Applying Virtual Reality in the Environmental Sciences: Four Years on From Building The Social Science for the Environment, Virtual Reality and Experimental Laboratory, What Have We Learnt?

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Abstract:

In 2003 the University of East Anglia's School of Environmental Sciences invested in a state-of-the-art facility to investigate how visual simulation might be used in environmental decision-making. The Social Science for the Environment, Virtual Reality and Experimental Laboratories (SSEVREL), as it is known, consists of a virtual reality theatre and an experimental laboratory designed for decision-making research. In this paper we discuss how the laboratories have been used and critically appraise them using three case study projects. We also examine how the real-time visual simulation market serves this field, in terms of the benefits and limitations of current projects, techniques and approaches.

Whilst the projects described suggest that SSEVREL has opened up exciting new research opportunities, they also illustrate the challenges face those wishing to develop a similar facility. These include the steep learning curve associated with stepping from GIS to VR, the costs associated with such a facility, and the challenges posed by differing research needs. Furthermore, the projects also illustrate a variety of hardware and software limitations that the real-time visual simulation market must address if VR is to be applied more widely in the environmental sciences.

1. INTRODUCTION

The communication potential of visual simulation methods has long been recognised by academics and practitioners in the field of environmental planning and decision-making; such technology has begun to move out of computer science and related departments, and into environmental science, forestry, landscape architecture and other applied fields. This has resulted in considerable use of both off-the-shelf solutions and custom systems to illustrate a variety of environments in both academic research and applied contexts (Batty, 2008; Bishop & Lange, 2005; Buhmann *et al.*, 2005). With the increasing availability of ever more powerful and affordable systems, such research is likely to increase in the future.

With the widened availability of visual simulation technologies, researchers at the University of East Anglia's (UEA) School of Environmental Sciences have, over the last few years, begun to apply visualisation techniques across a range of environmental issues. Areas of particular research interest include the visualisation of agricultural landscape change (Dolman *et al.*, 2001; Lovett *et al.*, 2002; Lovett., 2005; Appleton *et al.*, 2005), climate change impacts on the landscape (Dockerty et al., 2006; Dockerty et al., 2005; Appleton *et al.*, 2005) and the coast (Brown et al., 2006; Jude et al., 2006; 2007). Research has also investigated a variety of visualisation design issues (e.g. Appleton et al., 2002; 2003; 2005). The expansion of this field of study resulted in the investment in a state-of-the-art facility, known as the Social Science for the Environment, Virtual Reality and Experimental Laboratories (SSEVREL), which was opened in 2003. The aim of the facility is to investigate how visual simulation, based on Geographical Information Systems (GIS) data, can be used to assess the impacts of various types of environmental change, and to educate, inform and receive feedback from a variety of people including planners, policy makers, researchers and the general public. The facility is housed in a purpose-designed space within a new building and at the time of opening was believed to be unique in an Environmental Sciences department.

Four years on from the opening of SSEVREL, researchers are increasingly applying visual simulation in environmental decision-making, with a number of departments beginning to invest in similar facilities. In this paper we discuss how the laboratory was created and how it has been used. We also critically evaluate the facilities and the projects that have used them, as well as examining how the real-time visual simulation market serves this field, in terms of the benefits and limitations of current techniques and approaches.

2. THE SSEVREL FACILITY

The Social Science for the Environment, Virtual Reality and Experimental Laboratories (SSEVREL) consists of two elements; a virtual reality (VR) theatre, and an experimental laboratory for decision-making research. The idea for the facility was initially conceived as part of a larger proposal to construct a new building to foster collaborative interdisciplinary environmental sciences research. With this came the opportunity to incorporate plans for SSEVREL, with the VR laboratory planned enabling the development of research that was beginning to exploit visualisation to show landscape change based upon GIS databases (e.g. Dolman *et al*., 2001, Lovett et al., 2001) and the experimental laboratory facilitating experimental economics research. The facility was funded by the HEFCE [1] Joint Infrastructure Fund, with a total budget of £450,000 for the VR facilities and £75,000 for the experimental laboratory.

We were fortunate in that the new building presented us with a blank canvas on which we could work. This not only allowed SSEVREL to be placed in the basement area, which overcame the challenge of lighting issues, but allowed us to incorporate facilities such as underfloor cooling from the onset. The final design split the area into three; the VR theatre; the experimental laboratory; and separating the two, a control room.

2.1 Identifying Options for the Laboratories and the Solutions Chosen

Given the size and complexity of the project, the VR theatre element of the SSEVREL facility had to be equipped using a tendering process. To gain an insight into the range of potential software and hardware options to us, a number of visits were made to other VR facilities in both academic and non-academic settings. These proved extremely valuable, enabling the advantages and disadvantages associated with differing hardware and software systems and room configurations to be identified. This process quickly confirmed that a PC-based image generator system would be employed, as opposed to the now-obsolete SGI Onyx-based system that had been envisaged at the time of the original funding bid for the building. It also highlighted numerous layout issues, for example, that the noisy image generator hardware should be housed away from the theatre area, and that it would be advantageous to have user-configurable seating and furniture within the VR laboratory to provide maximum flexibility. Furthermore, given our interest in applying VR in stakeholder engagement, it was felt that the inclusion of a focus group area within the VR theatre would be beneficial to our research. The visits also identified a number of challenging questions that had to be addressed prior to the tendering process, the key question being whether stereo or mono projection should be used, and if so whether an active or passive system should be employed. Given our interest in the testing and evaluation of visualisation technologies, together with the lack of studies investigating the potential benefits and drawbacks associated with stereo projection, it was decided that an active stereo system would be our chosen solution, thus allowing future research to investigate its potential benefits.

During the visits to the facilities it also became apparent that as GIS users we would encounter a steep learning curve associated with the types of visual simulation technology and

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[1] http://www.hefce.ac.uk

concepts that would be used following the commissioning of the laboratories. This resulted in the purchase of some software and hardware prior to the tendering for the VR theatre, enabling the evaluation of some of the possible solutions. The process also identified two possible image generators and two systems for terrain generation that would meet our needs, which were subsequently reflected in the tenders for the laboratory. The experience gained from this software evaluation also enabled us to objectively assess each of the tenders enabling a preferred supplier to be identified.

2.1.1 Terrain Generation and Viewing Software

Although software was already available within the research group to produce detailed still images and animations for display on a standard PC, additional packages were required in order to take full advantage of the display capabilities of the SSEVREL equipment. In particular, we needed software for the creation and optimisation of landscape models for real-time display, and specialist run-time software to display that output across multiple projectors (see below). Terrain creation and display software of this type has typically been aimed at high-end users such as the military, and is priced accordingly. While some attempt has been made to allow more affordable software to output in standard formats compatible with these systems (e.g. OpenFlight format), this has not proved easy due to the complexity and variation of requirements, and a lack of users requiring such capabilities at this level has led to a stagnation in development. It is not therefore possible to use a single system to generate still, animated, and real-time output for both the VR system and PC display.

Two possible real-time terrain generation solutions were identified in the run-up to the tending process: TerraVista (Terrex), and the MultiGen-Paradigm (MP) range of software[2], both of which enable the creation of geospecific terrain databases from GIS-based data. These can subsequently be rendered on a range of hardware using run-time software: our choice for the image generator system was either Mantis (Quantum3D) or Vega (MP). The ability to also view the databases on laptops or on multiple computers in the experimental laboratory, or to distribute the models to end-users, was of great importance to our choice. The Terrex solution allowed the viewing of the terrain models on PCs using Audition (Quantum3D), which is freely available, whereas the MP solution required individual licences for its PC real-time viewer. This, together with the higher maintenance costs for MP products, meant that the Terra Vista/Audition combination was chosen for the terrain generation and viewing solution.

Terrain generation software forms only one element of the software required to create the types of landscape models that our research focuses on. A number of additional packages, to create the vegetation and building models that populate terrain databases, were also evaluated and selected, including RealNat (Bionatics), Xfrog (Greenworks), ModelBuilder (MP), and the Polytrans (Okino) format converter for 3D objects.

2.1.2 Virtual Reality Theatre and Portable Viewing System

The eventual solution chosen for the VR theatre element of SSERVREL was a 6 metre wide and 2 metre high 125° curved screen with three active stereo projectors and seated viewing for up to 20 people (Figure 1). The system is driven by a Quantum3D (Q3D) Independence PC-based image generator, allowing TerraVista content to be rendered using Mantis (Q3D) image generation software. Active stereo presentations can be viewed using stereo glasses, and support for interactive polling of participants is provided via wireless Xtol handsets. The main hardware is kept away from the audience area, with a control desk and PC allowing a pilot to navigate around the displayed environments. Using a custom-built software interface,

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[2] Both Terrex and Multigen products are now under the Presagis banner: http://www.presagis.com

users can interactively navigate around the database using a wireless joystick, load terrain databases, insert static feature models such as buildings, and change environmental parameters. Furthermore, the interface also allows recording and playback of view positions and simulation parameters, so that terrain databases of the same area under different environmental conditions can be compared explicitly. It is also possible to display other content on the main screen from any laptop via a VGA input. Such flexibility was sought to enable the laboratory to accommodate any future research plans, and to enable controlled conditions to be imposed for experimental studies.

Figure 1. The VR theatre and pilot desk (left) and the focus group area at the rear of the theatre, with the control room designed to house the computing equipment and to enable the observation of either the VR theatre or the experimental laboratory in the background.

Participatory decision-making underpins much of the research undertaken by the SSEVREL researchers, and as such, a portable VR viewing system forms one of the elements of the laboratories. Whilst landscape visualisation researchers at other institutions have built large custom VR viewing systems based on their own design (Stock *et al*., 2006; Stock and Bishop, 2007), or from off-the-shelf components (Miller *et al.*, 2008) for use in community participation events, we sought a smaller, less complicated solution. This resulted in the purchase of a Elumens VisionStation portable visualisation dome that can be connected to a laptop or PC (Figure 2).

Figure 2. The Elumens VisionStation can be taken to external stakeholder events.

2.1.3 Experimental Laboratory

The experimental laboratory was a replacement for an existing facility and was designed to enable a variety of experimental economics studies to be conducted. It consists of 20 networked PCs in a user-configurable workspace; desks and workstations can be moved to enable individual or group-based experiments. Given our interest in testing the use of visualisation technologies in decision-making, in the context of environmental valuation, and the group's experience of testing perceptions of visualisations, the PCs in the laboratory were all fitted with high performance graphics cards, enabling them to be used to present real-time visualisations.

3. EVALUATING SSEVREL FOUR YEARS ON - EXAMPLE PROJECTS

The SSEVREL facility has been employed in various contexts since its installation. Three interdisciplinary projects are now used to critically appraise the facility and the choices that were made during its development. These consist of a project bringing together coastal engineers, GIS and visualisation specialists to visualise coastal erosion models (Brown *et al*., 2006), a project testing the application of VR in choice experiments for the economic valuation of future environments (Bateman *et al*., 2006), and the development of a virtual campus model for landscape perception research. Whilst the projects described illustrate the innovative interdisciplinary projects that have benefited from the investment in the facility, they also exemplify the challenges faced by others wishing to develop a similar research facility and apply VR in the environmental sciences.

3.1 Visualising the Impact of Climate Change on Cliff Erosion along the North Norfolk Coast

Significant sections of the North Norfolk coastline comprise soft cliffs of glacial material that is prone to erosion. In recent years many of the sea defences that protect communities along this section of coastline have begun to approach the end of their design life, leading to rates of erosion of up to 2m per year in some locations. In several areas this has resulted in the loss of properties. Coupled with the likelihood that climate change will increase erosion, this is a serious and highly complex problem, and, with questions over the replacement of sea defences and the compensation of property owners, it is a controversial one (Brown *et al.*, 2006). In an effort to address this controversy, coastal management processes now seek to be more inclusive, and so managers and decision-makers are keen to use the potential of visualisation techniques to provide a common understanding of possible futures as a starting point for discussions.

Robust information is required to inform such decision-making processes. To address this, an interdisciplinary team of researchers from the Tyndall Centre for Climate Change Research's Coastal Research Programme have developed a cliff erosion model for this section of coast that is linked to a GIS interface (Walkden & Hall, 2002 – look up scapegis paper), giving the ability to predict likely coastlines at chosen points in the future. Building on ongoing Tyndall Centre research investigating the use of visualisation techniques in coastal management (Jude *et al.*, 2006; 2007; Jude, in press) it was decided to use the SSEVREL facilitate to assess and communicate the future risk from coastal erosion, by linking climate change with the predictive simulation model and the visualisation system (see Brown *et al*., 2006; 2007 for further details). The research determined whether such cliff erosion scenarios can be effectively illustrated using real-time simulation (Figure 3), both to assess the methodology used and its technical challenges, and to elicit feedback from coastal managers on the models produced.

Figure 3. Exploring the impact of future cliff erosion in the VR theatre.

The simulation was constructed using data from the Soft Cliff And Platform Evolution (SCAPE) model which was georeferenced and converted into GIS data using the SCAPEGIS extension for ArcView (ref). The resulting cliff erosion lines subsequently formed the basis of landcover maps and elevation models representing the coast in the future. From these, terrain models that could be displayed in the VR theatre on a desktop PC or laptop were created. Overall, the simulation was judged to be a success, overcoming difficulties such as deriving land cover changes from landform changes, and very positive feedback was received from coastal managers relating to the realism of the model and the recognisability of the landscape.

The success of this project emphasises how the use of visual simulation in environmental applications is heavily led by the technology's ability to interface with GIS data. This is particularly important as GIS modelling of some kind typically underpins any decision-making process, providing information on the issue's context and relevant factors, and modelling the likely impacts of the various outcomes. The ability of much terrain modelling software to import a wide range of GIS data types, file formats and projections is thus of great benefit as it makes the production of landscape models quicker and more flexible, allowing them to be used more widely. However, the use of a real-time environment did pose challenges when wishing to represent the cliff morphology in sufficient detail. In particular, the detailed cliff morphology provided by the high-resolution LiDAR elevation model was generalised by the software in order to produce an optimised real-time terrain model of the site.

The ability for users to interactively navigate and explore the cliff erosion visualisations was also key to the success of this work, and provided end-users with new insights into the problems arising from cliff erosion along the North Norfolk coast. However, the level of interactivity was limited to navigation around the model as opposed to making changes to the model itself. Indeed, recent developments on systems similar to those available in SSEVREL increasingly allow interactive elements within the models, such as trees or buildings which can be added, relocated, or removed. This is of great benefit when discussing alternatives during a public meeting or other session early in the decision-making process. However, tools that facilitate interaction with terrain itself still, in our experience, require development. In particular, there is a need for closer coupling of visual simulations and the underlying GIS data and environmental modelling. Ideally, such functions should enable audiences in decision-making processes to interact with process models (in the above example, perhaps to adjust the predicted changes in sea level and storminess) and view the resulting changes in the landscape. Allied to such software development should be experimental research aimed at identifying whether interactivity is beneficial and under what circumstances. This is particularly important as some projects have questioned the usefulness of real-time interactivity (Dockerty *et al*., 2006; Jude, 2007), and it is likely to be a major field for ongoing development.

In many environmental science applications, such as this cliff erosion study, decision-makers wish to explore a range of alternative 'what-if' scenarios. Whilst we have found that visual simulation is viewed as having considerable value in this application, our experience is that the ability to create a range of scenarios is not always matched by the ability to display them in a manner which allows easy assessment of the differences. Too often, only one model can be displayed at a time and there is a delay when switching between models, so the opportunity for meaningful comparison can be lost. While systems are available that enable end-users to choose from a menu of scenarios, or combination of options for the landscape they wish to explore, this still requires pre-constructed terrain models if the results are to be displayed quickly. This can limit the ability of such systems to be applied as interactive scenario development tools for use in decision-making processes, something that is sought by end-users (Jude, in press).

3.2 Testing the Application of VR in Choice Experiments to Value Environmental Change

The second example project stems from recent work in the field of cognitive psychology that suggests that, in some situations, numeric information may be less easy for people to evaluate than visual representations of the same data. In particular, when confronted with numeric information, individuals may make educated guesses based on part of the information (e.g. the cost) rather than formulating a choice based on all of the information presented (e.g. cost and percentage of landscape change). To investigate this, researchers from the Tyndall Centre for Climate Change Research and the Centre for Social and Economic Research on the Global Environment (CSERGE) at UEA designed and conducted a choice experiment (CE) in which standard approaches to conveying a land use change scenario, relying principally on numeric information in terms of land area, were contrasted with the same information presented using landscape visualisations. A third treatment combined both formats.

A case study based on the ongoing debate concerning the management of a site on the North Norfolk coast (see Jude 2003; Jude *et al*., 2007) was used as the basis for the experiment. This required the creation of 16 alternative landscape models in which the area of nature reserve, tidal saltmarsh and farmland at the site varied. For each choice set a VR model was created using TerraVista and viewed in Audition.

One of the challenges posed by this project was that, whilst experimental visualisation studies have used small sample sizes, choice experiments require large numbers of participants; for example, this study required 288 individual participants to cover the desired combinations and repetitions of material. This raises a significant issue that potentially limits the application of VR, and specialised projection systems, in such large-scale experiments - the logistics of presenting numerous models to large number of participants under controlled conditions. Indeed, such demands meant the VR theatre was unsuitable for this study. Fortunately, one of the advantages of the design approach taken and the choice of visualisation software for SSEVREL was that, once created, the VR models could be readily run on conventional PC machines, thus allowing the experimental laboratory to be used for the work.

Figure 4. A choice experiment in the experimental laboratory. This facility has highlighted the value of being able to conduct VR studies under controlled conditions.

The results from the experiment (see Bateman *et al*., 2006; Bateman *et al*., in review) show that the provision of visual information helps individuals to make more informed choice decisions when compared to those presented with the numeric information traditionally used in CE. Thus the combined VR-CE methodology developed represents an exciting prospect for the incorporation of complex real world environments within economic analyses. Furthermore, the new VR based approach to CE valuations overcomes the limitations associated with the use of numeric information to describe changes in the provision of environmental goods.

As well as providing insights into individuals' choice behaviour, this project highlights the potential value of VR in a range of environmental science applications. In particular, it illustrates how linking VR to GIS databases enables realistic, accurate and evaluable representations of real world environments to be generated. Whilst these can be, and often are, used in decision-making situations, the ability to control the content of the images and the manner in which they are presented highlights the potentially significant benefits of such technology in experimental research. Furthermore, once generated, such virtual environments are readily employed in either the laboratory or field. The study was however, very time-consuming to design, conduct and analyse. Indeed, the requirement to produce large numbers of VR models and to present different treatments and choice set combinations to large numbers of survey participants using a number of computers proved particularly challenging. For example, compiling just one of the terrain models required for the experiment took several hours on a high specification PC.

3.3 Developing a Model of the University of East Anglia Campus

SSEVREL researchers have a longstanding interest in testing and evaluating the design and perception elements of visualisation technology (Appleton & Lovett, 2003; 2005). As part of this research, work is underway to create a VR model of the university and its immediate surroundings (Figure 5). The aim of the work is to use the model for communicating and assessing development proposals on its architecturally-important campus, as well as providing a dataset for non-applied research investigating user perceptions of landscapes displayed via different systems, with ready access to the real-word landscape represented. Thus the models are being developed to allow them to be presented using both the theatre system and the portable visualisation dome.

Figure 5. The creation of a virtual campus model has highlighted a number of challenges, not least the need to balance realism with constraints posed by rendering hardware.

Considerable effort has been concentrated on producing a realistic model of the university, particularly in relation to the buildings. This process has posed numerous challenges relating both to the obtaining of accurate data on building size and structure, and to the acquisition and application of photo textures. Furthermore, bare-earth elevation information as processed from an aerially-sampled surface model (i.e. including trees, buildings, vehicles etc.) has proved to be largely inadequate for representing the complexity of levels within the built campus environment, such as the steps, ramps and elevated walkways with which everyday users are familiar; the boundary between "natural terrain surface" and "built environment" is blurred. The creation of realistic landscape elements is particularly important when working with local residents and other stakeholders who are extremely familiar with the landscape being simulated – indeed, the character of the landscape is often the issue under consideration. While libraries (images and 3D models) of buildings, trees, vehicles and other elements are available, either with software packages or separately, we have found that there is frequently a North American bias in their content, and additional time must be invested in creating appropriate native elements if working in Europe or another region. The ability to save and re-use collections of elements and settings in other projects is an advantage of some other software products which is not currently available in the systems chosen for the SSEVREL VR theatre.

Perhaps more than any other project the campus model has typified the steep learning curve facing those wishing to make the step from GIS to VR, necessitating serious consideration of display efficiency when constructing models. It has also strongly highlighted the importance of investing in training in order to maximise the efficiency of model production, especially important given that a number of software packages is required, each with its own foibles and incompatibilities that can prove frustrating to those without training. Furthermore, while training and support may be available for individual software packages, the underlying concepts and principles of 3D simulation, such as the management of detail for smooth display, are more difficult to absorb and must often be picked up in piecemeal fashion. One solution to this would be longer-term collaboration with researchers in computer science fields, something which is hoped will be achieved via joint studentships in the future.

Real-time visual simulation has its own benefits and limitations when compared to the use of static images, as we have found with our research. This project more than the others described, has highlighted the key disadvantage with real-time simulation - that despite evermore powerful graphics cards, real-time models are less detailed than static images or pre-generated animations. Thus when working in a real-time environment the ability to populate a terrain model with sufficient landscape features such as trees and buildings can be constrained by hardware limitations, with over-detailed models exhibiting low frame rates and slow responses to user navigation. This has not only proved problematic for the virtual campus project, but has meant that some projects, requiring the detailed representation of vegetation, are not suited to using real-time systems such as those in SSEVREL (e.g. Jude, 2007).

4. WHAT HAVE WE LEARNT FROM APPLYING VISUAL SIMULATION IN THE ENVIRONMENTAL SCIENCES?

Clearly, from the projects described, the SSEVREL facilities have enabled a number of projects to employ virtual reality in innovative environmental science research. Whilst these projects have been successful they have also highlighted a number of generic challenges facing those wishing to apply VR in their work.

As described above, our experience within the SSEVREL suggests that one of the largest challenges facing the increased use of visual simulation techniques by environmental researchers and practitioners is its complexity. For those approaching the field of visual simulation from outside the computer sciences, programming or graphics fields, the range of concepts and terminology to be picked up and applied is initially overwhelming. For example, considerable effort is necessary when creating models if they are to be both visually detailed and optimised for rendering in a real-time environment. This tradeoff can be approached in various ways and, it seems, these ways must be assessed via trial and error as no guidelines are available. In terms of ease of use, from our experience software interfaces are often complex, and acronyms and jargon are ubiquitous, but it is acknowledged that significant progress has been made, and continues to be made with regards to system accessibility. Issues of complexity are also significant in relation to file formats and the ease with which output and model components can be transferred between systems. For example, we have experienced considerable frustration caused by differing packages and their implementation of supposedly “open” and “standard” file formats, particularly the use of OpenFlight format to prepare models for the VR theatre. Again it is recognised that great strides have been made on this issue in the last 5-10 years, but there is still demand for greater flexibility, with Paar (2006) highlighting “ease of learning” and “interoperability” as the most desirable features of 3D simulation software in a landscape planning context. Academic users appreciate the opportunity to share output and collaborate with other institutions, but currently this can be difficult unless two systems happen to already use the same suite of products and formats.

Although we have found visual simulation software complicated to use, we have also found it to be lacking some of the functionality we, as environmental scientists, desire in our research. Amongst the capabilities that would prove useful is, as was noted earlier, greater interactivity with the terrain surface and its morphology. Overall, “interactivity” should step beyond simple real-time navigation to enable users to obtain a greater depth of information by querying aspects of the landscape, and altering features in the environment according to their preferences or interests. Such interactivity would ideally also include dynamic links to process-based environmental models, such as SCAPE. Sadly, GIS processing requirements commonly result in users being offered only a small a choice of pre-run models to display. This processing demand is a product of the highly complex environmental systems being modelled, and user demands for interaction and feedback commonly outstrip current capabilities. However, with the ever-increasing ability to create large volumes of modelling output, there needs to be a corresponding development of landscape visualisation methods. This is one area where we would have benefited from having more computer science expertise within the team; other groups have begun to develop their own software solutions to such problems rather than rely solely on off-the-shelf solutions (e.g. Stock and Bishop, 2006).

In parallel with the development of more interactive systems is the need to portray the dynamism of the natural environment in the models, particularly if they are to meet the desire of end-users (Jude *et al*., 2006). Whilst existing technology enables moving elements, such as vehicles and people, together with wind-affected vegetation and weather effects such as snow and rain, to be incorporated into landscape models, landscape elements are frequently portrayed in a “snapshot” manner in real-time systems. For example, it is difficult to represent the gradual temporal changes in cliff position other than via individual scenarios representing ‘snapshots’ in time, which, as highlighted by the cliff visualisation project, can be difficult for end-users to interpret. Further examples might include the maturation of vegetation, the succession of ecosystems, or the migration of river channels over time.

In terms of further capabilities sought, as the campus model project has illustrated, ever more powerful graphics capabilities are required if the levels of detail required to represent rich landscapes in a real-time environment are to be achieved. Allied to this, is the need for systems that enable the rapid switching between displayed information, as noted by the cliff erosion work. Whilst the desire for greater rendering capacity will probably remain a never ending goal, switching between scenarios should be achievable in the short-term. Both powerful graphics and faster switching between models could offer ways to address another current lack in visualisation systems – that of showing the levels of uncertainty associated with the future states shown (Appleton, 2004).

Relating to display capabilities, from the projects described it is clear that different applications require different presentation methods. For example, whilst the cliff erosion and campus model projects both benefited from the projection on the large VR theatre screen and the immersive environment it provides, the choice experiments illustrate how in some research applications such systems can prove impractical. Furthermore, our experience suggests that it can be difficult to bring communities and other stakeholders to a fixed facility, whereas mobile solutions allow you to meet them in their own environment, such as a village hall. Indeed, to date, much of our research has either used the visualisation dome or a standard data projector to present our work due to the nature of the projects in question. Such findings suggest that those planning a similar facility should consider both fixed and mobile display systems of different sizes, bearing in mind their likely need for the technology to be applied in a variety of settings. Indeed, further work critically comparing the utility of fixed versus portable display systems would be useful as both have potential benefits and drawbacks, not least associated with the logistical and set-up issues surrounding large portable display systems.

Whilst we have posed a number of challenges for systems developers, the future availability of visual simulation systems also provides significant research challenges and opportunities for academic studies. A key area, and one which we are interested in testing, is the potential benefits of such systems in the environmental sciences and decision-making. In particular, a major area of future research exists in gaining an understanding of how potential changes in what might be termed auxiliary environmental parameters, such as weather conditions, or the technology with which such information is presented, affects individuals’ perceptions. Whilst projects such as the choice experiments have begun to address these issues, they have only scratched the surface of the range of possible research opportunities that exists in this area. Furthermore, as such systems evolve there will be a continuing need for research to test and evaluate them to try to identify the potential benefits of visual effects such as stereo viewing, moving vegetation, animated human characters and vehicles, and fine control over lighting. It may be that some of these technological advances actually offer little benefit in terms of participants’ understanding of the landscape, or that the cost of implementing such systems outweighs their benefits. Furthermore, there are also concerns that the level of detail that is possible is not always matched by the level of accuracy and validity in the input data (Paar, 2006; Brown *et al*., 2006). High levels of realism may be unhelpful in some cases, since highly realistic and detailed models may imply a level of certainty over the future state that does not actually exist (Appleton and Lovett, 2005; Jude *et al*., 2006). However, despite these documented concerns, little empirical research on these issues is forthcoming.

In parallel with the need to evaluate the technology through further experimental research, is the potentially more exciting requirement for applied testing of the technology in real-world decision-making contexts. Whilst such research can be difficult to develop (Jude, 2007), it is necessary if end-user needs and potential technological and organisational barriers to the technology's implementation in participatory decision-making are to be identified. This is particularly important as there is the risk that technology can come before usability (Bishop, 2000; Orland *et al.*, 2001).

Whilst a number of exciting avenues for research exist, a significant practical limitation to wider adoption of visual simulation technology within the academic sphere is cost. Within a specialised field such as this, it is accepted that the price of hardware and software will naturally be higher than more mainstream equipment, although the academic pricing offered by some manufacturers does offset this. However, it is the ongoing maintenance and support contracts, which allow effective use to be made of the systems in the long term, that can be difficult to meet over that timescale, and funding can be harder to secure for such non-tangible items. Tailored agreements such as "best-efforts" maintenance funds, or lower levels of support assistance on projects which are not time-critical, can help to keep these costs manageable. There may also be significant features or capabilities which, although important to other sectors, are not vital for environmental management use of visual simulation, and could therefore be offered as additional cost add-ons or plug-ins to a cheaper, more basic system. It is noticeable that software which has a large "general" user base tends to have a corresponding user community where informal assistance can be sought and experience shared. Lastly, whilst it is recognised that dedicated time spent being taught to use a particular system by experts is invaluable, and should lead to significant time savings in later use, training costs can prove prohibitive.

A second challenge that potentially constrains the application of visual simulation in academic environment is the long-term funding of such a facility. In particular, whilst research funding streams take time to develop and are gradual, maintenance costs are immediate and unexpected costs can be significant. Furthermore, our experience suggests that to successfully attract funding VR must form a key element of a larger research project because obtaining funding for pure technique-based research is difficult. The interdisciplinary nature of our research interests can also prove problematic when trying to obtain funding. In particular, funding bodies are often unwilling to contribute towards even the most modest ongoing software and hardware costs associated with a project. Finally, the short-term project-based nature of academic research represents a particular challenge as developing and retaining expertise can prove difficult in the long-term.

5. CONCLUSIONS

Four years on from the opening of SSEVREL is it clear that, despite the steep learning curve that we have encountered with adopting visual simulation technologies in our research, it has enabled a number of innovative studies to be undertaken. Furthermore, as described, numerous opportunities are now available to further develop this work now that we have the infrastructure to do so. Whether the decision to invest in a VR theatre was a wise one remains open to debate, as we are yet to fully exploit the facility in all the types of experimental research it allows, and decisions will soon have to be made regarding potentially expensive hardware upgrades. One significant example is that despite our deliberations over the choice of a stereo projection system, we are yet to apply it in a research project. Hopefully however, this will be addressed by upcoming projects which will allow further use of this facility to be made in the near future.

Finally, our work suggests that there is clearly a potentially sizeable market for appropriately-priced visual simulation technologies in the field of environmental management and decision-making. Whilst there are numerous barriers that currently make this market largely untapped, they are not insurmountable, and it is hoped that the visual simulation industry as a whole will begin to work with environmental researchers and practitioners to address them and increase the use of this valuable tool.

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