart et al., 2004). Moreover, internal characteristics of VELs require specific concepts, such as the concept of coupling, in order to consider properly the continuous reciprocal causation, which exists in the learner/VEL/context system (Mellet-d'Huart, 2006; Winn, 2005)].

VR concepts and design

With respect to shared concepts, there have been several attempts to apply specific concepts of virtual reality (e.g., immersion, presence) to VEL design. Assumptions were made that a VEL, which would embody the most advanced criteria of immersion, interaction and realism, and generate a high sense of presence, would be most effective to support learning and training.

Experiments were developed, based on those principles. In order to evaluate their effectiveness, comparisons have been performed, for instance, between VELs highly immersive (Winn et al., 2002) or providing a high level of presence, and VELs developed on more classical educational criteria. As summarized by Winn (2005), *immersion* only provides added value for learning in some cases (depending on the content); it gives rise to a greater sense of presence, but there is no evidence that a high sense of presence improves learning.

Moreover, the fact that VR concepts (e.g., "immersion", "presence", "realism", "interaction") were used initially instead of learning concepts introduced major confusion. As a result, rather than concentrating on the aims of the learning application, emphasis was put on the means. The choice of means should remain as a second-order factor in the educational process.

As good, as immersive, as interactive as the technical virtual environment (VE) might be, it cannot produce formal learning *per se*, unless an accurate learning hypothesis is implemented and learning scenarios developed (*nota bene*: informal learning may always occur, but often not as expected).

Unsurprisingly, every experiment completed in order to verify the efficiency of the VR concepts application has only produced conflicting or poor results (Pujol-Tost, 2005; Winn, 2005). Because of this confusion, we lacked references to learning processes, didactics and pedagogy and we did not develop accurate concepts adapted to the unique characteristics of VR.

Let us acknowledge that VR concepts are useful for creating and exposing the unique properties of virtual reality as a computer-science domain. They may also be useful for characterizing the way a VEL will fulfill its requirements. But they have very little to do with modeling learning.

As for the concept of realism, especially for training, some experiments have focused on comparing the effectiveness of learning using different levels of realism. In medical simulation, an evaluation was set up to compare a full-scale, realistic simulator, with a very sophisticated human mannequin, to a learning-oriented desktop simulator (Nyssen, 2005). The evidence did not show better learning when a full-scale mannequin was used instead of the desktop application.

The existence of educational hypotheses implemented within the VELs along with the pedagogical support provided seems to have more effect on future learning than realism or the sole implementation of VR concepts. Another aspect concerns what exactly has to be communicated from the real world in the virtual one.

Realism is a fuzzy term unless its use is restricted to a perceptive fidelity (e.g., photo-realism). In order to be more specific, Burkhardt, Bardy, and Lourdeaux (2003) propose using the fidelity concept along with the characterization of which type of fidelity has to be considered (e.g., perceptive fidelity, psychological fidelity). Going further, we could, for instance, differentiate what is related to visual-spatial fidelity in order to support sensory-motor action; process and causation fidelity in order to manifest correct consequences to particular cause; or environmental fidelity in relation to what risks can be encountered in a particular situation.

Considering the embodied learner

What is really specific with VR compared to other information technologies is that body activities are supported by technology. Considering the user's body and activities is a particular focus that can be shared by different experts.

Virtual reality enables learning by doing; the learner's embodiment and embeddedness in learning situations (Mellet-d'Huart, 2006; Winn, 2003b) becomes a core issue. However, we lack proper references to consider an embodied learner in an accurate manner (Riegler, 2002; Reyes & Zarama 1998; Varela, Thompson, & Rosch, 1991). That made Winn (2003a) and Looi et al. (2004) note that virtual reality for learning, and more generally Technologically Enhanced Learning, suffers from a lack of scientific references. Learning theories are not sufficiently developed to provide guidance for making appropriate choices during the design period.

This topic questions the paradigms that explicitly or implicitly ground any application. If the Cognitivist paradigm skips the question of the body and rather focuses on information processes, the Constructivist paradigm offers very few clues for bridging learning and body activities. Only the Enactivist paradigm places the embodied dimension at the very center of the approach. Therefore, as initiated by Winn (2003a), we found an interest in exploring what neurosciences (e.g., biology of cognition, neurophysiology of action) teach us, and how they help us to understand how the body is involved both in virtual reality and learning activities.

New knowledge on human activities deriving from neurosciences, and a new tool resulting from virtual reality, have provided us with elements that contribute to understanding and supporting learning. Several elements are indeed available to rethink pedagogical approaches, didactics and individual guidance for learning (e.g., breaking down learning content into understanding, decision-making and realization can accurately be supported by VR).

Enhancing learning processes

From previous considerations, a question has emerged: How to exploit what is unique in virtual reality in order to make learning processes really easier and more efficient? In fact, if we look at the diversity of existing VELs, whether considering learning objectives or technical choices, we generally do not find any causal link between the characteristics of a VEL and its learning objectives.

As explained earlier, although numerous assets of VR are well known, different works have shown that we have not yet managed to pinpoint the unique characteristics of VR for learning (Dede et al., 2000; Winn, 2005). In fact, for a long time, rules to determine the choice of VEL features have been almost nonexistent.

Up to now, only intuition and creativity seem to have been used. However, such rules could exist provided that an accurate model of human action and learning activity can be used as a frame of reference. We met Winn (2005) and Looi et al. (2004), who underlined the current need of a global framework in order to approach, design and use VELs. One direction is to ground the design and the future use of virtual reality on an appropriate paradigm and theory of learning. As stated previously regarding virtual reality capabilities, the appropriate paradigm will have to take into account embodiment.

Although we think that each paradigm contains its own advantages and limitations, given that there is clear reference, that the design method, the design concepts and the future use of the application are performed in full coherence with the chosen paradigm, we believe that the Enactive paradigm is a particularly well-suited paradigm for the use of virtual reality for learning, and, of course, training. It fully considers embodiment and supports situational learning. Therefore, the design process will be learning-process based on an Enactive perspective, and will consider complexity from a threefold viewpoint.

Shared concepts and meta-model

Having suggested that the use of idiosyncratic VR concepts be limited to the technical sphere, we also propose to follow a Copernican change of viewpoint (Forte, 2005; Winn, 2003a, by considering the embodied learner as the cornerstone of VEL design and uses.

In order to investigate such perspectives, we have proposed a meta-model, called *meta-model of (en)action* (Mellet-d'Huart, 2006), which provides designers of VELs with a set of common concepts and landmarks. This meta-model has been developed from a heuristic perspective based on different disciplines. This approach replies to the noticeable lack of design methods, and helps deal with the complexity of the situation. Therefore, it should meet up with both researchers' and practitioners' expectations for enhancing design engineering methods and evaluation tools, in order to study the effective educational impact of virtual environments when used in training situations.

Such a framework is presumed to be applicable to the whole design process, from the earliest state of intention to the effective use of the system by final users in a normal context. It is also assumed to be shareable between multidisciplinary experts, and to constitute a common background to which they can refer their proposals and actions.

Thanks to this shared meta-model, and because of an overall approach to learning that includes didactics, pedagogy and learning processes, the uniqueness of virtual reality applied to learning is becoming progressively and increasingly clear.

This contribution is principally twofold:

1) modifying the way content or data are (re)presented in order to support specified learning;
2) involving the learner bodily in his/her learning activity.

As seen previously, a common and specific way of breaking down action and learning component comes along with this approach and constitutes a guideline to characterize the VE.

Conclusion and perspectives

VR applications in the field of adult learning are multiple and present a large panel of forms and purposes. It is not surprising that VR for training and lifelong learning shares numerous aspects with VR for education – they both have to do with human learning. Nevertheless, some differences exist due to the different biologic, social and economic characteristics of the users and respective learning contexts.

With respect to training in VEs, there has been an important legacy from simulation, along with a claim for realism that has limited the use of VR to a rather stereotyped standard of use. Insufficient consideration of the uniqueness of VR as well as misusing paradigms and learning models has impeded the full renewal of the learning approaches that could be supported by VR.

However, following one's hunch in designing new virtual environments could give way to more rigorous development, provided that appropriate engineering methods can be used to design new VEs. Only an engineered approach can offer effective applications in numbers and at a cost compatible with the economic requirements of the sectors involved in learning activities.

Engineering methods and instructional design need to be grounded on solid theoretical frameworks (Ausburn & Ausburn, 2004). Bases for such approaches exist: they place the embodied user at the very heart of the design process along with a learning situation. The *meta-model of (en)action* offers an illustration of a global reference frame in order to introduce more methods and coherence in the design of virtual learning environments.

Concerning the future of VR applied to training and lifelong learning, both technological blending (e.g., VR blended with artificial intelligence and learning content management systems), and virtual-real blending (e.g., tangible interfaces, props, augmented or mixed reality; Anastassova, Burkhardt, Mégard, & Leservot, 2005) are promising evolutions. On the one hand, videogames, serious games (Stone, 2005) (see Figure 13, an illustration of serious games for training), and e-learning will support the large development of VR-based training solutions. On the other hand, augmented and mixed reality will enable real on-the-job learning or combining real-time performance support with learning activities.

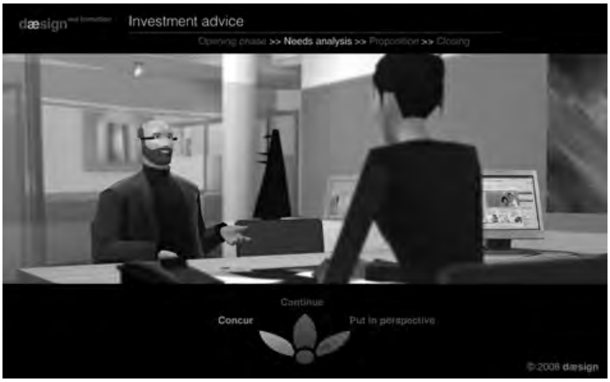

Figure 13. Serious Game for Counseling Training (Copyright Daesign 2007).

Virtual reality could also complete and enhance distance learning, thanks to telerobotic interfaces supporting the learner's distant/remote actions coordinated with other learners or trainers and/or connected to existing objects. Thanks to wearable computing, mobile applications will become increasingly sophisticated. More evolution is waiting to happen, but real efficiency of technologies to support learning will depend on our ability to develop new concepts and acquire new knowledge, to analyze learning processes and to develop methods to design adequate learning resources, to exploit the uniqueness of available technologies and, most importantly, integrate all of them into a coherent complex system. Learning sciences could become the optimum interdisciplinary space to reach such achievements and to support the development of virtual reality for learning.

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References

Aka, M., & Frasson, C. (2002). A new approach on flight training: ASIMIL. *International Conference in New Technology of Information and Communication* (pp. 307-314). Lyon.

Anastassova, M., Burkhardt, J.-M., Mégard, C., & Leservot, A. (2005). User-centred design of mixed reality for vehicle maintenance training: An empirical comparison of two techniques for user needs analysis. *Proceedings of HCI International*. Las Vegas, USA: LEA press.

Ausburn, L. J., & Ausburn, F. B. (2004). Desktop virtual reality: A powerful new technology for teaching and research in industrial teacher education. *Journal of Industrial Teacher Education*, *41*(4). Retrieved from http://scholar.lib.vt.edu/ejournals/JITE/v41n4/ausburn.html

Bailenson, J. N., Blascovich, J., Beall, A. C., Lundblad, N., & Jin, M. (2008). The use of immersive virtual reality in the learning sciences: Digital transformations of teachers, students, and social context. *Journal of the Learning Sciences*, *17*(1), 102-141.

Berthoz, A. (1997). *Le sens du mouvement.* Paris: Odile Jacob.

Boehm, B. W. (1986). A spiral method of software development and enhancement. *Software Engineering Notes*, *11*(4), 22.

Bricken, M. (1991). Virtual reality learning environments: Potentials and challenges. *Computer Graphics*, *25*(3), 178-184.

Burkhardt, J.-M., Lourdeaux, D., & Mellet-d'Huart, D. (2006). La réalité virtuelle pour l'apprentissage humain. In P. Fuchs (Ed.), G. Moreau (Coord.), B. Arnaldi & P. Guitton (Coords). Le Traité de la réalité virtuelle. Vol. 4 Les applications de la réalité virtuelle (pp. 43-100). Paris, Presse de l'école des Mines de Paris, 3rd edition.

Burkhardt, J.-M., Bardy, B., & Lourdeaux, D. (2003). Immersion, réalisme et présence dans la conception et l'évaluation des environnements virtuels. *Psychologie Française*, *48*, 35-42.

Chen, C. H., Yang, J. C., Shen, S., & Jeng, M. C. (2007). A desktop virtual reality earth motion system in astronomy education. *Educational Technology and Society*, *10*(3), 289-304.

Cobb, S., & Sharkey, P. M. (2007). *A decade of research and development in disability, virtual reality and associated technologies: Review of ICDVRAT 1996-2006*.

Crison, F., Lecuyer, A., Mellet d'Huart, D., Burkhardt, J.-M., Michel, G., & Dautin, J.-L. (2005). Virtual technical trainer: Training to use milling machines with multi-sensory feedback in virtual reality. *Proceedings of IEEE Virtual Reality Conference*. Bonn, Germany: IEEE press.

Da Dalto, L., Steib, D., Mellet-d'Huart, D., & Balet, O. (2007). CS WAVE: Virtual reality for welders' training. *Proceedings of the IIW 2007 International Conference*. Dubrovnik.

David, P., & Lourdeaux, D. (2001). *A simulator using virtual reality techniques for training driver to manual interventions on the tracks*. Poster presented at the WCRR'01 World Conference on Railway Research, Cologne.

Dede, C. J. (1995). The evolution of constructivist learning environments: Immersion in distributed, virtual worlds. *Educational Technology*, *35*(5), 46-52.

Dede, C J., Salzman, M. C., & Loftin, R. B. (1996). The development of a virtual world for learning Newtonian mechanics. In P. Brusilovsky, P. Kommers, & N. Streitz (Eds.), *Multimedia, hypermedia, and virtual reality* (pp. 87-106). Springer-Verlag.

Dede, C. J., Salzman, M. C., Loftin, R. B., & Ash, K. (2000). The design of immersive virtual environments: Fostering deep understandings of complex scientific knowledge. In M. J. Jacobson & R. B. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 361-414). Mahwah, NJ: Lawrence Erlbaum.

Di Blas, N., Gobbo, E., & Paolini, P. (2005). 3D worlds and cultural heritage: Realism vs virtual presence. In J. Trant & D. Bearman (Eds.), *Museums and the Web 2005: Proceedings*. Toronto: Archives & Museum Informatiks. Retrieved from http://www. archimuse.com/mw2005/ papers/diBlas/diBlas.html

Dimitropoulos, K., Manitsaris, A., & Mavridi, I. (2008). Building virtual reality environments for distance education on the web: A case study in medical education. *International Journal of Social Sciences*, *2*(1).

Duffy, V. G., Ng, P. P.W., & Ramakrishnan, A. (2004). Impact of simulated accident in virtual training on decision-making performance. *International Journal of Industrial Ergonomics*, *34*(4), 335-348.

Forte, M. (2005). Note on ecology of the virtual. In H. Thwaites (Ed.), *Proceedings of the 11th International Conference on Virtual Systems and MultiMedia: Virtual Reality at Work in the 21st Century* (pp. 787-798). Budapest Archaeolingua.

Frejus, M., Drouin, A., Thibault, G., & Schmid, A. (1997). Conception de systèmes de réalité virtuelle pour la formation d'agents de maintenance. *Proceedings of XXXII ème congrès de la SELF* (pp. 427-437). GERRA.

Fuchs, P., Burkhardt, J.-M. (Contrib.) & Lourdeaux, D. (Contrib.). (2006). Approche théorique et pragmatique de la réalité virtuelle. In P. Fuchs (Ed.), G. Moreau (Coord.), J.-M. Burkhardt & S. Coquillart (Coords.), Le Traité de la réalité virtuelle. Vol. 2. L'interfaçage, l'immersion et l'interaction en environnement virtuel (pp. 19-59). Paris, Presse de l'école des Mines de Paris, 3rd edition.

Gerbaud, S., Mollet, N., & Arnaldi, B. *(*2007). Virtual environments for training: From individual learning to collaboration with humanoids. *Dans Edutainment*. Retrieved from http://front.math.ucdavis.edu/0708.0712

Gratch, J., & Marsella, S. (2001). Tears and fears: Modeling emotions and emotional behaviors in synthetic agents. *Proceedings of the 5th International Conference on Autonomous Agents. Montreal, Canada*. Retrieved from http://ict.usc.edu/~gratch/agents01-emotion.pdf

Hill, R. W., Gratch, J., Marsella, S., Rickel, J., Swartout, W., & Traum, D. (2003). Virtual humans in the mission rehearsal exercise system. *KI Special Issue on Embodied Conversational Agents*. Retrieved from http://ict.usc.edu/files/publications/VirtualHumans.pdf

Kalawsky, R. S. (1996). Exploiting virtual reality techniques in education and training: Technological issues. (Advisory Group on Computer Graphics (AGOCG) SIMA Report No. 26). UK. Retrieved from http://www.agocg.ac.uk/reports/virtual/vrtech/title.htm

Kieferle, J., & Wossner, U. (2001). Showing the invisible: Seven rules for a new approach of using immersive virtual reality in architecture. *Proceedings of the eCAADe 2001: Education & curricula* (pp. 376-381). Helsinki, Finland.

Kozak, J. J., Hancock, P. A., Arthur, E. J., & Chrysler, S. T. (1993). Transfer of training from virtual reality. *Ergonomics*, *36*(7), 777-784.

Lecuyer, A., Coquillart, S., Kheddar, A., Richard, P., & Coiffet, P. (2000). Pseudo-haptic feedback: can isometric input devices simulate force feedback? *IEEE International Conference on Virtual Reality* (pp. 83-90).

Lin F., Hon, C. L., & Su, C.-J. (1996). Virtual reality-based training system for CNC milling machine operations. *Annual Journal of Institute of Industrial Engineer (HK)*. 13-16.

Liu, Y.-P., & Qiu, D.-T. (2002). CNC milling machine operations training ergonomics evaluation virtual reality environment. *Journal of South China University of Technology* (Natural science edition), *20*(9).

Loftin, R. B., & Kenney, P. J. (1995). Training the hubble space telescope flight team. *IEEE Computer Graphics and Aplications*, *15*(5), 31-37.

Loftin, R. B., Engelberg M., & Benedetti, R. (1993). Virtual controls in interactive environments: A virtual physics laboratory. *Proceedings of the 1993 Conference on Intelligent Computer-Aided Training and Virtual Environment Technology* (pp.191-202). NASA.

Looi, C.-K., Hung, D., Bopry, J., & Koh, T. S. (2004). Singapore's learning sciences lab: Seeking transformation in ICT-enables pedagogy. *Educational Technology Research and Development*, *52*(4), 91-115.

Lourdeaux, D., Fuchs, P., & Burkhardt, J.-M. (2001). An intelligent tutorial agent for training virtual environments. *5th World Multiconference on Systemics, Cybernetics and Informatics SCI'01*. Orlando Florida.

Maillard, M.; Gapenne, O., Gaussier, P., & Hafemeister, L. (2005). Perception as a dynamical sensorimotor attraction basin. In M. S. Capcarrere, A. A. Freitas, P. J. Bentley, C. G. Johnson, & J. Timmis (Eds.), *8th European Conference, ECAL: Advances in artificial life* (pp. 37-46). Springer, Lecture Note in Artificial Intelligence LNAI 3630.

Mantovani, F. (2003). VR learning: Potential and challenges for the use of 3D environments in education and training. In G. Riva (Ed.), *Towards cyberpsychology mind, cognition and society in the internet age*. Amsterdam: IOS Press. Retrieved from http://www.vepsy.com/ communication/book2/2SECTIO_12.PDF

Mantovani, F., Gaggiolo A., & Riva, G. (2003). Virtual reality training for health-care professionals. *CyberPsychology and Behavior*. 6(4) pp 389-395.

Maturana, H. R., & Varela, F. (1980). *Autopoiesis and cognition: The realization of the living, Boston studies in the philosophy of science*, *42*. Dordecht: D. Reidel Publishing.

Mellet-d'Huart, D. (2006). A model of (*en*)action to approach embodiment: A cornerstone for the design of virtual environments for learning. *Virtual Reality*, *10*, 253-269.

Mellet-d'Huart, D., Michel, G., Burkhardt, J.-M., Lécuyer, A., Dautin, J.-L., & Crison, F. (2004). An application to train in the field of metal machining as a result of research-industry collaboration. In S. Richir, P. Richard, & B. Taravel (Eds.), *Proceedings of Virtual Reality International Conference –IEEE VRIC2004*. ISTIA Innovation.

Mellet-d'Huart, D., Michel, G., Steib, D., Dutilleul, B., Paugam, B., Dasse, M., & Courtois, R. (2005). Usages de la réalité virtuelle en formation professionnelle d'adultes: Entre tradition et innovation. *Proceedings of First International VR-Learning Seminar*. Laval, France.

Michel, G. (2004). *Diagnostic de difficultés rencontrées par les stagiaires: analyse des difficultés définition de méthodes de diagnostic instrumentation du diagnostic*. Istres: AFPA.

Newell, A. (1990). *Unified theories of cognition*. Harvard University Press.

Nyssen, A.-S. (2005). Simulateurs dans le domaine de l'anesthésie: outils de formation et de recherche. Réflexions sur la validité et la fidélité. In P. Pastré (Ed.), *Approche par la simulation: de l'analyse du travail aux apprentissages professionnels*. Toulouse: Octares.

O'Regan, K., & Noe, A. (2000). Experience is not something we feel but something we do: A principled way of explaining sensory phenomenology, with change blindness and other empirical consequences. *ASSC Conference: The unity of consciousness: Binding, integration, and dissociation*. Brussels.

Ota, D., Loftin, B., Saito, T., Lea, R., & Keller, J. (1995). Virtual reality in surgical education. *Computers in Biology and Medicine*, *25*(2), 127-137.

Pantelidis, V. S. (1996). Suggestions on when to use and when not to use virtual reality in education. *Virtual Reality in the Schools*. Retrieved from http://vr.coe.ecu.edu/sug.html

Pastré, P. (2006). L'apprentissage par simulation: pour une véritable pédagogie des situations. In P. Pastre (Ed.), *Approche par la simulation: de l'analyse du travail aux apprentissages professionnels*. Octares.

Patel, M., Walczak, K., Giorgini, F., & White, M. (2004). Cultural heritage repositories as sources for learning materials. *The 5th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST 2004* (pp. 213-222). Brussels, Belgium. Retrieved from http://www.eg.org/EG/DL/WS/VAST/VAST04/213-222.pdf

Philipona, D., O'Regan, K., Nadal, J.-P., & Coenen, O. J. -M. D. (2004). Perception of the structure of the physical world using unknown multimodal sensors and effectors. In S. Thrun, L. K. Saul, & B. Schölkopf (Eds.), *Advances in neural information processing systems 16*. USA: Massachusetts Institute of Technology.

Psotka, J. (1995). Immersive training systems: Virtual reality and education and training. *Journal of Instructional Science*, *23*(5-6), 405 – 431.

Pugnetti, L., Mendozzi, L., Motta, A., Cattaneo, A., Barbieri, E., & Brancotti, A. (1995). Evaluation and retraining of adults' cognitive impairments: Which role for virtual reality technology? *Computers in Biology and Medicine*, *25*(2), 213-227.

Pujol-Tost, L. (2005). Interactivity in virtual and multimedia environments: A meeting point for education and ICT in archaeological museums. In H. Thwaites (Ed.), *Proceedings of the Eleventh International Conference on Virtual Systems and Multimedia: Virtual reality at work in the 21st century* (pp. 37-52). Ghent. Retrieved from http://aegean.academia.edu / LaiaPujolTost/Papers

Querrec, R., Buche, C., Maffre, E., & Chevaillier, P. (2003). SecuReVi: Virtual environment for fire-fighting training. In S. Richir, P. Richard, & B. Taravel (Eds.), *Laval Virtual – Proceedings of the 5th Virtual Reality International Conference*.

Regian, J. W. (1997). Virtual reality for training: evaluating transfer. In. R. J. Seidel & P. R. Chatelier (Eds.), *Virtual reality, training's future? Perspectives on virtual reality and related emerging technologies* (pp. 31-40). Springer.

Reyes, A., & Zarama, R. (1998). The process of embodying distinctions: A reconstruction of the process of learning. *Cybernetics and Human Knowing*, *5*(3), 19-33.

Rickel, J. W., Gratch, J., Hill, R., Marsella, S., & Swartout, W. (2001). Steve goes to Bosnia: Towards a new generation of virtual humans for interactive experiences. *AAAI Spring Symposium on Artificial Intelligence and Interactive Entertainment*. Stanford University.

Rickel, J. W., Marsella, S., Gratch, J., Hill, R., Traum, D., & Swartout, W. (2002). Toward a new generation of virtual humans for interactive experiences. *IEEE Intelligent Systems*, *17*(4), 32-38. Retrieved from http://ict.usc.edu/files/publications/ieee-is02-steve.pdf

Rickel, J. W., & Johnson, W. L. (1999). Virtual humans for team training in virtual reality. *Proceedings of the Ninth World Conference on AI in Education*. Amsterdam: IOS Press.

Riegler, A. (2002). When is a cognitive system embodied? In T. Ziemke (Ed.), *A Special Issue on Situated and Embodied Cognition. Cognitive Systems Research*. *3*(3), 339-348.

Riva, G. (2003). Applications of virtual environments in medicine. *Methods of Information in Medicine*, *42*(5), 524-534.

Rizzo, A. A., Buckwalter, J. G., & Neumann, U. (1997). Virtual reality and cognitive rehabilitation: A brief review of the future. *Journal of Head Trauma Rehabilitation*, *12*(6), 1-15.

Roussos, M., Johnson, A. E., Leigh, J., Vasilakis, C. A., Barnes, C. R., & Moher, T. G. (1997). NICE: Combining constructivism narrative and collaboration in a virtual learning environment. *Computer Graphics*, *31*(3), 62-63.

Roussos, M., Johnson, A. E., Moher, T. G., Leigh, J., Vasilakis, C. A., & Barnes, C. R. (1999). Learning and building together in an immersive virtual world. In W. Winn & M. J. Moshell (Eds.), *Special Issue on Virtual Environments and Learning*, *Presence*, *8*(3), 247-263. Retrieved from http://www.mitpressjournals.org/doi/abs/10.1162/105474699566215

Rundmo, T. (1997). Associations between the risk perception and safety. *Safety Science*. *27*, 197-209.

Salzman, M. C., Dede, C., Loftin, R. B., & Chen, J. (1999). The model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments*. *8*(3).

Sampolo, A. Z., & Henriques, P.G. (2006). Virtual reality technology applied in civil engineering education. In *A*. Méndez-Vilas, A. Solano Martín, J.A. Mesa González, & J. Mesa González (Eds.), *Current developments in technology-assisted education* (pp. 1351-1355). Spain: FORMATEX.

Seidel, R. J. (1997). Lessons learned or lessons not yet learned (but often revisited) about the design application and management of learning technologies. In R. J. Seidel & P. R. Chatelier (Eds.), Virtual reality, training's future? New York: Plenum Press.

Smith, A. B. (1995). Using virtual reality for the simulation of infrared environments for human training. *Proceedings of 33rd Annual Southeast Conference* (pp. 101-109). ACM.

Stone, R. (2005). Serious gaming - Virtual reality saviour? In H. Thwaites (Ed.), *Proceedings of the 11th International Conference on Virtual Systems and MultiMedia: Virtual Reality at Work in the 21st Century* (pp. 773-786). Budapest Archaeolingua.

Swartout, W., Hill, R., Gratch, J., Johnson, W.L., Kyriakakis, C., LaBore, C., Lindheim, R., Marsella, S., Miraglia, D., Moore, B., Morie, J., Rickel, J., ThiÚbaux, M., Tuch, L., Whitney, R., & Douglas, J. (2001). Toward the Holodeck: Integrating Graphics, Sound, Character and Story. *Proceedings of the 5th International Conference on Autonomous Agents* (pp. 409-416).

Szekely, G., & Satava, R. M. (1999). Virtual reality in medicine. *BMJ*, *319*.

Tchounikine, P., Baker, M., Balacheff, N., Baron, M., Derycke, A., Guin, D., Nicaud, J.-F., & Rabardel, P. (2004). *Platon-1: Quelques dimensions pour l'analyse des travaux de recherche en conception d'EIAH*. (Specific Action Report: fondement théorique méthodologique de la conception des EIAH). Paris: CNRS, STIC Department.

Thurman, R. A., & Mattoon, J. S. (1994). Virtual reality: Toward fundamental improvements in simulation-based training. *Educational Technology*, *34*(8), 56-64.

Tinker, P. (1992). Real training in the virtual world. *Proceedings of WESCON/92 Conference Record* (pp. 372-375). Electronic Conventions Management.

Tisseau, J. (2004). *CERV Manifest*. Retrieved from http://www.cerv.fr/fr/ page_pres_manifeste.php

Traum, D., Swartout, W., Marsella, S., & Gratch, J. (2005). Fight, flight, or negotiate: Believable strategies for conversing under crisis. *The 5th International Conference on Interactive Virtual Agents*. Kos, Greece. Retrieved from http://people.ict.usc.edu/~traum/Papers/saso-neg-final.pdf

Varela, F. J. (1994). Autopoiesis and a biology of intentionality In B. McMullin & Murphy, N. (Eds.), *Proceedings of a Workshop within ESPRIT BRA 3352: Autopoiesis & perception*, School of Electronic Engineering, Dublin City University. Retrieved from ftp://ftp.eeng.dcu.ie/pub/alife/bmcm9401/varela.pdf

Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind: Cognitive science and human experience*. Cambridge, MA: MIT Press.

Wasfy, A., Wasfy, T., & Noor, A. (2004). Intelligent virtual environment for process training. *Advances in Engineering Software*, *35*(6), 337-355.

Waterworth, J. A. (1999). *Virtual reality in medicine: A survey of the state of the art*. Retrieved from http://www.informatik.umu.se/~jwworth/medpage.html

Winn, W. (1993). *A conceptual basis for educational applications of virtual reality* (Technical Publication R-93-9). Seattle: University of Washington.

Winn, W. (1995). The Virtual Reality Roving Vehicle project. *Technological Horizons in Education Journal*, *23*(5), 70-74.

Winn, W. (1997). *The impact of three-dimensional immersive virtual environments on modern pedagogy*. (HITL Technical Report R-97-15). Seattle: University of Washington.

Winn, W. (2003a). Beyond constructivism: A return to Science-based research and practice in educational technology. *Educational Technology*, *43*(6), 5-14.

Winn, W. (2003b). Learning in artificial environments: Embodiment, embeddedness and dynamic adaptation. *Technology, Instruction, Cognition and Learning*. *1*, 87-114.

Winn, W. (2005). What we have learned about VR and learning, and what we still need to study. In S. Richir, P. Richard, & B. Taravel, (Eds.), *Proceedings VRIC'05, First International VR-Learning Seminar*. Laval, Angers: ISTIA.

Winn, W., & Windschitl, M. (2001). Learning science in virtual environments: The interplay of theory and experience. *Themes in Education*, *1*(4), 373-389.

Winn, W., Windschitl, M., Fruland, R., & Lee, Y. (2002). When does immersion in virtual environment help students construct understanding? *Proceedings of International Conference of the Learning Societies*. Seattle, WA.

Wojciechowski, R., Walczak, K., & Cellary, W. (2005). Mixed reality for interactive learning of cultural heritage. *First International VR-Learning Seminar, in conjunction with the 7th International Conference on Virtual Reality, VRIC - Laval Virtual 2005* (pp. 95-99). Laval France.