What is the Value of Virtual Reality for Conceptual Learning? Towards a Theoretical Framework

Denise Whitelock
IET, The Open University
Walton Hall, Milton Keynes MK7 6AA, England
E-Mail: d.m.whitelock@open.ac.uk

Paul Brna
Computing Department
Lancaster University, Lancaster LA1 4YR, England

Simon Holland
Computing Department
The Open University, Walton Hall, Milton Keynes MK7 6AA, England
E-Mail: s,holland@open.ac.uk

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There is little principled empirical work that has been carried out on the effectiveness of Virtual Reality Environments for educational purposes. We briefly review recent work, and propose a theoretical framework for research into the relationship between Virtual Reality Environments and conceptual learning. The proposed framework suggests that experience obtained through working in a particular class of Virtual Reality Environments automatically improves both performance and conceptual understanding on a specific range of tasks. This framework is a contribution to providing a stronger theoretical basis for a rigorous approach to the selection of appropriate tools for training and education. Such foundational work is necessary for a more coherent approach to harnessing the power of Artificial Intelligence and Educational Technology to provide more efficient and effective usage.

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Introduction

The usefulness of Virtual Environments (VEs) in training has been well established (see for example distributed interactive simulations on DARPA'S SIMNET). However, the utility for supporting learning in domains with a high conceptual content remains relatively unexplored. We have detailed reports from Brooks [Brooks et al, 1990][Chung et al, 1989] about how haptic devices effect task performance but only anecdotal evidence is provided about how such systems help students dispel misconceptions about their notions of force fields. In the enthusiasm for promoting Virtual Reality as a major factor in future (and present) environments for training and education we believe there is a need to investigate the various properties of such environments in promoting conceptual learning. We would suggest that in order to make use of VR systems to promote

conceptual learning students will have to become engaged in ``sense making'' activities [Perkins, 1992] and not to be subjected to drill and practice ``contextually welded'' experiences [Salomon &Perkins, 1989] as have been offered in previous VR training environments. Hence it is necessary to understand the elements of a Virtual Reality system that will encourage students to become engaged in tasks that will not just allow them to display knowledge and carry out smooth executions of tasks but to become involved in activities that require explanation and extrapolation. What aspects of the VR system must the student experience to promote these types of experiences?

The approach we take to the problem of assessing the ways in which virtual reality can affect conceptual learning is through the development and application of an abstract framework which is derived from work by Zeltzer [Zeltzer, 1992][Zeltzer, 1991]. This framework allows us to control the complexity of the problem by focussing on some of the issues while discarding other aspects of Virtual Reality. The advantage of such an approach facilitates the development of a well defined programme of experimentation which should provide the basis for the kind of taxonomic information which will be useful for the design and application of future Virtual Reality Environments that stress conceptual understanding within education and training contexts.

In order to make progress on this important problem we reduce the complexity by initially describing Virtual Reality Environments in terms of three abstract properties: autonomy, interaction, and presence [Zeltzer, 1992][Zeltzer, 1991] It may be the case that the best balance of factors for promoting effective conceptual learning may differ significantly from the best balance for typical applications investigated so far which are related to task performance and the acquisition of sensory-motor skills. Apart from its scientific importance, discovering which factors are important for conceptual learning which could well include the notions of conceptual fidelity [Hollan et al, 1984] and epistemic fidelity [Wenger, 1987]. Our findings have clear implications for the design and development of virtual environments.

The Need for a Theoretical Framework

There is evidence that, in suitable application areas, virtual environments can offer an effective medium for training in certain classes of application: for example, the effective coordination of sensory-motor skills; the gaining of situation awareness by use of simulations; and training in design skills. The commercial success of virtual environments in pilot training has led to speculations about the application [Krueger, 1982] of virtual environments to other areas of education, for example virtual science laboratories. It has been argued that such an approach could give students access to virtual experiments involving the use of otherwise prohibitively expensive equipment.

There has been little emphasis on learning in such environments. The research completed to date which emphasise the educational application of VEs has been primarily concerned with developing co-ordinated sensory motor skills and situation awareness (e.g. virtual planetaria, virtual cadavers, etc). However empirical evidence on the effectiveness of

virtual environments for promoting learning of conceptually rich subject matters is very scarce.

Recently however there has been a shift towards a more explicit constructivist view of learning with VEs [Rose, 1995][Winn, 1993]. Such work seeks to locate learning within a very general educational setting. However there seems to be little attempt to provide a detailed framework within which to assess the relationship between the structure and form of a VE and the nature of the conceptual learning that takes place.

Other educational research seeks to explore issues in visualisation and in computer supported cooperative problem solving. Current work at Lancaster follows this line: the ``Distributed Extensible Virtual Reality Laboratory'' (DEVRL) project sets out to explore a similardomain to ScienceSpace (see below) [Dede et al, 1994] through tasks requiring significant degrees of cooperation for successful completion. (Other English universities involved in the DEVRL project include Nottingham and University College, London. See URL http://www.comp.lancs.ac.uk/computing/research/cseg/projects/devrl/ for the virtual classroom.) Additionally there is an emphasis on highly distributed contexts. As with ScienceSpace, there is an interest in providing alternative perspectives such as allowing a participant to ride a cannonball fired from a gun. The participant may be able to see his/her ``body''.

The most relevant work on the issue of how learning is mediated through the use of VR to date is that of Dede et al on the ScienceSpace project. Dede and his colleagues promised an empirical evaluation of the effectiveness of VEs for the remediation of misconceptions [Dede et al, 1994]. NewtonWorld, one of the three VEs produced, makes use of multisensory cues (i.e. visual and tactile cues) indicating the presence of potential energy, friction etc. Students can also ``become'' one of the balls in NewtonWorld, or be located at the centre of mass and so on. The formal evaluation that has been reported primarily featured an exploration of the issue of how the different forms of sensory feedback affected students in terms of prediction, engagement and so on [Dede et al, 1996].

This work is a useful contribution to the larger effort required to establish a clearer understanding of the costs and benefits of VEs for conceptual learning. In particular, they raise issues concerning the ways in which a VE can be augmented - augmented Virtual Reality (to distinguish this from augmented reality). To handle augmented VEs is an important issue in the educational uses of VR. Addressing this issue will need to draw on recent research on the effectiveness of different modalities for communicating 'augmentations'. Factors such as prior experience and the nature of the task are likely to be highly relevant [Cox &Brna, 1995].

In addition, there are various technical dimensions or factors which distinguish between different virtual environments, for example: resolution, latency, size of display, ocular field of view, binocular overlap, quality of optics, ocular separation, interpupillary distance, compactness, weight, comfort, ease of use, enhancing cues [Carr &England, 1995].

There has been discussion together with some research [Kalawsky, 1993][Carr &England, 1995][Brooks et al, 1990] on the extent to which these various factors help or hinder training in sensory motor skills and situation awareness in particular tasks, but there has been virtually no systematic work on which factors have a bearing on conceptual learning. We propose the adaption and extension of Zeltzer's model as a route towards attaining this goal [Zeltzer, 1992][Zeltzer, 1991].

Zeltzer's Cube

Zeltzer's unit cube model for characterising virtual environments identifies three essential components that all such systems must have, and three dimensions or properties that can be used to compare virtual environments [Zeltzer, 1992][Zeltzer, 1991]. The three components are:

1.   a set of models, objects or processes
2.   a means of modifying the state of these models
3.   a range of sensory modalities to allow the participants to experience the virtual environment

The three properties that Zeltzer proposes for measuring and comparing virtual environments are:

•   Autonomy - the extent to which objects can respond to events and stimuli (both from each other, the environment and the user)
•   Interaction - the degree of access to the parameters or variables of an object
•   Presence - a measure of the fidelity of sensory cues that engender a subjective sense of "physical presence" or "direct experience". Note that this property can be domain-specific.

These distinctions have led us to select three properties of VE s to incorporate into our own model which is open to systematic testing. The advantage of using this approach is that it applies not only to virtual environments; it can be applied equally well to conventional desktop computer simulations and physical apparatus. This creates the possibility of a comparison of conceptual learning using both virtual and physical environments within a unified framework.

Defining a Model that is Open to Test

The properties that we have chosen of representational fidelity, immediacy of control and presence - effectively define a finite, but still large, space of VE classes. The property of representational fidelity requires further subdivisions relating to: technical fidelity; representational familiarity; and representational reality. Technical fidelity is the degree to which the technology delivers realistic renderings, colours, textures, motion etc. However, not all infidelities appear to be equally serious: it would appear that 3D audio provides some additional supports for activities in a VE: Wenzel et al provide evidence that the combination of simple auditory cues (for direction, distance and contact) within a VE certainly can aid users [Wenzel et al, 1991]. So it would appear that some deficiencies in graphics quality can be compensated for with the help of audio. (The

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technical problems of providing accurate 3D audio are not to be underestimated. Thus we would anticipate that not all uses of 3D audio will be of assistance.)

Representational familiarity is the extent to which the environment that is simulated is familiar to the user. An unfamiliar world might be a simulation of the 'surface' of Jupiter. Representational reality is the extent to which the world is possible. For example, we could simulate a world in which Newtons Law of Gravitation was an inverse cube law.

Immediacy of control is related to the medium through which control is channelled. We assume that the use of hand motions close to those used in the real world to achieve a corresponding 'real' effect illustrate nearly perfect immediacy. At the other end of the spectrum, communicating instructions through a command line interface is an example of low immediacy. Intermediate positions are possible depending, for example, on how much of the hand's flexibility is supported for control purposes.

Presence is an awkward concept since it has to be considered in at least two ways: as a subjectively reported phenomenon and as a set of repeatable objective measures [Kalawsky, 1993]. Steed et al have not found a correlation between these two types of measures and concede that self report could emphasise the subject's global rather than local experience [Steed et al, 1994]. No agreed precise objective measures exist, but taking a simple view, we may go from a 2D Window on the World system with low objective presence to a fully immersive system with haptic features, a head mounted display and 3D audio.

Our model then leads us to ask to what extent do different values of these properties encourage
      a) high levels of task performance, and
      b) clear understanding of the conceptual content.

Ellis stresses that ``a large part of our physical sense of reality is a consequence of internal processing, rather than being something which is developed only from the immediate sensory information we receive'' and hence we posit that conceptual progression and the genetic epistemology of a domain could play a role in conceptual learning [Ellis, 1991].

An Example Domain
The domain we suggest merits attention is that of particle dynamics. This domain is fundamental to many (dynamic) simulations for which Virtual Reality is thought to be of help. It is also a domain for which the conceptual misunderstandings that students are likely to have been well researched - [White &Horowitz, 1990][White, 1983][Viennot, 1979][McCloskey, 1983][McDermott, 1984][Larkin et al, 1980][diSessa, 1982][Clement, 1982][Caramazza et al, 1981] and many others. Even undergraduates and postgraduates have problems [McCloskey, 1983][Viennot, 1979], and their misconceptions are difficult to change. Evidence suggests that people use a non-Newtonian framework to understand motion. A model of commonsense understanding of motion based on work by Whitelock [Whitelock et al, 1991][Bliss et al, 1989][Whitelock, 1987] and further developed by

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Whitelock [Whitelock, 1990], gives a causal structure to this framework, and explains why commonsense ideas about motion should be highly resistant to change by abstract argument or presentation.

However, the model suggests that in environments where the effects of gravity, air resistance and friction, etc. can be varied, directly experienced action upon objects could lead to changes in this deeply held commonsense understanding of motion. This argument leads to the consideration of the way in which `immediacy of control' affects the learning of improved models of motion. There is some relatively limited evidence that command line input may even promote problem solving: Svendsen performed an empirical study which suggests that a command line interface may well be preferable to a direct manipulation interface for students learning to solve the Tower of Hanoi problem [Svendsen, 1991]. While there is quite a difference between the problem of conceptual change in models of motion and how to solve the Tower of Hanoi problem, we might expect a similar result.

A further factor is the representational fidelity of simulations and the effectiveness of learning. This fidelity may be broken in several ways: through failure of the technology to deliver the planned fidelity; through deliberate design decisions to put users into realistic but unfamiliar environments (e.g. [Brna, 1989][diSessa, 1982]); and through putting people into unrealistic worlds (e.g. [O'Shea, 1989]). While the literature is ambiguous as to whether conflict is the major factor in conceptual change, the indications are that some conflicts can be beneficial (e.g. [Twigger et al, 1991][Brna, 1987]). We may therefore expect that some conflicts caused by representational infidelity will lead to conceptual change (and some will not).

Reflecting upon a number of combinations of Zelter's properties leads us to generate some key hypotheses about VEs and conceptual learning.

1. A high presence value and a high degree of immediacy of control (ie autonomy and interaction) leads to a high degree of implicit learning. By that we mean maximising the ability to perform tasks consistent with an improved understanding.
2. A low value for immediacy of control (autonomy and interaction) is more likely to be associated with explicit learning i.e. students' awareness of their conceptual understanding.
3. The degree of representational 'infidelity' owing to technical failings in Virtual Reality Environments has a smaller effect on conceptual understanding than appropriately designed infidelities.

Summary

There is little principled empirical work that has been carried out on the effectiveness of Virtual Reality Environments for educational purposes. The proposed framework suggests that experience obtained through working in a particular class of Virtual Reality Environments automatically improves both performance and conceptual understanding on a specific range of tasks. This framework is a contribution to providing a stronger

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