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Determining Principles for the Development of Virtual Environments for Future Clinical Applications

by

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Abstract

For over two decades, academic and clinical research projects have exploited Virtual Reality (VR) technologies in investigations of possible future treatments of numerous human conditions, from systematic desensitisation procedures for certain phobias, through the use of distraction therapies in pain management, to novel exposure processes for post-traumatic stress disorder (PTSD). However, it has often been argued that the development of client-specific simulations for the treatments of some conditions using VR "immersive" technologies, with its historical issues of low fidelity, high cost, poor reliability and limited usability, would be extremely time-consuming and almost impossible to tailor on a patient-by-patient basis. Research into the domain of restorative environments (REs) suggests that the natural beauty and peacefulness of real-world scenes of nature can lower stress levels, and restore an individual's attentional capacity and cognitive function. However, not everyone, and especially not patients in many inner-city hospitals, clinics and care homes, are able to venture out into the countryside or coastal areas to benefit from what nature can provide. The possibility, therefore of developing engaging VR scenes of areas of natural beauty and evaluating their impact following presentation to such patients becomes a compelling challenge. Yet, despite the interest in healthcare VR applications being traced back to the early 1990s, very little has been reported on research programmes evaluating virtual reality-based restorative environments.

The aim of the present research, therefore, was to determine and demonstrate a range of principles for the development of virtual natural environments (VNEs), using low-cost commercial-off-the-shelf simulation technologies, for bedside and clinical healthcare

applications. A series of studies have been conducted to systematically investigate different aspects of the VNEs on a wide variety of participants, ranging from undergraduate and postgraduate students, hospital patients and clinicians, to West Country villagers. The results of these studies suggest that naturalistic environmental spatial sounds can have a positive impact on user ratings of presence and stress levels. High visual fidelity and real-world-based VNEs can increase participants' reported ratings of presence, quality and realism. The choice of input devices also has a significant impact on usability with these types of virtual environment (VE). Overall, the findings provide a strong set of principles supporting the future development of VNEs.

The research was also carried out in order to investigate the exploitation of new digital technology approaches in the generation of believable and engaging real-time, interactive virtual natural environments. Highly transferrable tools and techniques, such as a 24-hour day-night cycle system, fully animated virtual animals, a simulated "virtual window" view with animated curtains, and a user exploration tracking/logging system have been developed, in order to support the cost-effective generation of distributable scenarios that can be modified and updated relatively easily, and with minimal resources, thereby delivering a system that can be regularly modified and updated to meet the needs of individual patients.

The flow chart on the next page shows the structure of this thesis and the content of each chapter.

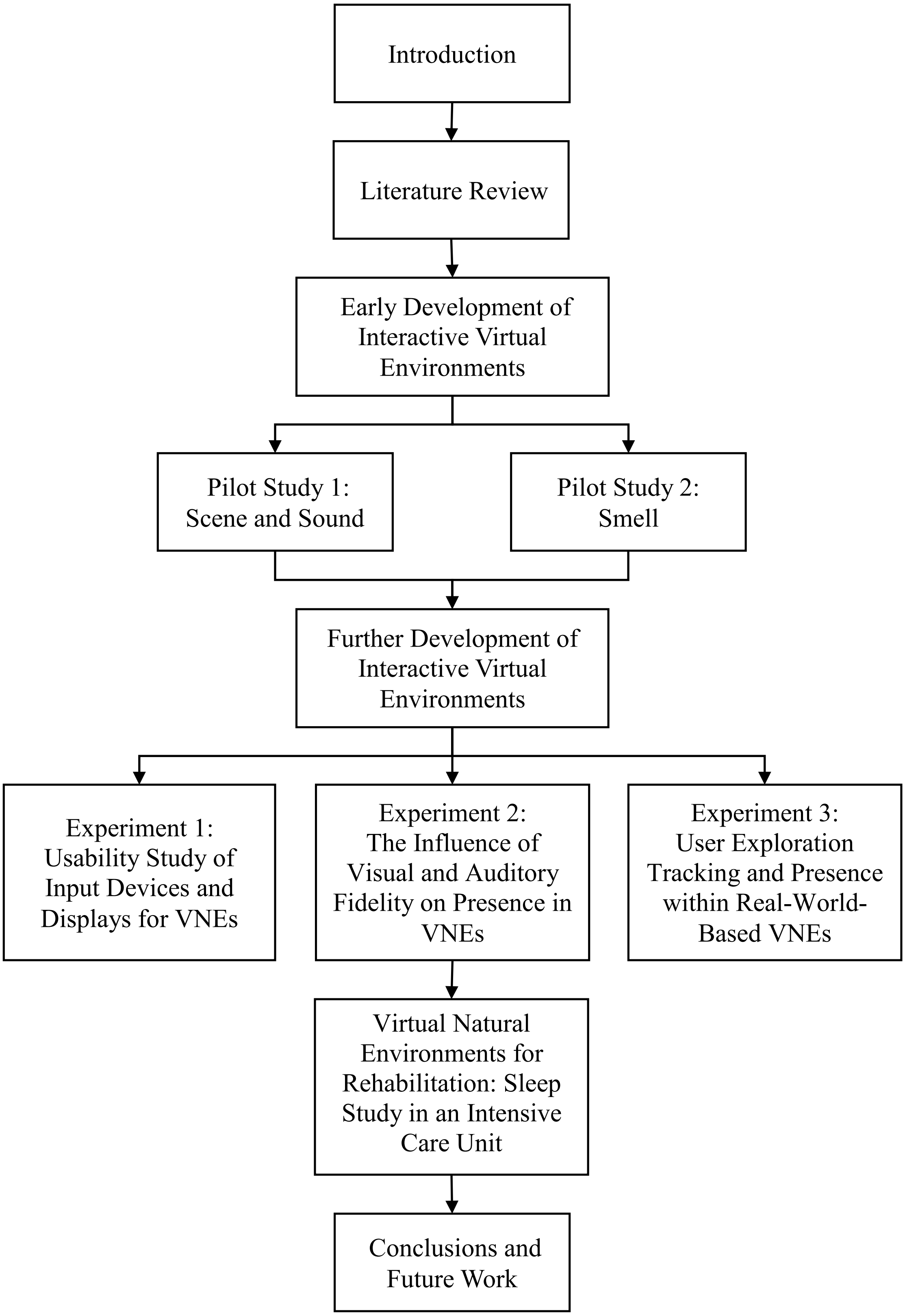

Figure 1 A Flow Chart of the Content of Each Chapter

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List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
ANOVA	Analysis of Variance
ART	Attention Restoration Theory
CAVE	Cave Automatic Virtual Environment
CBT	Cognitive Behavioural Therapy
COTS	Commercial off-the-shelf
DTM	Digital Terrain Model
EDA	Electrodermal Activity
EEG	Electroencephalography
FAAST	Flexible Action and Articulated Skeleton Toolkit
FOV	Field of View
FPC	First Person Character
FPS	Frames Per Second
GIS	Geographic Information System
GSR	Galvanic Skin Response
GUI	Graphical User Interface
HIT	Human Interface Technologies
HMD	Head-Mounted Display
HR	Heart Rate
HRV	Heart Rate Variability
ICT	Information and Communication Technologies
ICU	Intensive Care Unit
IDE	Integrated Development Environment
NASA-TLX	National Aeronautical and Space Administration Task Load Index
PQ	Presence Questionnaire
PTSD	Post-Traumatic Stress Disorder
QEHB	Queen Elizabeth Hospital Birmingham
RCDM	Royal Centre for Defence Medicine
RCSQ	Richards Campbell Sleep Questionnaire
RE	Restorative Environment
SCR	Skin Conductance Response
STDEV	Standard Deviation
SUS	System Usability Scale
UDK	Unreal Development Kit
UE	Unreal Engine
VE	Virtual Environment
VH	Virtual Heritage

VNE	Virtual Natural Environments
VNE	Virtual Natural Environment
VR	Virtual Reality
VRET	Virtual Restorative Environment Therapy

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Chapter 1 Introduction

Since the early days of Virtual Reality (VR), from the late 1980s to the mid-1990s, there have been many attempts to develop a wide range of interactive 3D solutions to support medical and psychological interventions (e.g. Stone & Barker, 2006; Stone, 2011). According to Stone (1996), "Virtual Reality refers to a suite of technologies which permit intuitive interaction with real-time, three dimensional databases." Despite the failure of the VR industry to achieve its immersion technology "domination" in the late 20th Century (Stone, 2001; Stone, 2012), the clinical, surgical and psychological medicine domains of VR have survived and still present the VR research community with considerable challenges (Stone et al., 2014).

From the early part of 1900s, through to the early 2000s, and despite the fact that VR systems were still primitive and significantly expensive (in stark contrast to the situation today), VR applications were being developed to support psychological therapies including the treatment of phobias (Stone & Barker, 2006; Stone et al., 2014). It was argued that the advantage of exposing patients or clients to VR therapies was that the therapists or experimenters could effectively control the simulated – sometimes even fantasy-like - realities, whilst they were presented in a safe setting, such as a therapist's office or clinic. This was in striking contrast to the traditional psychological therapies that actually exposed patients to real-world, potentially threatening environments, where a large number of uncontrollable sights, sounds, smells and events could "flood" the patient with undesirable experiences (Stone et al., 2014).

VR applications have been successfully used for distraction therapy in pain management and control (Hoffman et al., 2004; Sharar et al., 2007). The success of distraction therapy lies in the extent to which a patient's attention can be distracted or "channelled" away from the conscious perception of pain by using alternative forms and optimum levels of sensory stimulation, such as visual, auditory, haptic (force/touch), proprioceptive (joint position and motion), even olfactory (Stone et al., 2014). The VR technologies used for distraction therapy systems are promising, as they can deliver a range of multi-sensory simulations to the end users using a wide range of commercial off-the-shelf (COTS) display and interaction devices.

The use of multi-sensory VR applications was argued to also be capable of creating engaging virtual scenes for *imaginal exposure* which is a technique used widely in cognitive behavioural therapy (CBT) to treat phobias and related psychological problems, including post-traumatic stress disorder (PTSD. Hoffman et al., 1998; Vincelli, 1999). Traditional CBT requires patients to describe their traumatic event(s), step-by-step and repeatedly, to the therapist or counsellor. Alternatively, therapists may actually talk patients through a scenario that can elicit stress (Rothbaum et al., 2000). Such processes of CBT help patients to avoid remembering significant negative learning (or cognitive) experiences that elicit many psychological conditions. Rizzo et al. (2009) claimed that one of the main advantages for using VR to support psychological therapies was that the patients could be "immersed" within realistic simulations of incidents leading to trauma, with the "emotional intensity" of the traumatic scenes being "precisely" controlled by the therapist. However, there are some Human Factors issues of VR in these cases. Firstly, today's VR technologies are unlikely to achieve true "immersion", as the end users of VR systems have to wear cumbersome, low-resolution, narrow field-of-view head-mounted displays (HMDs), and are typically expected to use input devices that do not support intuitive human movements or gesture. VR "immersive" technologies are not just confined to the use of

HMDs. Other technologies, including Cave Automatic Virtual Environments (CAVEs) have been used to suggest ideal contexts for the treatment of psychological conditions, although some argue that such technologies have issues of high cost, poor reliability and limited usability (Stone, 2008; Stone, 2012). Secondly, in some VR simulations for treating PTSD (Rizzo et al., 2009), the content of the traumatic events tend to be pre-programmed, generic simulations, as opposed to "subtle", "client-specific", "client-relevant" experiences (Stone et al., 2014). Finally, some psychologists have suggested that it is impossible to capture all of the objective events that may lead to the triggering of an individual's personal PTSD experience, as even if the VR applications are developed by very large commercial gaming organisations, the production of client-specific simulations would be extremely time-consuming and expensive (Stone, 2012).

These concerns have prompted the present study to consider a VR simulation which is not based on the traumatic event or events that induce psychological problems. Instead, a more generic form of VR system that may offer potential in psychological and physical rehabilitation therapies has been investigated. Restorative environments are peaceful places of natural beauty that can significantly reduce human reactivity to stress, and restore cognitive or attentional capacities to their "necessary levels for adaptive function" (Evans & McCoy, 1998).

Significant global attention is being paid to the relationship between human physical and mental well-being and the urban and natural environments in which they find themselves. Study findings suggest that natural environments can lower stress levels, whereas urban settings with few natural features can have a negative influence on emotional state (Ulrich, 1981; Kaplan, 1995; Hartig et al., 2003). Other research results demonstrate that the psychological "assistance" from nature may also help to restore the individual's attentional capacity and cognitive function following mental activities (Kaplan & Kaplan, 1989; Berto, 2005; Berman et al., 2008) and following fatigue generated by directed attention (Kaplan, 1995).

For virtual reality-based restorative environments, there is currently a lack of research. Given the concerns of the Human Factors issues related to the VR exposure therapies mentioned above, no one study in this area has evaluated the exploitation of VR techniques in support in the development or evaluation of appropriate immersive virtual environments.

VRET (Virtual Restorative Environment Therapy) is an ongoing project being conducted by Human Interface Technologies (HIT) Team at the University of Birmingham. The long-term aim of VRET is to develop a range of virtual restorative environments (VREs) for the assistance of patients who experience a diversity of psychologically related symptoms (e.g. post-traumatic stress disorder, anxiety, attention deficit disorder, general pain and sleep deficit) and who are unable to access and experience real natural environments. Other aims for the VRET project are to conduct Human Factors research, using the VEs established as a test base, into a variety of interactive applications and software interfaces, as well as developing novel psychophysiological measures of human performance, presence and well-being as the research progresses.

1.1 Aim and Objectives

As a fundamental part of the VRET project, the present study aims to determine the principles for the development of virtual natural environments, using low-cost commercial-off-the-shelf (COTS) simulation technologies, for bedside and clinical applications. To this end, six specific objectives were defined at the outset of the research.

The first objective was to demonstrate that virtual natural and urban environments of an appropriate fidelity could be developed using appropriate COTS software and hardware tools and technologies.

The second objective was to compare the differences of the influence of natural and urban VR set-ups on participants' stress levels, and to investigate any potential restorative effects related to the use of realistic background sound in both VEs.

The third objective was to investigate the technical and methodological issues of integrating odour into a VE, and to discover if odours would evoke a physiological response that could be detected, logged and measured objectively and inconspicuously in real time.

The fourth objective was to determine the effects of the level of fidelity of a virtual natural environment. Furthermore, the research set out to addresses the importance of different factors of fidelity in VEs, in order to deliver methodological suggestions for future VE design and optimisation in terms of balancing VE system performance and user experience, thus helping to develop low-cost, effective VE systems for widespread use (e.g. hospital, clinic, home) restoration and rehabilitation procedures.

The fifth objective was to identify usability issues with four different COTS control devices selected for potential VR interaction exploitation by a range of patients who may present with differing perceptual, cognitive and residual motor capabilities. This aim was stimulated by early hospital observations indicating that even some of the most popular products (such as the Xbox controller or the Wii Nunchuk Controller) could cause serious problems for some patients in their attempts to maximise benefits from the VEs.

The sixth objective actually fell outside the scope of the healthcare bias of the first five, in that, as part of the studies relating to fidelity and VE acceptance, an opportunity was presented which involved participants living locally to the real-world area modelled during the VE development process. Hence, it was decided to investigate whether or not participants would navigate and accept (or be critical of) a virtual natural environment based on a local area differently than a VE based on a non-local area.

1.2 Thesis Structure

The remaining of the thesis is organised as follows:

Chapter 2 includes a literature review which looks at related VR studies, drawing attention to the human factors issues of VR exposure therapies and the lack of research in VR-based REs. This chapter continues by describing the system requirements for the development of virtual reality-based REs, including a survey of VR software and hardware technologies, and the measurements of presence and usability for VR applications. It concludes with a selection of software development tools, a VR system hardware specification, and questionnaires for the measurement of presence and usability.

Chapter 3 describes the early development of two virtual environments, including a general design workflow and some fundamental design aspects, such as the virtual reconstruction of a real-world location, including 3D modelling and texturing, lighting, sound effects and navigation.

Chapter 4 covers two early pilot studies evaluating different features of VEs - scene, sound and smell. The first pilot study investigates user preferences, together with basic human health and well-being issues, by comparing responses to imagery of natural and urban environments replicated in a VR world. The second pilot study considers the methodological issues associated with integrating smell or odours into a VE. These studies build strong foundations on which the subsequent research reported in this thesis has been built.

Chapter 5 introduces the further development and exploitation of the virtual environments produced during the research, by seeking potential features that can be added, and, thus, enhancing the end users' navigational experiences and preserving the longevity of the virtual experience. Such features include time-of-day effects, new 3D and software assets, more interactive and more dynamic, motivational activities, a software tool capable of recording the navigational activities of the end users, and additional (potentially "patient-friendly") interaction methods, including easier selection of viewpoints via single button clicks and the use of non-contact motion sensors.

Chapter 6 investigates the impact of visual and auditory fidelities, and the accuracy of representation of a localised VE (i.e. the sense of presence and acceptance on the part of end users of a VE based on a location in the vicinity of their town or village). Additionally, as presence is significantly associated with usability in VEs (Sylaiou et al., 2010), this chapter also addresses usability issues of a number of input devices.

Chapter 7 investigates whether or not the use of VNE or Virtual Restorative Environment Therapy (VRET) system could promote better levels of relaxation and improvements in sleep quality of intensive care patients. This study also aims to determine the modification based on feedback from intensive care staff and patients to improve the future development of VRET.

Chapter 8 is an overview of the previous chapters, presenting the principles for the development of virtual natural environments, using low-cost commercial-off-the-shelf (COTS) simulation technologies, for bedside and clinical applications. A discussion of the limitations of the approaches is given. Finally, the chapter considers other areas in which this research can be extended.

Chapter 2 Literature Review

2.1 Introduction

Virtual reality-based restorative environments is a very new field of research. This chapter begins with a review of the real-world evidence supporting the restorative effects of natural environments (Section 2.2). In Section 2.3, related studies addressing the use of virtual reality technologies for physical and psychological health care applications are reviewed, including distraction therapy and VR simulation for the treatment of Post-Traumatic Stress Disorder (PTSD), as well as virtual reality-based restorative environments. Research problems, such as Human Factors issues with VR therapies, and the significant absence of relevant research in the field of VREs are discussed.

The next Sections determine the requirements for the development of virtual reality-based REs. Sections 2.4 and 2.5 evaluate the appropriateness of current VR software and hardware technologies. Section 2.6 explains the definitions and relationship between immersion and presence, identifies the main factors affecting a user's presence during VR exposure, and lists both subjective and objective methods to measure presence. Section 2.7 demonstrates the importance of usability as part of the VR system design process, and discusses methods for measuring VR system usability.

2.2 Real-World Based Restorative Environments

Research into the effect of an individual's exposure to urban, rural ("green") and coastal ("blue") environments on human physical and psychological well-being has, over the past 4 to 5 years, gained significant interest. Study findings show that natural environments can lower an individual's stress level, whereas city settings with few natural features can have a negative influence on an individual's emotional state (Ulrich, 1981; Kaplan, 1995; Hartig et al., 2003). Research results point out that psychological "assistance" from nature can also help to restore the focus, attentional capacity and cognitive function of an individual following mental activities and fatigue generated by directed attention, such as a proof-reading task which is highly demanding of directed attention, or a directed-forgetting task which suppresses information in short-term memory which mainly comprises directed-attention abilities (Kaplan & Kaplan, 1989; Kaplan, 1995; Berto, 2005; Berman et al., 2008). These settings, often referred to as "restorative environments" (REs), have been widely studied.

Some of the studies reviewed have addressed the effect on human well-being of REs when presented as simple as a view from a window. Natural window views (e.g. of lakes, gardens and trees) tend to have a more effective influence on restoration of attention than views of building structures, including brick walls (Tennessen & Cimprich, 1995). Through-window views of natural elements from single-storey houses improves well-being which includes effective functioning, a sense of "at peace" and distraction factors (indicated by such participant comments as: "Life is interesting and challenging", "Relaxed", etc.), as opposed to views of man-made objects that have no significant effect on well-being (Kaplan, 2001a). Natural elements in the workplace have also been shown to play a crucial role in improving an employee's well-being (Kaplan, 1993). In Ulrich's study (1984), two matched groups of 23 patients recovering from surgery were allocated to rooms with a window view of a group of trees or of a brick wall (Figure 2.1). The results suggested that the patients with the more natural view experienced shorter stages of rehabilitation after surgery and less pharmaceutical pain relief than those facing the brick wall.

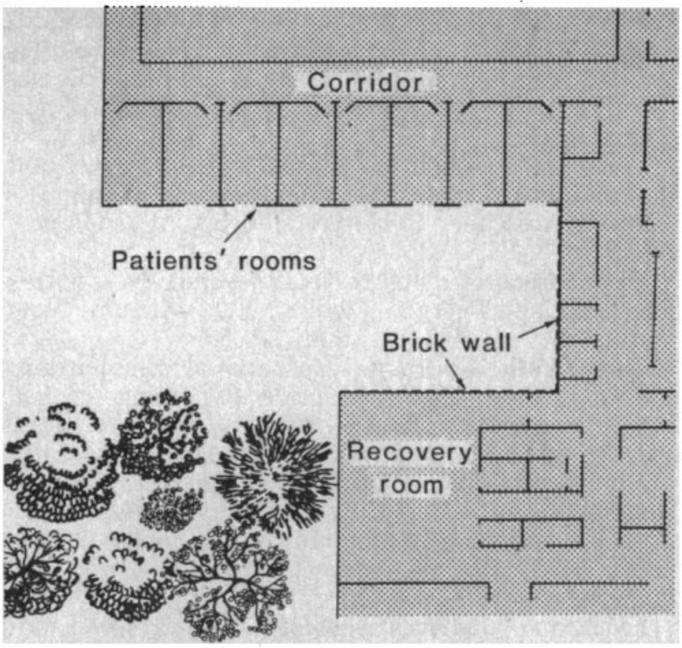

Figure 2.1 A Plan of the Study Hospital Indicating Different Window Views to the Plants and Brick Wall from Patients' Rooms (Ulrich, 1984).

In 2007, research conducted by the Japanese Forestry and Forest Products Research Institute found that 15 to 20-minute exposures to natural forest settings had a positive impact on physiological measures, such as significantly reduced blood pressure, pulse rate and salivary cortisol levels, and also improved subjective ratings of comfort, calmness and refreshed feelings, in stark contrast to similar exposures in a urban environment (Tsunetsugu et al., 2007; Park et al., 2007). A reduction of blood pressure was also demonstrated in a study after roaming within a natural setting, whilst the effect was weakened when participants were exposed to city conditions (Hartig et al., 2003).

The theories of how and why natural environments have restorative effects remain controversial (Valtchanov et al., 2010). Ulrich, in describing his *Affective Response* theory on restorative environments, claimed that the initial affective response of individuals to a visual pattern (such as a natural scene) was intense and potentially automatic. Patterns seen outside of nature are described as being more intimidating and arousing than those seen in nature environments. The initial affective response to a pattern dictates the cognitive outcome immediately afterwards, resulting in various effects on human well-being, including restoration of attentional capacity (Ulrich, 1981; Ulrich et al., 1991). In contrast, Kaplan proposed an *Attention Restoration* theory (ART), suggesting that an individual's first response to an environment was cognitive instead of affective. The individual's attentional capacity recovers as a result of exposing an individual to what Kaplan calls a "fascinating nature environment" where that capacity improves relatively slowly (Kaplan used the phrase in a "bottom-up" fashion) whilst the individual is "lost" in the rich natural features he or she is experiencing. Urban settings also have bottom-up stimuli (such as flashing lights, loud city noises, dynamic signs), although they are less restorative than natural settings as they draw an individual's attention towards them as he or she attempts to overcome the stimuli (Hartig et al., 1991; Kaplan, 1995; Kaplan, 2001b). Research results indicate that an individual performs better in attention tests after exposure to natural restorative environments (e.g. ocean, lakes, rivers and mountains) than those exposed to city settings or geometric drawings (Berto, 2005). This study also suggests the attention to REs is effortless, and therefore agrees with Kaplan's ART approach.

2.3 Virtual Environments for Healthcare

Of course, real-world natural environments may not be easily accessed by many people, including those in hospitals, rehabilitation centres, hospices, care homes or the housebound

(Depledge et al., 2011). Virtual Restorative Environments may be an alternative in these situations. Since the 1990s, studies have been conducted to implement virtual reality technologies for physical and psychological health care applications, including treatment for phobias (e.g. Rothbaum et al., 1995; Carlin et al., 1997).

2.3.1 Distraction Therapy

Distraction therapy is also one of VR's practical applications. Research results show that patients with major burns who receive VR distraction therapy during medical treatments, report a reduction of pain levels (Hoffman et al., 2004; Sharar et al., 2007; Hoffman et al., 2007). In a widely-cited paper, Hoffman et al. (2000) describe the development of a VR distraction therapy system – *SnowWorld*. Burn patients are instructed to shoot snowballs at virtual targets (e.g. snowmen, penguins and igloos) in a virtual "ice canyon" scene displayed on a VR head-mounted display (HMD) with a head-tracking function. The authors argued that patients' attention was drawn in this interactive VE by strong visual and auditory simulations of cold features, such as snow, ice and splashing sound effects of snowballs, so much so that they have less available mental or conscious resource to bring to bear on the processing of pain signals. In their further studies, this hypothesis has been supported by the measurement of functional magnetic resonance imaging (fMRI) - a procedure that measures brain activity by detecting associated changes in blood flow. The results showed a greater reduction in pain-related brain activity during exposure to *SnowWorld* than a control condition of no VE experience (Hoffman et al., 2004).

A between-subject study reported by Gold and colleagues of pain distraction for intravenous (IV) injection divided 20 children randomly into two groups. One group was exposed to a VR sledge game displayed on an HMD during IV injection, while the other group undertook a control condition of normal IV procedure without distraction. The reported pain intensity was significantly higher in the control group than in the VR distraction group. There was also a signification positive correlation between anxiety and pain (Gold et al., 2006). Research showed that participants receiving VR distraction treatment, such as exposure to a VR shooting game reported significantly longer tolerance times to ischemic (often quite excruciating) pain and significantly lower distress ratings than those participants who had not received any virtual distraction (Magora et al., 2006).

A recent study addressed using a virtual natural environment (in fact, the Virtual Wembury VRE described later in this thesis) as a form of distraction therapy during a simulated dental visit. Sixty-nine participants were, using rating scales, divided into low and high dental anxiety groupings and randomly allocated to one of three VR conditions displayed on a HMD. These were an active condition with fully interactive VE (i.e. participants were able to free roam within the VE using a Zeemote™ JS1™ thumbstick controller), a passive condition using a recorded video of a virtual walk within the VE, and a control condition with a black visual display. The results showed that the participants with greater dental anxiety scored significantly lower on the rating of vividness of memories of the dental procedures in the VR conditions than in the control condition. As a result, the authors suggested that VR distraction therapy might reduce the possibility of postponing a future dental appointment on the part of those who exhibit fear or apprehensiveness at visiting dental clinics (Tanja-Dijkstra et al., 2014).

2.3.2 Post-Traumatic Stress Disorder

A series of studies have used VR systems to assist with the treatment of post-traumatic stress disorder (PTSD). One of these virtual reality systems was named “Virtual Iraq”, in effect a combat-like environment which offered sound, smell and haptic feedback relating to the trauma during a patient’s exposure. The virtual scenes were presented using an HMD, and other stimuli could be controlled and modified during the exposure by an experimenter or therapist, who was provided with the means to trigger events and incidents in the virtual scenarios. Twenty patients completed the treatments. Sixteen of them reported a greater than 50% decrease in symptoms after the virtual treatment, such that they would not need further treatment (Rizzo et al., 2009). An earlier case study of the use of VR therapy for veterans with PTSD also showed improvement in PTSD symptoms (Gerardi et al., 2008). This study suggested that the VR should be customised based on individual’s experience to take better effect. However, some psychologists have suggested that it is impossible to guarantee capturing all of the objective events – both major and minor – that may lead to the triggering of a single individual’s personal PTSD experience, as even if the VR applications are developed by very large commercial gaming organisations, the production of client-specific simulations would be extremely time-consuming and enormously costly (Stone, 2012). Another case study involved the treatment of a 9/11 World Trade Center attacks survivor with severe PTSD. A virtual scene in which gradually-increased exposure levels of the traumatic event were presented using an HMD in a single-participant case study demonstrated a significant reduction in depression and PTSD symptoms (Difede & Hoffman, 2002).

It is debated that the key advantage of the VEs described in the applications above is that it can provide patients with controllable, safe and (if considered necessary) fantasy-like or “escapist” scenarios. In contrast, real-world treatments may expose patients to environments with potential risk and a whole host of uncontrollable auditory, visual and olfactory stimuli that could rise to intolerable levels for patients with psychological issues (Stone et al., 2014).

2.3.3 Virtual Reality-Based Restorative Environment

At the time of writing, the literature describing studies of VR-based natural restorative environments appears to be very limited indeed. A study conducted by Valtchanov et al. (2010) suggests that virtual forest environments can produce restorative effects. 22 participants were assigned to two conditions - nature (a virtual photorealistic forest) versus control (a slide show of artistic paintings). The VE was delivered to participants using an HMD with head-tracking module and a haptic feedback system which was a "rumble platform" that vibrated whenever a "step" was taken, or when the virtual body collided with virtual objects. The participants were pre-stressed by self-described stressful experiences accompanied by loud urban noise, followed by the Markus-Peters Arithmetic Test (Peters et al., 1998). They were then exposed to the VE or the slide show for 10 minutes. Measurements of stress level, fatigue and affect were employed by measuring skin conductance, heart rate and affect (emotion) questionnaires. The results of this study showed greater positive affect and lower skin conductance after exposure to the forest than the control condition. No significant main effects on heart rate variability were found when exposed to the virtual natural environment.

A more recent study (Annerstedt et al., 2013) investigated the effect of sound on human stress levels in a virtual forest environment with water (e.g. a stream). Thirty participants were randomly and equally assigned into three groups undertaking one of three conditions: two conditions of a virtual forest with and without sound, and one control condition without VE and sound. The VE was displayed using a CAVE system and the sound was delivered using a 5.1 surround sound system. Prior to the exposure, the participants were asked to complete a Trier Social Stress Test (Kirschbaum et al., 1993) and a mathematics task for a total time of 15 minutes. Then, a VR exposure started and lasted for another 15 minutes. The physiological response data were collected throughout the entire process, including heart rate, heart rate variability (HRV), electrocardiography, and salivary cortisol. Subjective measures of anxiety were also collected before and after each condition. High frequency (HF) activity of HRV was associated with relaxation and significantly increased during exposure to the forest setting with soundscape. However, the HF magnitude decreased in the VE condition without sound. The authors argued that the silent environment might provide a "surrealistic experience" that may well be frightening for some participants. There were no significant main effects of HF or cortisol on stress recovery in the control condition (Annerstedt et al., 2013).

2.4 Software Technologies

Virtual Reality development tools have become highly accessible and affordable in recent years. This section evaluates the more popularly used software packages for the development of interactive VEs.

2.4.1 Game Engines

The term 'game engine' refers to a software framework developed for tasks related to the creation of video games and include such features as a rendering module, physics module, multimodal output (e.g. visual image, sound, haptic feedback), scripting facility, networking, and so on. These features help game developers to focus more on making the game unique (Mat et al., 2014), as opposed to delivering something that consists of sterile 3D worlds with very few realistic environmental effects and predictable, repetitive animations. The features of the two most popular game engines - Unreal Engine (currently version 4.6.1) and Unity3D (currently version 4.6) are detailed described below.

The Unreal Engine (UE) is created by Epic Game Inc. and has a free development kit (UDK). The UE has also been free for academic use since August 2014 and has been successfully used in both the gaming industry (e.g. Gears of Wars, Unreal Tournament) and filming industry (e.g. Pacific Rim) (Unreal, 2014). Unreal offers the feature of visual scripting using the C++ programming language, as well as its own programming language, called UnrealScript. Other features of visual, animation and resource management are also available in UE, such as dynamic particles (e.g. smoke, snow, fire, and dirt), a robust animation system, a landscape system including a number of terrain and foliage tools, post-process image effects (i.e. computer graphics effect to reproduce imaging artefacts of real-world cameras. Mittring, 2012). The games developed for the UE support multiple platforms, including desktop systems (PC, Mac and Linux), mobile systems (iOS and Android), game consoles (e.g. PlayStation4 and Xbox One) and other web-based platforms (e.g. HTML5 and SteamOS). Development of VR simulations using UE 4 requires systems with Windows 7 64-bit or above or Mac OS X 10.9.2 or above, a 2.5 GHz Intel Dual-core or AMD processor or faster, graphics card with DirectX 11 compatibility and 8 GB system memory (Unreal, 2014).

The Unity3D game engine was first released by Unity Technologies in 2005 (Unity3D, 2014). Unity has an advanced import pipeline that supports almost all of the major 3D modelling, animation applications, such as 3ds Max, Maya, Modo, Cinema 4D etc. Whenever modifications of an asset have been saved in these applications, Unity automatically re-imports the asset and makes the changes instantly visible in the editing window (Wang et al., 2010). Unity supports imported scripts or scripts written in its integrated development environment (IDE) – MonoDevelop using JavaScript, C# and Boo programming languages (Suvak, 2014). There are a number of 3D assets available in the integrated Unity Asset Store, allowing simpler workflow and shorter development period for both video games and serious games for training and educational purposes (Minocha & Burden, 2013). Unity provides an intuitive and user-friendly development interface and toolkits, and is popular with small and medium-sized studios, and independent, or 'indie' developers. Consequently, it has a vast and fast-growing community that shares valuable resources and helps to resolve problems during game development (Liao & Qu, 2013). Similar to UE, Unity also provides a robust cross-platform publishing feature. These platforms include standard desktop and laptop computer systems (Windows, Mac OS and Linux), mobile systems (iOS, Android, Windows Mobile and BlackBerry), web browsers (Internet Explorer, Safari, Google Chrome and Firefox) and game consoles such as PlayStation, Xbox, Wii (Oak & Bae, 2014). The system requirements for development using Unity3D are any PC or Apple Macintosh with Windows XP SP2 or higher or Mac OS X 10.6 or higher, a graphics card compatible with DirectX 9 and any CPU released since 2004 (Unity3D, 2014).

There are many other game engines showing strong competitiveness. For example, Kaplanyan (2009) claimed that CryENGINE (the original engine behind the action game *FarCry*) could generate artist-level graphics with its Flowgraph tool. However, it urgently needs a robust support community and a lower learning curve. HeroEngine has received praise for managing large-scale online multiplayer games. It offers several open-world maps and the ability to travel between these maps seamlessly, although it suffers from the lack of intuitive programming tools and requires a higher learning curve than the other major game engines (Clyde & Wilkinson, 2012).

2.4.2 3D Modelling Software

Recently, the expansion of 3D modelling and digitising technologies has simplified the 3D model creation/modification workflow significantly. Also, commercially available online resources of 3D models are, today, numerous, and this also helps to accelerate the VE development process. However, there are still relatively heavy demands for bespoke, or custom modelling in VEs, especially for reality-based objects that are distinctive in their domain or possess unique features. Two of the most popular 3D modelling software packages are Autodesk's 3ds Max, currently version 2015 and Google SketchUp (version 2015).

Autodesk 3ds Max is a powerful 3D modelling, animation and rendering software package (Yu et al., 2011). There are two available packages of 3ds Max: the normal 3ds Max and 3ds Max Design software. The former is widely used in the media and entertainment industries, while the latter is ideal for architecture, designing and civil engineering because of its ability to interact with other design tools such as Autodesk's AutoCAD. Both packages are free for educational institutions. 3ds Max has robust modelling abilities and a flexible plug-in mechanism (Murdock, 2012). The 3ds Max modelling module offers a large selection of toolkits that allows the user access to the modifying functions of the editable model. In addition to the modelling toolkits, the current version of 3ds Max (at the time of writing) also features an advanced animation toolset, a fully configurable user interface and its own dedicated programming language (Murdock, 2014). Furthermore, 3ds Max supports a wide range of data export formats such as FBX and OBJ, allowing easier integration and asset-sharing with other 3D modelling packages or game engines. The recommended system requirements for 3ds Max are any laptop or desktop PC running Windows 7 (32-bit or 64-bit) or above with 8 GB of RAM or above, an Inter i5 or AMD Phenom or higher processer, and an NVIDIA GeForce GTX or ATI Radeon graphics card with 2GB RAM (Derakhshani & Derakhshani, 2014).

Google SketchUp has rapidly gained a strong reputation because it has a simpler and more intuitive user interface than many other 3D modelling packages (Silva & Tal, 2014). The standard version of SketchUp is free for all users, which is another main advantage that contributes to its popularity. SketchUp is gradually becoming an educational tool in engineering, mechanical and sustainable design courses because of a shorter learning curve (Martín‐Dorta et al., 2008). SketchUp offers convenient terrain tools which use imported digital terrain data from Google Earth as a template for landscape-based 3D modelling (Kada et al., 2003; Van Lammeren et al., 2008). Additionally, the "Match Photo" tool is one of SketchUp's exclusive features. This tool allows users to exploit photographs of an object taken from different angles as textures to simplify the 3D geometrical modelling process (Tal, 2010). SketchUp is compatible with most of 3D modelling, CAD and even 3D printing systems. The integrated 3D and extension warehouse offers abundant valuable and free resources for SketchUp users. In addition to the Windows platform, the latest version also supports the Apple Macintosh operating system. The recommended system requirements for SketchUp 2015 are any PC or Mac running Windows 7 or Mac OS X 10.8 (Mountain Lion) or higher with 2.1 GHz Intel or higher processor, 8 GB RAM, 3D graphics card with 1GB RAM or higher and with support of OpenGL 2.0 or higher (Google, 2014).

Other 3D content generating tools are also available, such as Autodesk Maya, DAZ 3D, MAXON Computer's CINEMA 4D and Modo from Foundry Visionmongers Ltd; free and open source 3D software also exists, including Blender.

2.4.3 Texture Processing Software

A texture, in the field of computer graphics, refers to details including images or colours that are added to the surface of a 3D model (Catmull, 1974). Adobe Photoshop has been dominant in the field of texture editing since its first release in 1988 (Reding, 2012). The latest version of Photoshop (again, at the time of writing) is CC 2014.2. Photoshop can edit and combine textures with different layers. It has the capability to edit image colour modes such as greyscale, RGB (red, green and blue) colour, CMYK (cyan, magenta, yellow and key/black), and so on. (Weinmann & Lourekas, 2012). Photoshop supports most image formats (e.g. JPEG, BMP, PNG, TARGA, TIFF, RAW, etc.). Photoshop's function can be even extended by its robust plugin system (Harrington, 2012).

Other texture processing tools such as Foundry's Mari, Pixologic's ZBrush and Autodesk Mudbox, are also becoming popular.

2.5 Hardware Technologies

According to Stone (2012), the interactive hardware devices for VE can be "traditional" (e.g. keyboard and mouse, joystick, flat screen, projector, etc.) and "non-traditional" such as the HMD, the CAVE, Haptic Displays, Olfactory Displays, and so on. During the final decade of 20th century, the VR industry failed to convince end users of VR systems to accept their marketing hype that the so-called "immersive" interfaces such as HMDs and instrumented gloves would dominate today's VR hardware territory. This obviously did not come true. Consequently, a large portion of those users still prefer to use standard keyboard and mice as input devices for VR, rather than novel commercial off-the-shelf products (Stone, 2001; Stone, 2012). In addition, newer versions of traditional controllers (e.g. Microsoft's Xbox controller, the Nintendo Wii's Nunchuk, the Zeemote JS1 controller, etc.) have, over the past few years, gradually been integrated within a wide range of VR systems (e.g. Lange et al., 2009; Lapointe et al., 2011).

Another result of the early failure of the immersive VR technology community has meant that flat screens and projectors are still the standard visual output for most VR applications (e.g. Cherni et al., 2011; Ali et al., 2014). Meanwhile, recent studies have investigated the suitability of new, lighter and (in the main) cheaper HMDs with higher resolutions and wider fields of view, such as Sony's HMZ series (e.g. Steed & Julier, 2013; Budziszewski, 2013), the Oculus Rift (e.g. Bolas et al., 2013; Nilsson et al., 2014) and the Vuzix Wrap (e.g. Nicholson, 2011; Khuong et al., 2014).

As described in Section 2.6.1.1, the frame rate of the VR application should be much higher than 15Hz in order to evoke a user's sense of presence (Barfield et al., 1998). In addition, the system hardware requirements of 3D applications built by modern game engines are of a relatively high standard. Taking all factors into consideration, a VR system running on Windows 7 64-bit platform for example, requires an Intel i5 processor, 8 GB RAM, a graphics card with DirectX 11 compatibility, in order to achieve smooth VR user experience.

2.6 Immersion and Presence in Virtual Environments

Immersion is commonly identified as a psychological state categorised by feeling one's self to be "encased" by, involved in, and interacting with an environment that delivers a non-stop stream of stimuli and experiences (Stanney & Salvendy, 1998; Witmer & Singer, 1998). In the field of Virtual Reality, immersion often refers to a "description of the technology" and the degree of immersion is sometimes only determined by the VE's visual quality and multimodal sensory display technology (Slater & Wilbur, 1997; Bowman & McMahan, 2007). Witmer & Singer (1998) also showed that offering users with a feeling of isolation from reality is closely influenced by the choice of software and hardware of the VE system.

The definition of presence is commonly referred to as the subjective sense of "being there" – being within a VE rather than in the space in which the participant is physically located (Held & Durlach, 1991; Sheridan, 1992; Sheridan, 1994; Smets et al., 1995; Ellis, 1996; Slater & Wilbur, 1997; Draper et al., 1998). However, some researchers have debated that presence would be better defined as the degree of "successfully supporting action in the environment" (Zahorik & Jenison, 1998; Flach & Holden, 1998). These authors have argued that the user's experience is defined in terms of a close association with actions, as opposed to appearances. Such a definition was also supported by other studies of virtual body movement, suggesting that the feeling of "being there" was based on the "capability to *do* there" (Slater et al., 1998; Schubert et al., 2001). Slater (2003) distinguished immersion and presence as following:

- Immersion is considered with regard to the objective dimension of the technology (i.e. the nature of the hardware and software used) that is offered by a VR system;
- Presence is defined in terms of the user's subjective response to a VR system.

In terms of the relationship of immersion and presence, Slater et al. (2009b) suggests that presence is user reaction to a VE possessing some degree of immersion. The fidelity of a VE to its real-world counterparts is important to evoke presence.

2.6.1 Factors Contributing to Presence

Slater & Wilbur (1997) suggest that different levels of immersion within VE systems will have a substantial impact on the user's sense of presence. Therefore, VR system factors are important for triggering user presence in VEs, such as such as field of view, the displayed image frame rate, the latency or delay between the user's input and the system's reaction to that input, the fidelity offered by a variety of multi-sensory displays, the quality of rendering, the realism of the displayed images, the freedom of interaction, the extent of tracking, and incidences or occurrences of simulator sickness, and so on (Sanchez-Vives & Slater, 2005; Gerard, 2005).

2.6.1.1 The Visual Display System

The human visual system is accepted by most to be the most powerful sensory system and computer users can be enormously sensitive to visual stimuli (Kalawsky, 1993). Kalawsky (1999) demonstrated that even tiny irregularities on a computer screen (e.g. unremarkable distortions or lags) can be detected by system users. Studies have reviewed standards that may be used for developing the visual elements delivered to end users. For example, a field of view (FOV) of 100 degrees or more is demanded to produce an immersive VE (Kalawsky, 1993). In another study, after comparing different update rates (i.e. 10, 15 and 20Hz) on users' sense of presence level in a relatively low fidelity virtual Stonehenge scene, it was suggested that 15Hz was a threshold for the participant to feel present in the VE (Barfield & Hendrix, 1995; Barfield et al., 1998). This theory was proved by a study conducted by Meehan et al. (2002), who found that the increase in a sense of presence was indicated by the variation of heart rate to the frame rate (variation of heart rate significantly increased between 15 FPS (frames per second) and 30 FPS, and between 15 FPS and 20 FPS). In addition, head tracking, stereoscopic, and larger screen size can also improve perceived presence (Hendrix & Barfield, 1996a; Barfield et al., 1999; Antley & Slater, 2011).

2.6.1.2 Visual Realism

The contribution of visual realism to presence is a controversial topic. Mania & Robinson (2004) reported no significant statistical effect on presence due to differing levels of shadow quality. One study only found an increased presence rating when the users were in front of a virtual cliff, whereas no significant differences on presence between the conditions of different quality of shadow, texture and lighting were found (Zimmons & Panter, 2003). However, Welch et al. (1996) suggest that higher image realism and shorter latencies are associated with greater reported presence. Uno & Slater (1997) investigated the effects of simulating physics (e.g. elasticity, friction and collision) on presence in a virtual bowling game. They demonstrated that, whilst a higher level of friction realism significantly increased the ratings of presence, there were no main effects on presence caused by the other physical factors. The visual quality of virtual representations of the user's body has also been shown to have a significant association with presence ratings (Slater et al., 1998). One study suggested that presence ratings increased due to shadow quality, from conditions of no shadows, through "baked" shadows (i.e. static textural representations of shadows), to real-time shadows (Slater et al., 1995a).

A later study investigated the influence of visual realism, specifically lighting, on presence (Slater et al., 2009a). This study suggested that visual realism can be defined as a a combination of geometric realism and lighting realism, and both forms had real-time and non-real-time factors. After comparing conditions with or without shadows and reflections in a VE, higher presence ratings were shown to be related to higher visual realism. A recent study suggested that higher presence ratings and lower anxiety levels were strongly associated with more graphically realistic human avatars in a virtual interview scenario (Kwon et al., 2013).

2.6.1.3 Sound

Even if the visual effects are usually the most convincing and noticeable, sound technologies can be efficiently exploited to compete with visual effects or in some situations may even be presented alone (Kalawsky, 1993). Within VEs, sound can be presented to achieve two important effects, localisation and sonification (Begault, 1994; Durlach & Mavor, 1994; Bowman et al., 2000). Localisation refers to the production of 3D sound in a way that can be spatially localised by the end user, and sonification is defined as a means of using sound effects to delivery particular kind of information (e.g. sound of footsteps, wind). Aural feedback may contain sound generated by user's own activities, other individual's activities, and by natural or ambient sounds (Gabbard et al., 1999). Hendrix & Barfield (1996b) showed that presence ratings were higher in experimental conditions with spatialised sound than conditions without sound or non-spatialised sound. Other research, supports these findings, suggesting that sound can be used to improve presence and VE users' performance by enhancing those users' physical and spatial awareness (Bowman et al., 2000).

2.6.1.4 Interaction Between User and VE Systems

Interaction with VE systems needs to be natural or highly intuitive, efficient and appropriate for end users (Bowman, 1999). Slater et al. (1995b) demonstrated that participants roaming in a VE using an HMD-mounted electromagnetic tracking device which detected participants' head-movement patterns whilst they were "walking "on the spot, rated their presence higher than those who used a mouse for roaming. A further study (Slater et al., 1998) also suggests that reported presence has a significant positive connection with the amount of body movement. Studies have investigated the impact of haptic feedback on presence. A more recent study suggested that the use of force feedback in such driving tasks as speeding-up and turning, where the effects were generated by a Novint Falcon controller, can improve user presence in a virtual driving simulator (Jin, 2010). Emma-Ogbangwo et al. (2014) showed that using full body gesture recognition control can enhance a sense of presence and co-presence in a multi-player VE.

2.6.1.5 Side Effects

Studies suggest that it is important to minimise undesirable health issues related to use of VEs, such as motion sickness (i.e., cybersickness), physical discomfort and any adverse psychological symptoms during using a VE system (Hix & Gabbard, 2002). Such health issues should be identified as side effects (Stanney & Salvendy, 1998). Witmer & Singer (1998) demonstrated that reported simulator sickness ratings and those of presence had a significant negative relationship. Early research results reported that traditional motion sickness is related to the individual's age. The susceptibility of motion sickness is believed to be highest from 2 to 12 years of age, declines quickly from 12 to 21 years old, then declines more slowly until the age of 50. After 50 years of age, there were almost no cases of motion sickness reported (Reason & Brand, 1975). However, Arns & Cerney (2005) showed that younger participants reported lowest motion sickness ratings when using VEs. The sickness ratings had an upward tendency with the increase of age. In addition, the scores for 50 years and older were greater than those for the younger participants. When cybersickness is likely to occur, participants usually withdraw from the exposure to the VE (voluntarily, or at the request of the experimenter) or, if they persist, can actually adapt to the simulated environment, suppressing symptoms over time (Reason & Brand, 1975).

2.6.2 The Measurement of Presence in Virtual Environments

There is no doubt that the scientific evaluation of the utility of a Virtual Environment throughout the stages of design, testing and implementation is essential, but highly challenging, due to the myriad of hardware, software and interactive content features that can form part of a VE system. Sanchez-Vives & Slater (2005) believed that a measure of the effectiveness of a VE is indispensable because of the requirement to ensure the best distribution of budget and technical resources, "trading" between computer processing capacity and the extent of sensory representations. However, the principles for measuring the effectiveness of a VE, let alone the development and availability of credible metrics, were frustratingly absent in the early days of Virtual Reality. Nickerson (1992) found that it was not clear from research at the time how to determine that a VE system is sufficient for the purpose of virtual training. Witmer & Singer (1998) suggested that the effectiveness of VEs was linked to the reported presence. The followings section will discuss the evaluation of the effectiveness of VEs or how well an existing VR engages an end user – in other words, presence in VEs. Based on previous research, the measurement of presence comprises subjective measurement and objective measurement.

2.6.2.1 Subjective Measurement of Presence

At the time of writing, the most frequently used methods for measuring presence are based on subjective ratings, typically captured through the use of questionnaires. These questionnaires are usually based on 5-point or 7-point Likert scales in which, for example, the lowest rating of presence is 1 (i.e. no feeling of presence), and the highest score of 7 reflects the maximum reported level of presence (Slater & Usoh, 1993; Barfield & Hendrix, 1995; Lessiter et al., 2001). In an often-cited paper, Witmer & Singer (1998) proposed a revised Presence Questionnaire (PQ) for VEs that was claimed to have high reliability with good internal consistency of presence data. Witmer & Singer (1998) categorised the parameters of presence into three types:

- Involved/Control - how involving the VE was and how involved in the environment the participants were; the reaction of the VE to a participant's control;

- Natural - how natural the interaction was, the consistency of the VE to real-world and how natural the control was;
- Interface Quality - the extent to which the participants were distracted or hampered in their performance by control or display devices.

Witmer & Singer (1998) also introduced an Immersive Tendencies Questionnaire (ITQ) to predict presence, taking into account an individual's personal circumstances, such as susceptibility to simulator sickness, or the extent to which they can become engrossed in films, TV programmes or books. They suggest that higher levels of involvement obtained with media (i.e. films, TV programmes or books) are accompanied by higher ratings of presence in VEs.

Schubert et al. (1999) created the Igroup Presence Questionnaire (IPQ) by merging earlier proposed questionnaires, such as Witmer & Singer's PQ, the Slater-Usoh-Steed questionnaire (Usoh et al., 2000) and a presence questionnaire from a previous study (Regenbrecht et al., 1998), plus some items to take account of new technologies. This questionnaire consisted of 75 questions mainly focusing on virtual gaming applications. These questions were categorised into three presence factors and five immersion factors. The three presence factors were:

- Spatial presence, the sense of being in the space of the VE;
- Involvement, the subjective experiences of awareness and attention processes;
- Realness, the sense of realness due to the VE.

The five immersion factors related to user interaction with the VEs or the sensory technologies of the VE were (Schubert et al., 1999):

- Quality of immersion, how rich and consistent was the multi-sensory output that was delivered;

- Drama, the extent to which the VE presented a story-line;
- Interface awareness, the distraction from the VE due to the awareness of the interface;
- Exploration of VE, the ability to explore the VE;
- Predictability, the ability to predict and expect future content.

The International Test Commission-Sense Of Presence Inventory (ITC-SOPI) questionnaire attempts to measure presence across a variety of media, such as film, video and computer games (Lessiter et al., 2001). 44 out of 63 original questions in ITC-SOPI were retained based on a factor analysis with over 600 participants. These factors were:

- Sense of physical space, including items such as the sense of location in the environment, the feeling of visiting the displayed scene;
- Engagement, with items such as sense of involvement, intensive user experience;
- Ecological Validity, with items such as the naturalness of the scene, the believability of the displayed environment;
- Negative Effects, including items such as nausea, dizziness, headaches.

The questionnaire developed by Slater, Usoh and Steed comprise seven 7-point ordinal scale questions that can be divided into three themes (Usoh et al., 2000):

- The sense of being there;
- The extent to which the VE constitutes "reality" for the participants;
- The extent to which the VE seems more like a "place".

These themes were summarised from the study's conclusions on the factors of presence and were all firmly associated with the results of presence. The Slater-Usoh-Steed questionnaire has already been used frequently in presence research, as it is quicker and easier to use when compared to other questionnaires (e.g. Bouchard et al., 2008; Kober et al., 2012).

The Slater-Usoh-Steed questionnaire was chosen for this research (see the experiments reported in Sections 6.3 and 6.4). As reported in Chapter 6, the studies that evaluated the level of presence used within-subject designs, where participants undertook multiple conditions and were asked to complete a presence questionnaire after each condition. Although there were rest times between conditions, a questionnaire that was quick to administer, not too big as to be laborious, would be preferred. In addition, the internal consistency (which is a measure of the consistency of results across items within a test (Henson, 2001)) of the presence questionnaire (i.e. the Slater-Usoh-Steed questionnaire) was excellent in the fidelity study (see Section 6.3.3) and was good in the experiment focusing on the impact of real-world based VE on local participants (see Section 6.4.4).

Questionnaires have been demonstrated to be inappropriate for some conditions. The research conducted by Usoh et al. (2000), for example, suggested that presence questionnaires may only be effective when comparing the same type of virtual environment. This research used the Slater-Usoh-Steed questionnaire during a between-subjects experiment. The participants were divided into two groups with same sample size (n = 10), and each group completed a simple task in one of the two conditions - virtual office and real office. After the test, every participant was asked to complete the Slater-Usoh-Steed questionnaire (i.e. complete the Slater-Usoh-Steed questionnaire twice). No significant main difference in reported presence was found between the real and virtual condition. Usoh et al. (2000) then suggested that such a questionnaire may be useful when the participants were exposed to the same type of environment (e.g. two virtual scenes). However, its utility was doubtful for the comparison of presence across environments (e.g. virtual environment compared to real-world environment).

2.6.2.2 Objective Measurement of Presence

One objective approach for evaluating presence is behavioural measurement. Here, presence is defined as a phenomenon such that participants within a VE perform as if they were located within a corresponding physical world (Slater et al., 2009b). Freeman et al. (2000) compared behavioural measures of postural responses to motion-based video (i.e. a video sequence captured from a running vehicle) between different display interfaces. The results showed greater postural responses to stereo (3D) display technologies than monocular (2D) displays.

A specialised behavioural method of evaluating presence exploits the use of physiological measures and techniques. Some previous studies have used metrics such as skin conductance ("galvanic skin response" or "electro-dermal activity") and heart rate (Macedonio et al., 2007) to measure presence in VEs, and showed a strong positive correlation between heart rate variability and presence (Meehan et al., 2002; Antley & Slater, 2011; Fröhlich & Wachsmuth, 2013). In addition to the common physiological measures, neuro-imaging techniques have been employed for the evaluation of presence in VEs, such as Functional Magnetic Resonance Imaging (fMRI), Transcranial Doppler (TCD) and Electroencephalography (EEG) (IJsselsteijn, 2002; Baumgartner et al., 2006; Alcañiz et al., 2009). In recent research, EEG capture of insula activation (the insula being a small brain structure associated with the generation of subjective, emotional feelings associated with, amongst other factors, decision making), associated with presence, was collected in a between-subjects experiment (Clemente et al., 2014). Participants were divided into two equal-sized groups (n = 10). Each group had three levels of navigation control (i.e. static images, videos, full interaction) in a VE. Results showed that the interactive condition was accompanied by higher insula activation for Alpha and Theta bands than other conditions with no controls.

However, the use of physiological measures is only credible for the VEs that can deliver adequate stimuli to activate observable physiological responses (Meehan et al., 2002). Physiological responses are less obvious if the VEs are not stimulating, stressful, or thought-provoking enough, such as a simple virtual room with normal chairs and tables.

2.7 Usability in VR Systems

ISO 9241 Part 11 (ISO 9241-11, 1998) defines usability as “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.” As supported by many studies, presence is significantly associated with usability in VEs. (Sylaiou et al., 2010; Chalil Madathil & Greenstein, 2011; Busch et al., 2014). Strictly, the evaluation of presence is, or should be, part of a detailed usability study (Kalawsky, 1999; Hix & Gabbard, 2002). Usability studies set out to evaluate the ease of an application or device and to detect issues that must be solved or avoided to advance the design and functionality of the application or device (Nielsen, 1994). Usability issues of VEs are distinctive to previous studies of conventional human-computer interfaces, including web pages, because of the markedly different types of novel (or “unconventional”) user and system interfaces (e.g. multimedia input/output devices, visual displays, HMDs, gloves, etc.; (Stanney et al., 2003).

As Stanney & Salvendy (1998) suggested, the implementation of (then) present VE systems was restricted by health issues (e.g. incidences of nausea, vomiting, and so on) that may threaten the user's experience (i.e., presence, immersion) and general well-being, both pre- and post- the VE exposure. Previous studies demonstrated that the level of presence rated by the users is part of a strong relationship between the usability of a VE system and users' performance (Fontaine, 1992; Zeltzer, 1992).

2.7.1 Measurements of Usability

Traditional desktop computer system-based usability questionnaires lack the unique features of VE systems, such as navigation within a VE, latency of visual image, field of view, and so on (Shneiderman, 1992) Therefore, a specially designed questionnaire (VRUSE) has been proposed specifically to measure the usability of VR systems (Kalawsky, 1999). 100 five-point Likert scale questions have been divided into ten usability factors of VE systems. Those factors are:

- Functionality, the function delivered by user interface to achieve the goal;
- User input, the naturalness of the control and interaction offered by the input devices;
- System output, how understandable and clear the displayed information is, and how necessary it is to the application;
- User guidance and help, the possibility of supporting user requests for online help;
- Consistency, the user's experience with a VR system should be consistent;
- Flexibility, the user's interaction with a VR system should be flexible;
- Simulation fidelity, an underlying model or simulation to control the VE is required for an efficient VR system;
- Error correction, error correction should be delivered prior to final modification;

- Immersion/Presence, the user's sense of "being in" or immersed in a VE;
- Overall system usability, the overall extent of the ease of use of the VR system.

When using this questionnaire, the flexible factors listed above can be omitted if they are not appropriate to the evaluation context. VRUSE has been widely used for usability studies of VR system for rehabilitation. For example, Fitzgerald et al. (2008) used an abridged version of VRUSE for the evaluation of a therapeutic exercise training and monitoring programme called E-Motion. Three sections (functionality; user guidance and help; flexibility) were removed. This study suggested that the results of the usability study could provide both a systematic and a complete evaluation of the VR system.

Another line of usability research has developed a methodical software tool known as the Multi-criteria Assessment of Usability for Virtual Environments (MAUVE) system (shown in Figure 2.2). This system toolkit has not been released by the authors, however it offers a structured comprehensive method for realising usability in VE system design and evaluation (Stanney et al., 2003).

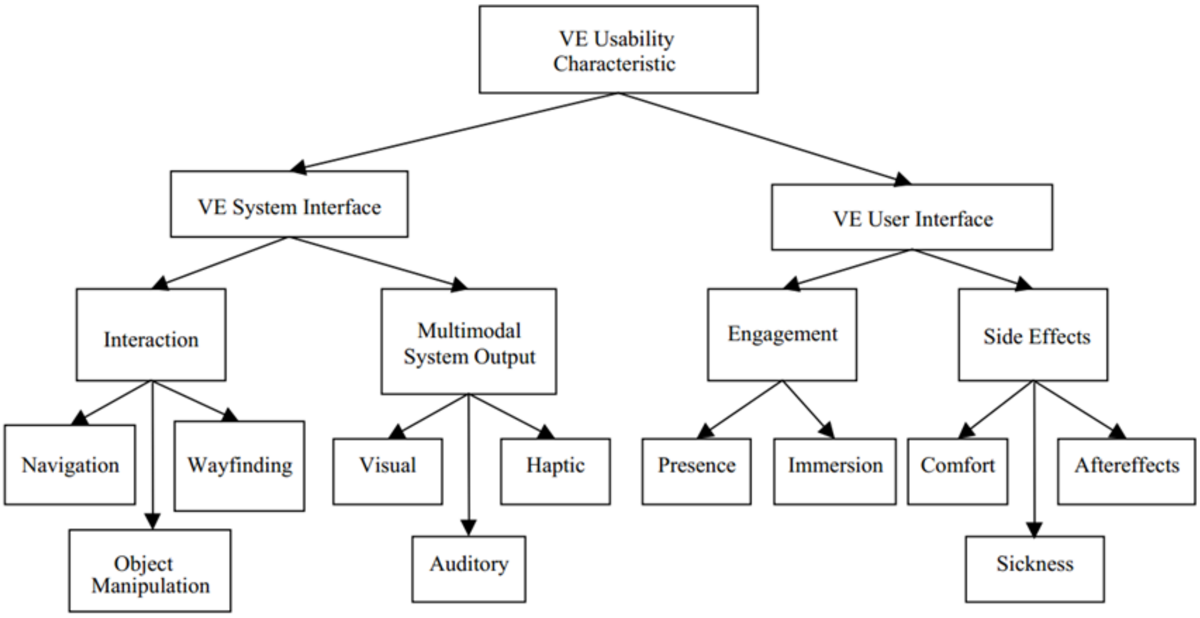

Figure 2.2 A Usability Criteria Assessed by MAUVE (Stanney et al., 2003)

2.8 Conclusion

The use of VR and simulation for a range of psychological treatments have been demonstrated to good effect since early, primitive and expensive VR technologies were first applied to this domain in the 1990s. However, although VR treatments of, for example, PTSD have met with different levels of success, some psychologists argue that there are some major human factors issues with the delivery technologies, such as heavy, low-resolution, narrow field-of-view HMDs, cumbersome and unreliable user input devices that do not support intuitive human movements or gesture, and so-called large-scale VR "immersive" technologies, such as CAVEs, which are argued to suffer from significant issues of cost, poor reliability and usability (Stone, 2008; Stone, 2012). In addition, the development of key events within a VR therapy, based on the sensory and psychological factors which are expected to trigger a user's unique and very personal response to a traumatic event, it is argued, can be extremely time-consuming and expensive. Finally, with today's VR technological capabilities, recreating the traumatic experience accurately to an appropriate level of fidelity, again for the individual concerned, is almost impossible.

The present research has, therefore, adopted an early focus on the exploitation of VR, not for triggering traumatic events, but as a more generic form of simulation-based therapy that may offer great potential in less dramatic, but equally important psychological and physical rehabilitation healthcare applications. Previous studies suggest that exposure to natural restorative environments (REs) can restore the attentional capacity and cognitive functions of humans following mental activities and fatigue. However, taking this research into the domain of VR and Virtual Restorative Environments (VREs), only a very limited number of relevant research studies were discovered. Indeed, only a small handful of studies were found to report that virtual natural environments *may* possess restorative qualities.

A survey of VR software and hardware technologies has been conducted to determine some early system requirements for the VEs developed during the present research. Games engines that are widely used for creating so-called “serious games” have been carefully examined. The Unity3D engine has been chosen for the present study for a number of reasons, in comparison to its competitors in the VR game engine market. Unity supports all of the high-fidelity standards and latest computer graphics technologies. In addition, it has the ability to import most popular formats of 3D assets. Unity also has a vast and fast-growing community. Finally, it supports multiplatform publishing.

Both 3DS MAX and Google SketchUp have been chosen as the modelling toolkits for the present research, as they are supported by Unity. In addition, these two 3D modelling packages together provide a much wider support of 3D assets which can be reused with various degrees of modification. For desktop image processing and 2D artwork, Adobe Photoshop has been chosen, as it is one of the dominant products in the field of texture generation for VR and simulation.

Hardware technologies including input devices, visual and olfactory displays have been briefly reviewed as part of the early design decision process for the multisensory VR systems to be described later in this thesis.

Presence is the subjective response to a VR system, and is the measurement of a user's experience and of the fidelity of VEs. The factors that contribute to presence have been discussed, including visual display, visual realism, sound effects, the interaction between the user and the VR application and the incidence of side effects. Methods for both subjective and objective measurements of presence have been reviewed. The Slater-Usoh-Steed questionnaire has been selected for this research (see the experiments reported in Sections 6.3 and 6.4), as it is quicker and easier to use and has been shown to possess good internal consistency (see Sections 6.3.3 and 6.4.4).

The study of usability is an important part of the overall VR system design. The VRUSE questionnaire has been chosen to evaluate the usability of input device and display of the VR systems developed in the present research (see the usability study reported in Section 6.2), as it is a complete, systematic and flexible measure, specifically designed for VR systems.

Chapter 3 Early Investigations: Development of Interactive Virtual Environments

3.1 Introduction

In the previous chapters, the restorative effects of natural environments have been confirmed and the concept of Virtual Restorative Environments has been proposed. Therefore, in order to prove such theory and to support the early pilot studies of evaluation of different design aspects of the VEs, the early studies addressed the possibility and appropriateness of using the latest Virtual Reality technologies for the development of virtual restorative environments.

In this chapter, the early development of two virtual environments is described. These two virtual settings are a large-scale virtual coastal environment (referred to as "Virtual Wembury") and a smaller-scale urban enclave (the reason for choosing Wembury will be described in Section 3.2). In Section 3.2, a general design workflow of Virtual Wembury is presented. From Section 3.3 to 3.7, the fundamental design aspects of a virtual environment have been described in detail: virtual reconstruction of Wembury terrain, 3D modelling and texturing, lighting, sound effects and navigation. Section 3.8 reports the development of the virtual town scene.

3.2 An Overview of the Early Development of Virtual Wembury

Virtual Wembury, was the first selected “blue-green” environment to be recreated using 3D computer generated techniques. Further to the discussion of real-world and virtual natural restorative environments covered in Sections 2.2 and 2.3.3, it has also been suggested that the presence of water features in rural and urban scenarios (i.e. the presence of visible amounts of standing or running water that may dominate, or be a secondary feature within a scene) may further improve mental health and well-being (Depledge & Bird, 2009; White et al., 2010). UK health-and-the-environment initiatives such as the Green Gyms and, more recently the Blue Gym, are based on the premise that exposure to woodland and coastal habitats offer natural health-enhancing benefits (Depledge & Bird, 2009). Research studies have investigated the evidence for the fact that the Green and Blue Gym concepts are attracting considerable attention from the healthcare domain, in relation to post-trauma rehabilitation and recovery. Using a “preference satisfaction approach”, at a more basic level, Luttik (2000) and Lange & Schaeffer (2001), showed that those engaging in house purchase and hotel room selection were more likely to pay premium rates (on average 10% more) for views involving water. However, Ulrich et al. (1991), using a range of psychophysiological measures (including blood pressure and skin conductance) with 20 participants exposed to a stressful video, found no significant difference in subsequent responses to rural videos featuring predominantly vegetation or predominantly water. A more recent study by White et al. (2010) discovered a more positive effect. Using 120 photographs of natural and built scenes, where proportions of “blue”/“green”/urban environments in each scene were controlled, White et al. conducted two studies in which well-being was rated in terms of stated-preferences (attractiveness, willingness to visit and pay for a hotel room) and subjective reactions. Both natural and urban scenes containing water were associated with higher well-being than those without water on all measures, with the effect sizes remaining consistently large. Urban environments containing water were rated just as positively as green spaces on three of out of four of measures.

The early development of Virtual Wembury as described in this chapter is a virtual reconstruction of a coastal path, complete with beach and field areas, plus water (i.e. a small brook leading to the open sea), vegetation (e.g. trees, bushes, grass etc.) and buildings (including a representation of St Werburgh's Church).

The Virtual Wembury environment was developed using a range of 3D modelling, image processing and gaming engine software toolkits. The virtual terrain of the environment was based on commercially available Digital Terrain Model (DTM) data. DTM databases typically consist of dense fields of digital elevation points. For the Virtual Wembury terrain, these were provided at an accuracy of 5 metres horizontally and 1 metre resolution for height. The DTM database is barren of any plants, man-made constructions and other non-terrain features, providing designers with a digital height dataset of the plain terrain only. The initial Virtual Wembury DTM terrain data covered an area of approximately $9km^2$, including the area from Heybrook Bay to St Werburgh's church (Figure 3.1).

Figure 3.1 The Real World Area of Virtual Wembury (sourced from google.co.uk/maps)

Once the DTM model was converted into a grey-scale heightmap (which will be described in Section 3.3.1.1), it then was ready to be import into a game engine for further development. For the current study the Unity3D game engine was chosen as discussed in Section 2.6.3. Unity is a multi-platform game development system, including a range of native tools for developing VE applications as mentioned previously, and a powerful rendering engine, delivering users with the capability to explore and interact with 3D scenes in real-time.

The heightmap was then imported into Unity's terrain system (a process described in Section 3.3.1.3) and "painted" with a high-definition texture, which was converted from an aerial photo of 12.5 cm resolution (see Figure 3.2). This textured terrain provided the development of Virtual Wembury with a 3D template which was invaluable in assisting the placement of natural and man-made elements such as trees, grass, the brook, buildings, paths and walls. The models used in this scenario were either sourced from the Web (e.g. Google SketchUp 3D Warehouse, TurboSquid.com), or “built” from scratch using 3D modelling software (e.g. 3DS MAX, Google SketchUp).

Figure 3.2 High Definition Aerial Photograph for Wembury Bay (sourced from Getmapping.co.uk.)

A wide range of photos, videos and sound tracks were also captured from the real-world Wembury environment. Digital photos were firstly used for reference purposes during the 3D structure modelling process. Then, these photos were selected and post-processed in Adobe Photoshop to provide a rich resource of detailed textures for modelling natural and man-made objects. Sound files, recorded during surveys undertaken along the coastal path at Wembury, were evaluated to consider their suitability for the virtual scene. If the ambient noise levels were unacceptable, ready-made sound tracks were acquired from the Web (e.g. 3dmodels-textures.com/Soundfx, freesoundeffects.com). Sounds of birdsong, water, wind and footsteps were then imported into the VE (see Section 3.6), to generate a spatial background sound effect which differs depending on the end user's position within the virtual world. The initial Virtual Wembury environment used a directional daylight system (see Section 3.5) and embedded skybox with high-resolution photo of the sky dome (see Section 3.4.2.3).

As the early version of Virtual Wembury contained a relatively small number of contents, it runs on most mainstream PCs and laptops with graphic cards with DirectX 11 compatibility. A range of control (data input) devices were integrated with the Virtual Wembury system, such as Microsoft's Xbox controller and general gaming joysticks.

3.3 Virtual Reconstruction of Wembury Terrain

In order to accurately and efficiently recreate the digital version of the Wembury landscape, the following workflow was implemented, based on three key steps.

3.3.1 Generating 3D Terrain Mesh of Virtual Wembury

First, a grid of height values of the area was converted to a continuous greyscale heightmap. Second, using image processing software (e.g. Adobe Photoshop), the heightmap was converted into a standard RAW format (as shown in Figure 3.3) which was compatible with most image and landscape editing applications. Finally, the standardised heightmap was imported into landscape editors (e.g. 3DS MAX, Unity3D) and a 3D mesh model of the desired terrain was automatically generated using such data.

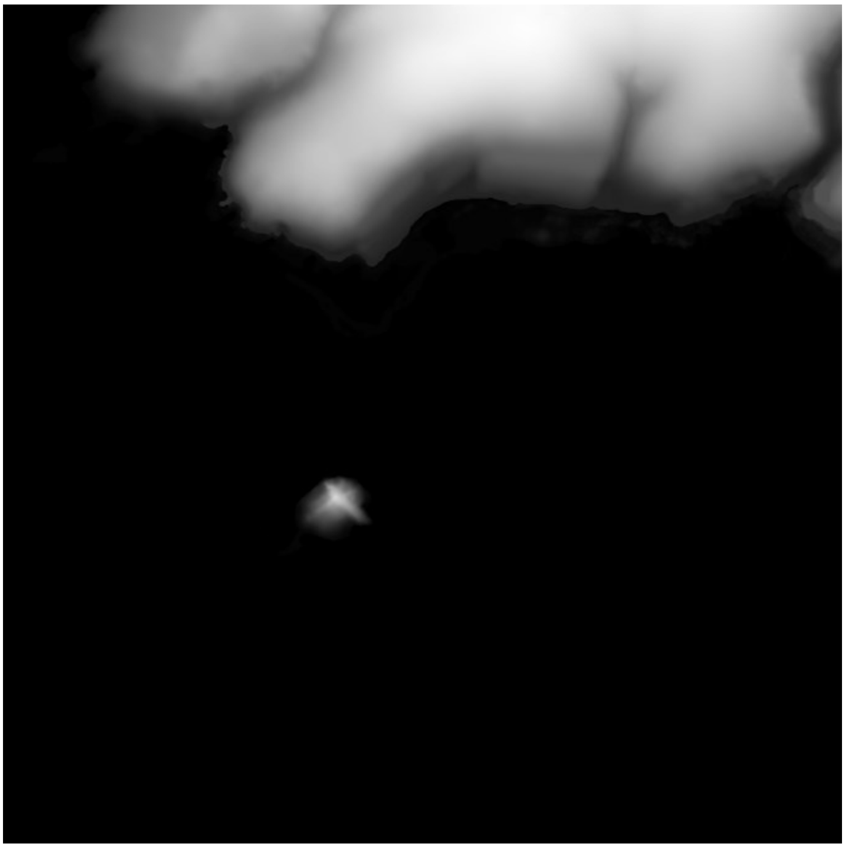

Figure 3.3 Greyscale Digital Heightmap of Virtual Wembury

3.3.1.1 Converting Digital Terrain Data into Greyscale Heightmap

The Digital Terrain Model (DTM) data used for Virtual Wembury is commercially available from Getmapping plc. Undesirable surface features such as structures and vegetation were removed by Getmapping. This process reduced the polygon of the final terrain model, and exposed the true ground level. However, some of the terrain features were not removed by the producer of the DTM data, such as the bodies of water. It was necessary to remove or partially eliminate these features in order to meet the spatial requirement of implementing virtual water simulation. This modification can be achieved in image processing tools as a semi-automatic procedural, which will be described further below.

The DTM dataset consists of two files, a main ASCII text file which contains a set of floating point values of coordinates and height values, and a *.prj file with extra projection information. These two file were imported into the Global Mapper (which is a geographic information system (GIS) software created by Blue Marble Geographics) and converted into a continuous greyscale heightmap resulting in a lossless bitmap image file (BMP). The greyscale has a value range of 0-255, which represents the lowest (i.e. black, value: 0) elevation to the highest (i.e. white, value: 255) of the area.

3.3.1.2 Standardising the Digital Heightmap

The acquired digital heightmap image file was then imported into image post-processing software, such as Adobe Photoshop. There were a series of settings and adjustments needed to be applied in Photoshop, such as image colour mode, resolution, sea-level and format.

The BMP files generated from DTM data in the Global Mapper usually include RGB (red, green, and blue) channels, although such images appear to be greyscale. To eradicate the unnecessary colour information, the colour mode was switched to greyscale in Photoshop.

The resolution of the unmodified heightmap varies depends on the real-world size of the area being modelled. For the heightmap created for Virtual Wembury, the resolution was 3180 × 3180. However, the supported resolutions of standard RAW format by most image and landscape editors are $2^n \times 2^n$ based, such as 256 × 256, 1024 × 1024 to a maximum of 4096 × 4096. To prevent data loss and maximise the detail and fidelity of the landscape, the highest resolution was chosen. The method of image enlargement was a Bicubic smoother which added smoother gradients to the cap between existing pixels during the enlarging process. Such a method prevents sharp edges or needle-shaped landscape artefacts in the final terrain model, which occurs as a result of random greyscales generated in other non-optimised methods.

As described above, the bodies of water (the ocean in this occasion) were not removed in the DTM data. Therefore, the following procedure was applied for lowering the "sea-level" of the heightmap. Firstly, the area of the land above the sea-level was selected on the heightmap. Secondly, the image greyscale output level of this selection was increased (see Figure 3.4), so that the area of the land above the sea-level had a higher output value towards 255 (i.e. white). The result of such process was that the area of the land above sea level were lifted in the final terrain model.

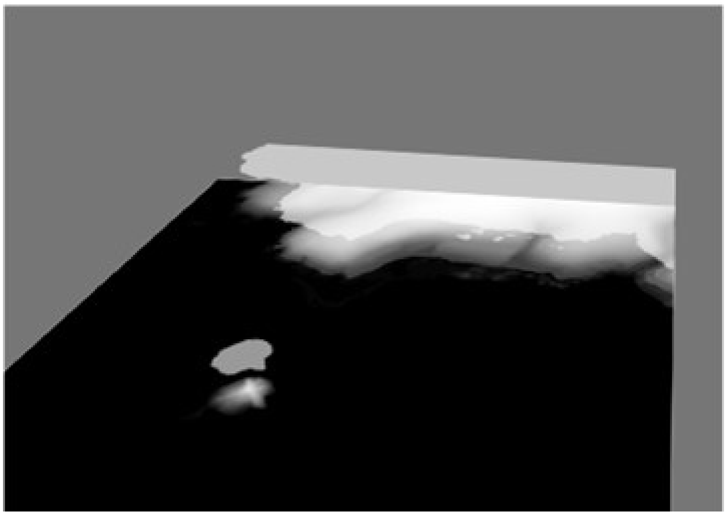

Figure 3.4 Image Processing of the Heightmap for Removing the Sea Surface

The processed image was saved as a standard 16-bit greyscale RAW format in 4096 × 4096 resolution which was ready to be imported to landscape editors or real-time rendering engines (e.g. 3DS MAX and Unity3D).

3.3.1.3 Generating 3D Terrain Model of Virtual Wembury in Landscape Editors

There are two methods of generating the 3D terrain meshes of Virtual Wembury. These are described in detail as follows.

1. Using 3DS MAX for Creating the 3D Terrain Model of Virtual Wembury

This method, as described below, created a 3D landscape mesh in 3DS MAX and was capable of precisely controlling the amount of polygons in terms of virtual environment design and optimisation (see Figure 3.5). There were three main steps for this process. Firstly, a plane was created for the terrain which had a size of 3500 × 3500 and 200 segments of width and length (which defined the number of points that divided the mesh of the plane in its x and y axis; the larger the number was, the more detailed the model would be). Secondly, an embedded Displace Modifier with the processed heightmap image was applied to the plane. The modifier generates the displacement by "pushing" outward the light colours in the heightmap more strongly and further than the darker colour, resulting in 3D displacement of the geometry of the represented landscape. Lastly, the optimisation level of the 3D mesh was adjusted by adding a ProOptimiser (which is an optimisation tool that helps to reduce the number of vertices in an object while preserving the object's appearance) to the displaced plane.

As shown in Figure 3.5, a ProOptimiser with an optimisation level of 10% vertex was applied to the right-hand terrain model in the image, which caused an approximate 18,000 face reduction (out of 20,000). As a result, these two terrain models cannot be distinguished at distance. Therefore, in the current studies, such a method was used for some Wembury-based scenarios, in which the end users did not have a relatively close view of the Wembury terrain (e.g. on a virtual boat in the offshore area close to the small island in Wembury Bay (the Great Mewstone)). Conversely, in most situations where detail at a short range was demanded, the embedded terrain system of Unity3D was employed, as described below.

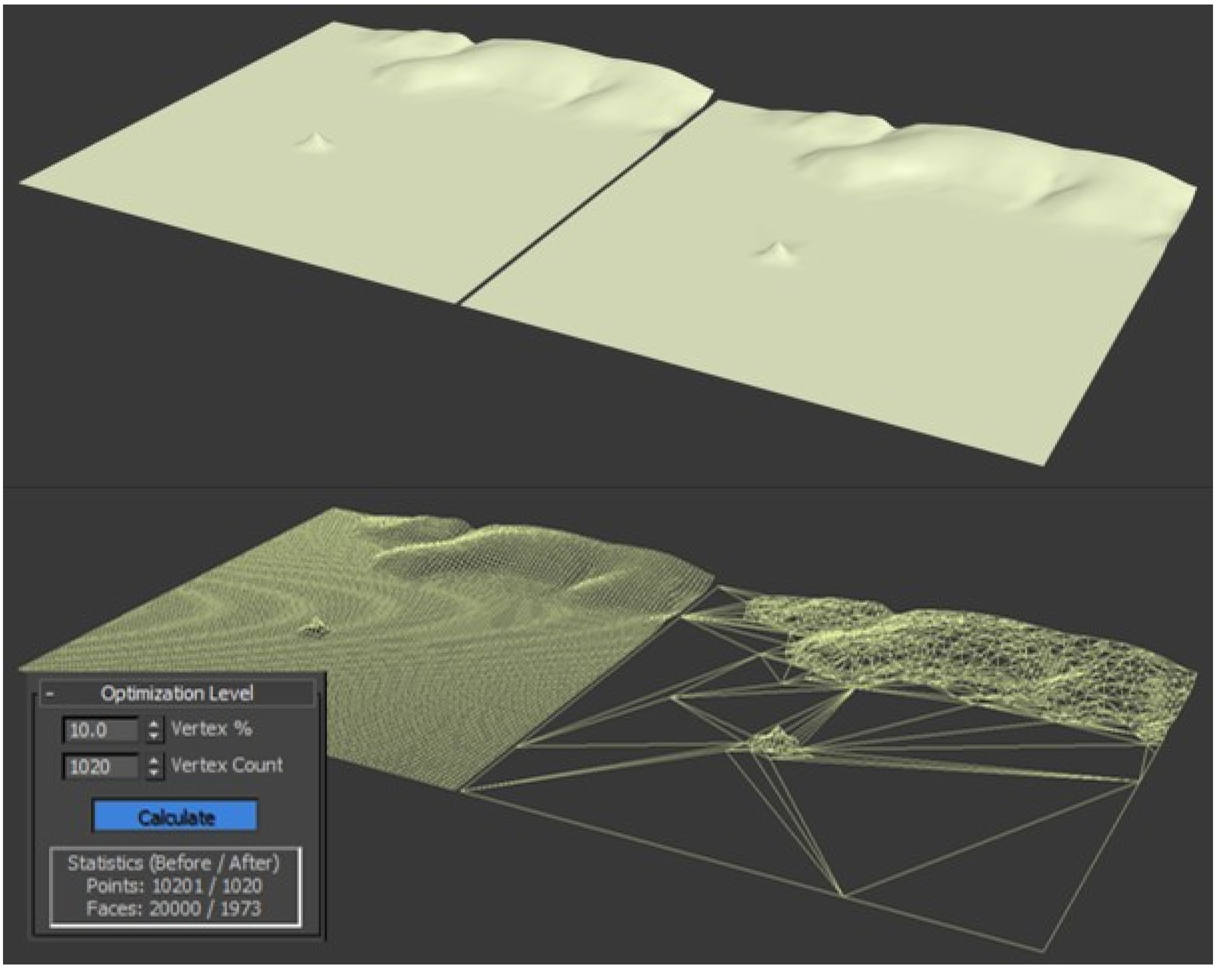

Figure 3.5 Two Digital Terrain Models of Virtual Wembury in Different Optimisation Levels (The terrain models on the right side had a 90% vertex reduction while the left ones did not).

2. Using the terrain system of Unity3D for generating of a detailed terrain of Virtual Wembury

Although the 3DS MAX solution of creation digital terrain is ideal in terms of VE system performance and the optimisation for terrains in the distance, the terrain system provided by Unity3D also has a range of advantages for large scale nature scenes such as Virtual Wembury. For example:

- The terrain system has dedicated height tools (such as heighten/lower, set height and smooth tools) for manual adjustment of the surface of the terrain where necessary.

- There are categorised tools for adding textures, vegetation and other details to the terrain in order to make the terrain creation easy and quick.
- Simulated wind effects are included in the terrain system where trees and grass in "Wind Zones" will bend in a realistic animated fashion.
- At runtime, the terrain rendering is optimised for rendering efficiency while in the editor (Unity3D, 2014).

In order to create such a terrain system for Virtual Wembury, a few steps were implemented with regard to the features of the terrain system as mentioned above. An empty flat terrain was created with a size of 3180 × 3180 (in metres), which matched the real-world size of the chosen area. A maximum height of 160 metres was also set for the terrain system according to the greatest elevation of this area. Then, the heightmap of Wembury was imported to the terrain system. Finally a flat shaded terrain mesh was generated automatically in Unity3D (see Figure 3.6).

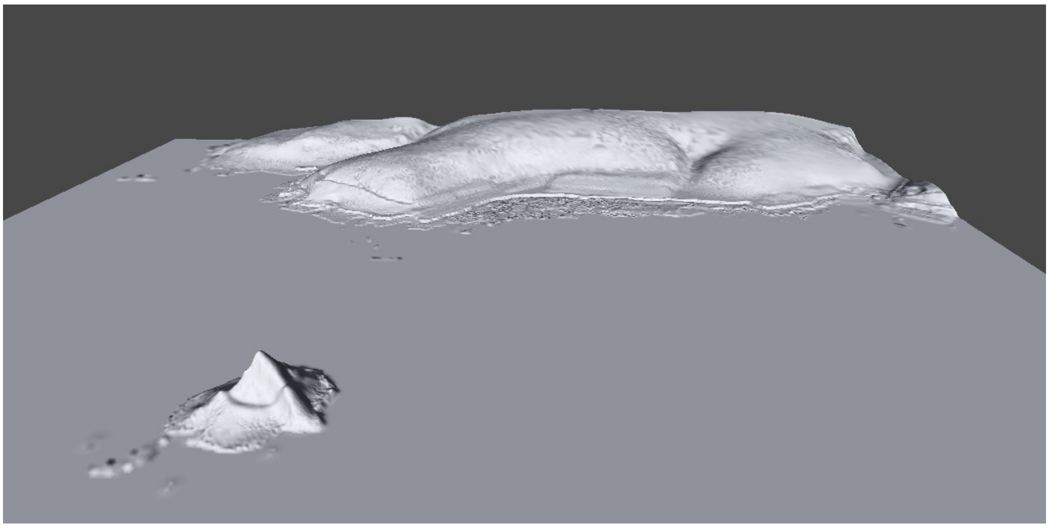

Figure 3.6 A Screenshot of the Terrain 3D Mesh in Unity3D

3.3.2 Terrain Textures of Virtual Wembury

There are two categories of textures in the virtual terrain system of Unit3D. One is the base texture which covers the entire surface of the landscape, also known as the "background" image. The other is actually a selection of textures that can be "painted" onto different areas to simulate different ground conditions (e.g. meadow, rock, sand, path etc.).

For Virtual Wembury, a high definition aerial photograph (as shown in Figure 3.2) was sourced from Getmapping (Getmapping.co,uk) and used as the background image of the main terrain model. The size of the texture was set to 3180 × 3180 which equals the size of the terrain. After the texture mapping process, a virtual terrain model complete with visualised aerial photo texture was completed (Figure 3.7). This initial terrain was acted as a template to assist in the placement of other virtual assets, including 3D vegetation, the brook, rocks and man-made objects.

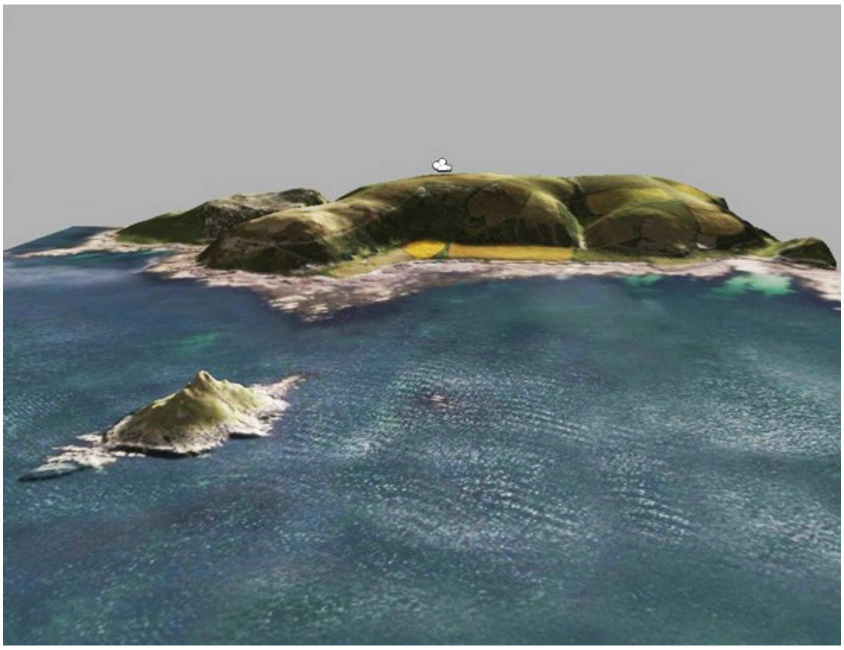

Figure 3.7 A Screenshot of the Virtual Wembury Terrain Textured with High Definition Aerial Photograph

Approximately twenty other textures were selected, most of which were processed from photographs taken *in situ* at Wembury, in order to simulate the original context and achieve higher fidelity and realism (Figure 3.8). An image processing tool (Seamless Texture Generator) was used to make the images seamless and to remove the visually distracting effect caused by repeating textural patterns. These textures were painted onto the terrain using the Unity terrain texture toolkits as a manual process.

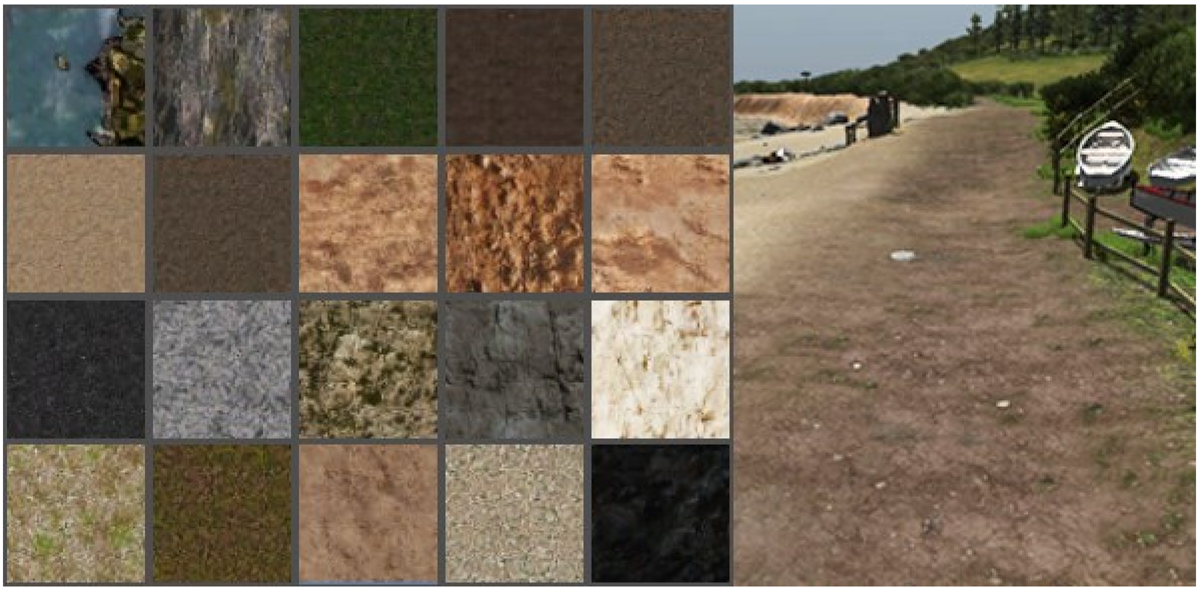

Figure 3.8 Terrain Textures of Virtual Wembury. Right image: A screenshot of the costal path using high definition texture post-processed from photographs of Wembury footpath.

3.3.3 Growing Virtual Vegetation in the Virtual Terrain system

Based on the surveys conducted at the real-world Wembury site and the digital terrain template, a variety of local vegetation types were "planted" onto the landscape. Different species of plants that were identified as specific to West Country coastal environment were created using the embedded tree creator (which allows users to make tree models within the Unity3D editor), such as gorse (Figure 3.9). Three sets of different detail levels of gorse plant were created to represent the diversity of the natural features. Other common European foliage and vegetation such as pine trees, oak trees, ferns and other bushes, grass and flowers were added to the selection as shown in Figure 3.10.

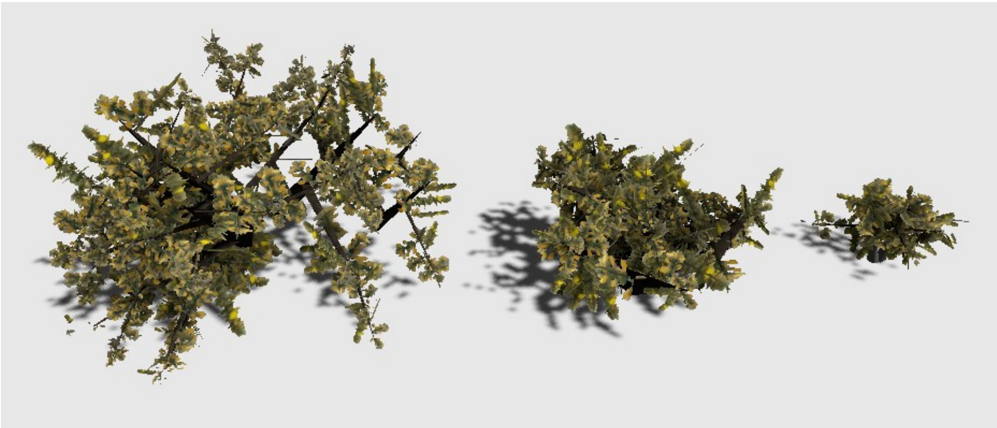

Figure 3.9 A Screenshot of Virtual Gorse in Wembury

Figure 3.10 A Screenshot of Some Examples of the Vegetation Planted in Virtual Wembury

As part of the terrain engine in Unity3D, wind effect moves in pulses to create realistic natural forms of movement amongst the trees. Meanwhile, such trees in wind zones will bend and swing in a natural animated way. Wind zones were defined throughout the extent of Virtual Wembury, in order to provide a realistic differentiation for the strength and patterns of wind. For example, on the lower ground where the vegetation was dense, the wind was set to soft and gentle. On the higher open ground, the strength of the wind was increased and companied by high frequency turbulence, in order to simulate heavy and constant sea breeze near the coastal edge.

3.4 3D Modelling and Texturing Technologies in Reconstruction of VEs

There are a number of man-made structures as well as natural objects in the virtual reconstruction work of Wembury. While some of these can be represented in the virtual world using Web resources, the majority of objects are unique to this area, such as St Werburgh’s Church (Figure 3.11), Wembury Marine Centre, a wooden footbridge (Figure 3.12), and a unique landmark feature which is the boundary of the area that belongs to the National Trust (Figure 3.13).

3.4.1 3D Modelling Procedure for Virtual Natural Environments

The geometric shapes of the models were firstly created in 3D modelling software (e.g. 3DS MAX, Google SketchUp Pro), referring to the photos or videos which were captured during the surveys in local area. Then appropriate textures were generated in Photoshop by using either the photos from local surveys or high-definition, ready-made textures from Web resources.

Figure 3.11 St Werburgh's Church Wembury - Virtual 3D Model versus Real World Photograph.

As shown in Figure 3.12 and Figure 3.13, these post-processed textures were imported into Unity3D and used for 3D materials. These materials consisted of textures and shaders. Shaders are used to produce appropriate levels of colour within a texture, such as simple diffuse shaders, bumped diffuse shaders and bumped specular shaders. Examples of these are described in the following section. In current studies, both bumped diffuse shaders and bumped specular shaders were employed. The former was used for non-reflective surfaces such as wood, or a muddy path. The latter was used for reflective surfaces, such as riverside wet rocks, metals, and so on.

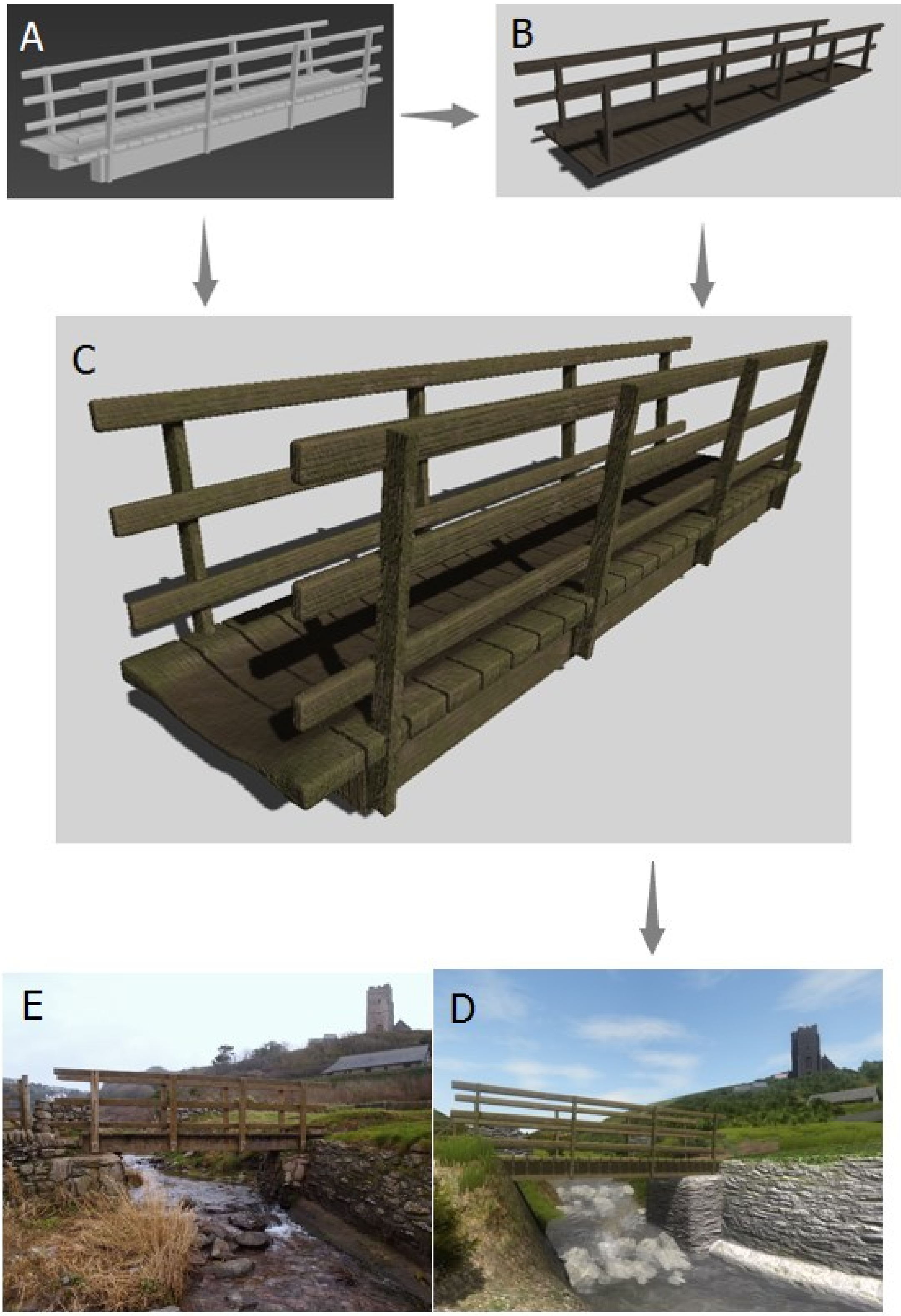

Figure 3.12 The 3D Reconstruction Procedure of a Footbridge in Virtual Wembury. Image A: a shaded model of the footbridge; Image B: an early low-fidelity version of the footbridge; Image C: the latest version of the footbridge with high definition textures; Image D and Image E: Virtual footbridge versus real world footbridge.

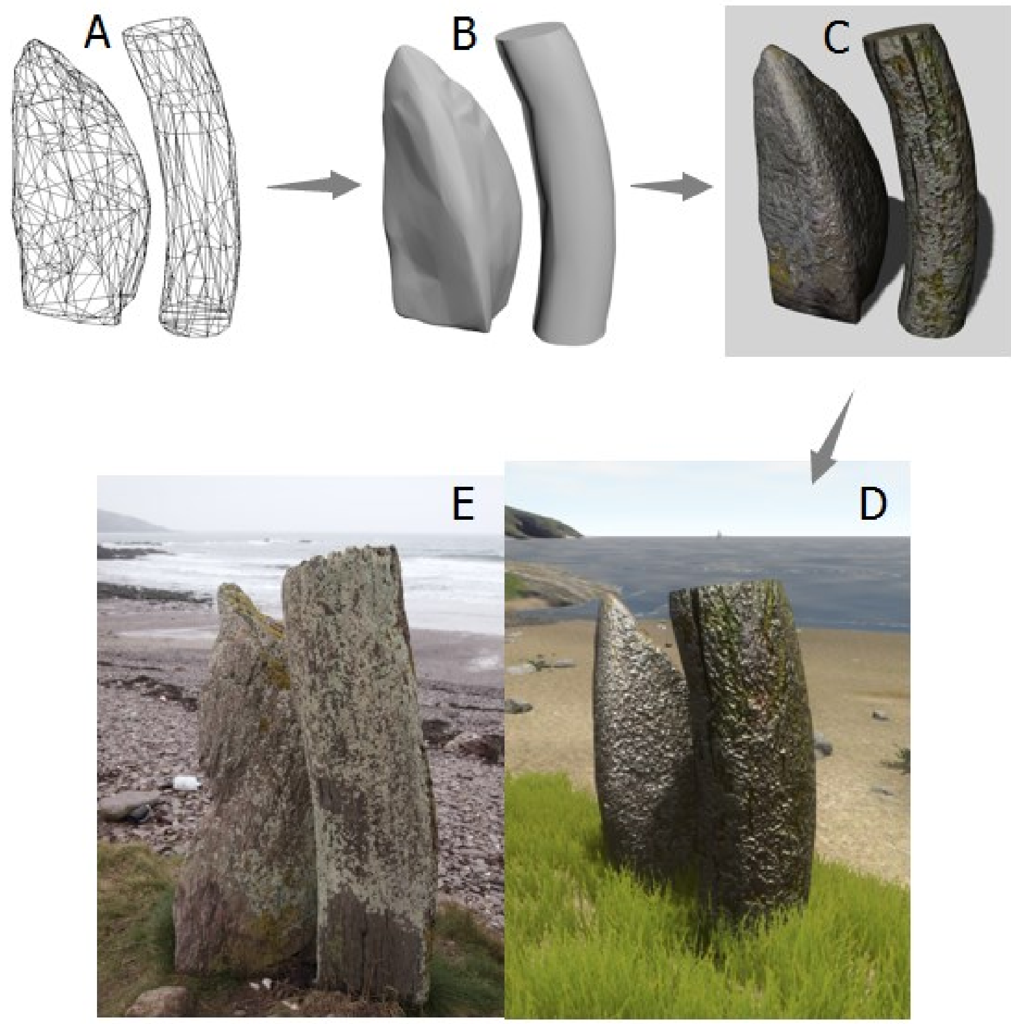

Figure 3.13 The 3D Reconstruction Procedure of a Landmark in Virtual Wembury. Image A: a Wireframe model of the landmark; Image B: a shaded model of the landmark; Image C: the landmark with high definition textures; Image D and Image E: Virtual landmark versus real world.

3.4.2 3D Texture Techniques for Virtual Wembury

In the previous section, a general way of constructing 3D models and texturing was described. However, there were some other techniques and issues adopted during the texturing process, which will be discussed below.

3.4.2.1 Introducing Advanced Texturing Shaders to Virtual Wembury

Texturing Shaders affect the level of lighting and colour of textures. There were a wide range of shaders used in the current version of Virtual Wembury, and included Bumped Specular, Transparent, and Reflective shaders.

Figure 3.14 shows the visual differences between four common used shaders. The shader used in Figure 3.14A is a Diffuse shader, which simply increases/decreases the lighting on the surface as the angle between the surface and/or the light increases or decreases.

The Specular shader (Figure 3.14B) calculates the lighting based on the diffuse shader. In addition, a specular highlight, which depends on the user's viewing (i.e. virtual camera) angle to the surface, is added.

In Figure 3.14C, the Bumped Diffuse shader calculates the lighting strength in the same way as the diffuse shader. Additionally, a special texture (Normal Map) is used to simulate small surface lighting details. This simulation uses the colour value of each pixel on the Normal Map to calculate the lighting of the model. This is actually more efficient in terms of real-time performance than using actual geometry meshes for enhancing details. Therefore, this method has been implemented widely in the current project.

Like a Bumped diffuse shader, the Bumped Specular Shader (see Figure 3.14D) adopts the same technique of computing lighting strength and small surface details. Furthermore, specular highlights have also been added. This shader is generally used for models with smooth and/or reflective surface, such as wet rocks on the beach.

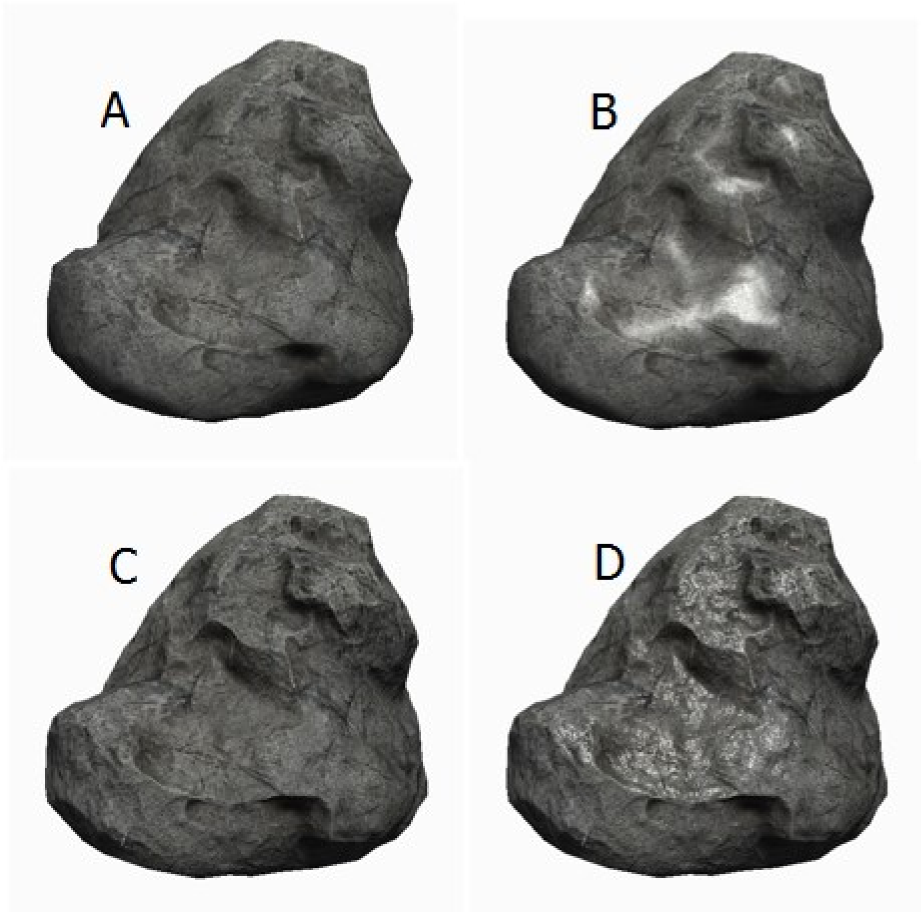

Figure 3.14 Samples of Different Texturing Shaders of a Rock Model. Image A: Diffuse Shader; Image B: Specular Shader; Image C: Bumped Diffuse Shader; Image D: Bumped Specular Shader.

3.4.2.2 Water Shaders for Blue Areas within Virtual Environments

Water shaders are special shaders that combine a number of texturing shader properties, such as specular highlight, bumpiness, transparency, reflection and so on. In Virtual Wembury, there were two types of water shader used to simulate the “blue space” of this restorative environment.

The first was a water shader for the simulation of ocean expanses, as shown in Figure 3.15. Two versions of Unity water (Unity water 3 and 4, which simulates water effects with real-time reflections) were compared (see Figure 3.15). Some positive feedback have been given in terms of virtual water quality by the users of the Virtual Restorative Environment Therapy (VRET) systems (which will be discussed in Section 6.3.4). However, there are still some issues with water shaders. For example, the water shaders adopted in this project had an enormous impact on system performance (i.e. reducing the frame rate by approximately 10 to 20 frames per second), especially for large-scale environments with a high proportion of blue space. Consequently, trade-offs between performance and fidelity had to be made, including having to make compromises with the calculation of ocean waves (i.e. decreasing the polygon of the water mesh), resulting in a flatter appearance of the ocean plane. Alternatively, a displacement map was used in order to offer extra bumpiness to the ocean waves.

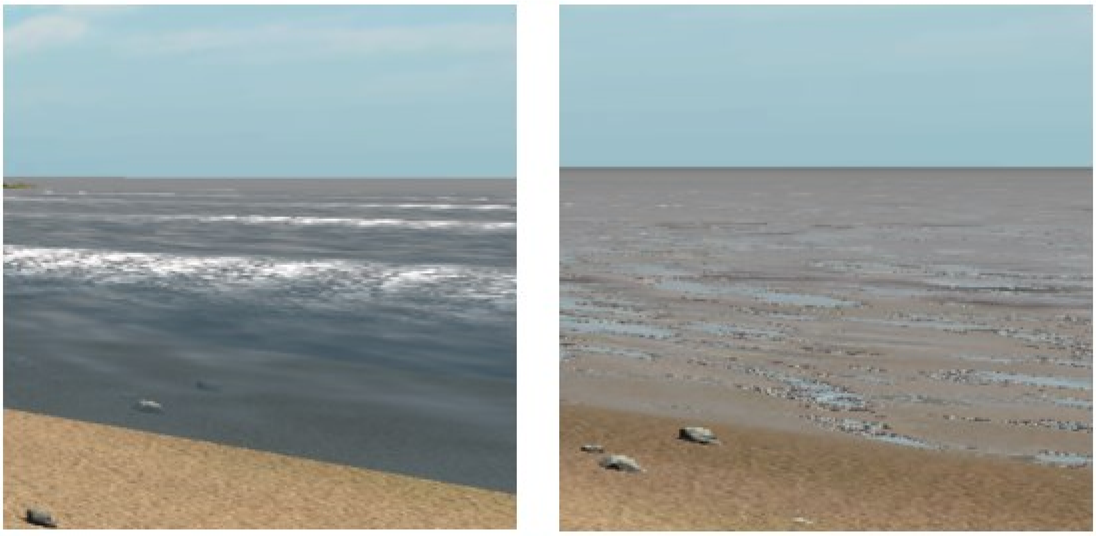

Figure 3.15 Two Versions of Water Shader for Ocean Effects. Left: Unity Water 3; Right: Unity Water 4 (Unity3D, 2014).

The other water shader is used for the brook model in the virtual Wembury beach area (see Figure 3.16). It is a specially modified version of the standard Unity water shader. The normal Unity water shaders do not support the flow of water, such as rivers, waterfalls and brooks. A method that scrolls the water textures along their axes was created for such purpose. The result of this method is a dynamic and realistic water stream effect as shown in Figure 3.16.

Figure 3.16 Screenshots of the Virtual Brook

3.4.2.3 Simulation of Sky in Virtual Wembury

A dark cloudy day is one of the most distinguishing features of the South Devon coastal area, such as Wembury. In order to recreate such scenarios, a standard Unity3D Skybox shader with high definition panoramic photograph texture was employed (Figure 3.17).

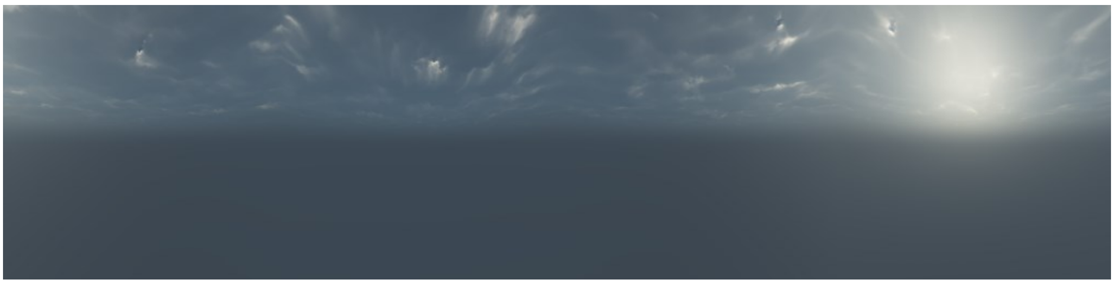

Figure 3.17 A Panorama of Overcast Weather

A Skybox is a cube with six textures attached to each of the internal surfaces. Such seamless textures were generated from a panorama of the sky in image post-processing software (e.g. Photoshop). The images were then imported and allocated into a Unity texture material with a Skybox shader. Finally, this material was rendered at run-time to simulate a realistic sky in virtual scenes, as shown in Figure 3.18. Other skyboxes of different weathers and time of day were also developed (e.g. sunny, sunset).

Figure 3.18 A Screenshot of Virtual Wembury with an Overcast Skybox

3.4.2.4 Solution to an Issue of Transparent Textures

When using transparent materials or standard Unity natural materials, there may be an issue of undesired "white edges", as shown in Figure 3.19B. This is because Unity3D uses a "down-sampling" method to smoothly render the textures. If the edges of the texture have semi-transparent areas and the background colour is very different from the colour of the edge, these different colours will be eventually mixed by down-sampling. As a result of such mixture of colours, a "white edge" issue can occur.

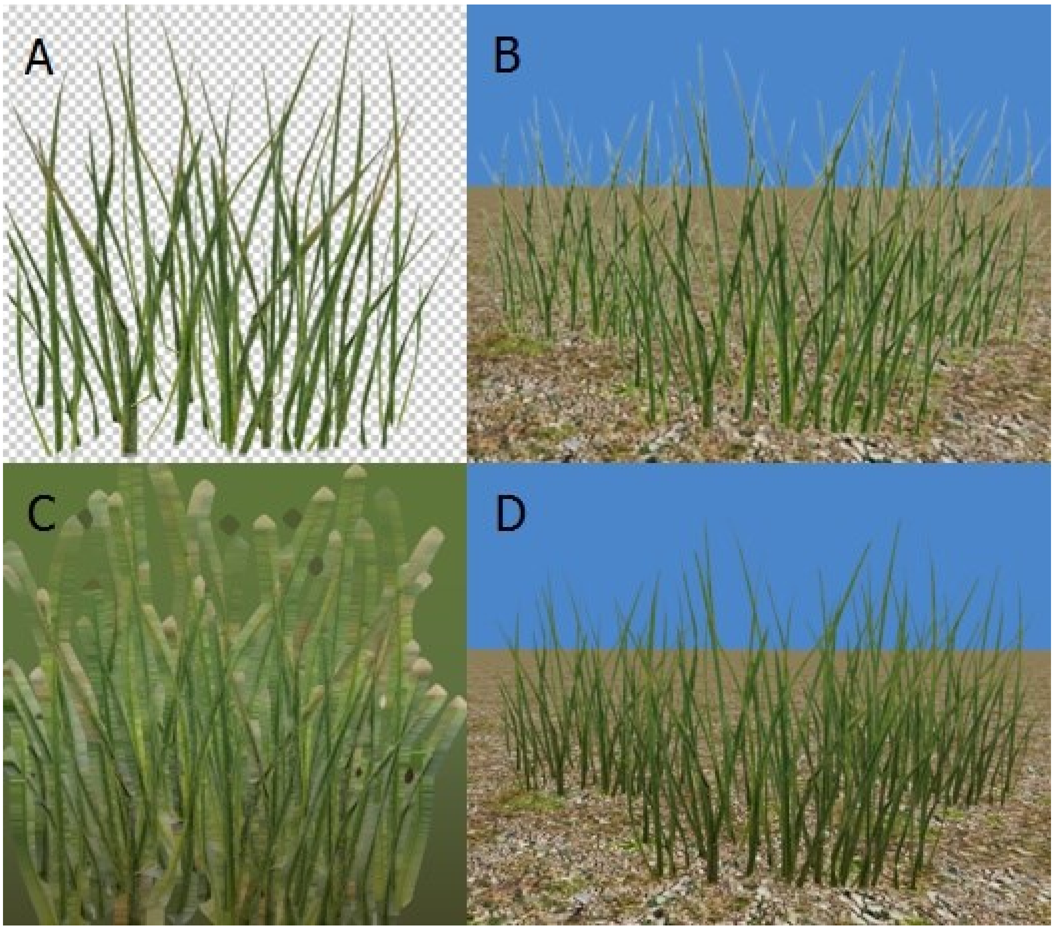

Figure 3.19 A Comparison Between Grass Textures with (image C, D) and without (image A, B) Edge Padding

The solution to this involved dilating the pixels along the edge of textures (i.e. adding an edge padding) in Photoshop to cover the semi-transparent area (Figure 3.19C). Also, a background colour of the median colour of this image was added. As shown in Figure 3.19D, the white edges (Figure 3.19B) was removed by using this method.

3.5 Using Dynamic Lighting Effects in Virtual Scenes

There are several types of lighting used in the Virtual Wembury scenario, including directional lights, global ambient light, spot lights and point lights. Directional lights affect all of the objects in the virtual setting, acting like the sun. It also generates real-time shadows of all visible objects in the scene (see Figure 3.12C and Figure 3.13C). Soft shadows - which simply soften the edge of the shadow - were used for Virtual Wembury instead of hard shadows. In addition, a Unity shadow method called "Shadow Cascades" was used to fade out shadows in terms of distance, giving the shadows extra depth. Together with soft shadow effects, these methods guaranteed a more realistic shadow and lighting effect, especially for long-distance views.

Other lighting effects, such as the global ambient light settings, controlled the overall lighting and tint of the scene. The spot lights and point lights were both used to enhance the lighting at some places which were too dark in comparison to the real world view (e.g. the back of the church and some parts of the coastal path where the light was blocked by the bushes).

3.6 Sound Effects of Virtual Wembury

The sound in Virtual Wembury consisted of two components.

- The sound of the motion accompanying the user's movement through the virtual environment (i.e. the sound of footsteps).
- Soundscapes (e.g. roaring waves, blowing sea-breeze, birdsongs and general coastal ambient noise).

In Virtual Wembury, the walking sound effect is triggered if any movement of the user has been detected. In addition, five slightly different sound tracks of a single footstep play randomly and seamlessly. This method forms a more realistic walking sound with less repeated, and thus, recognisable auditory patterns.

3D sound effects were also used to generate a virtual soundscape map. As shown in Figure 3.20, multiple sound tracks were placed in different locations within the whole virtual scenario. The direction and location of the sound effect can be sensed by users in terms of head pan angle (left and right) and strength of the sound. For example, the volume of the sound of the ocean wave will increase as the user moves closer to the sea. And if the brook is to the left of the user, the running water sound coming from left sound channel will be louder than that from the right sound channel.

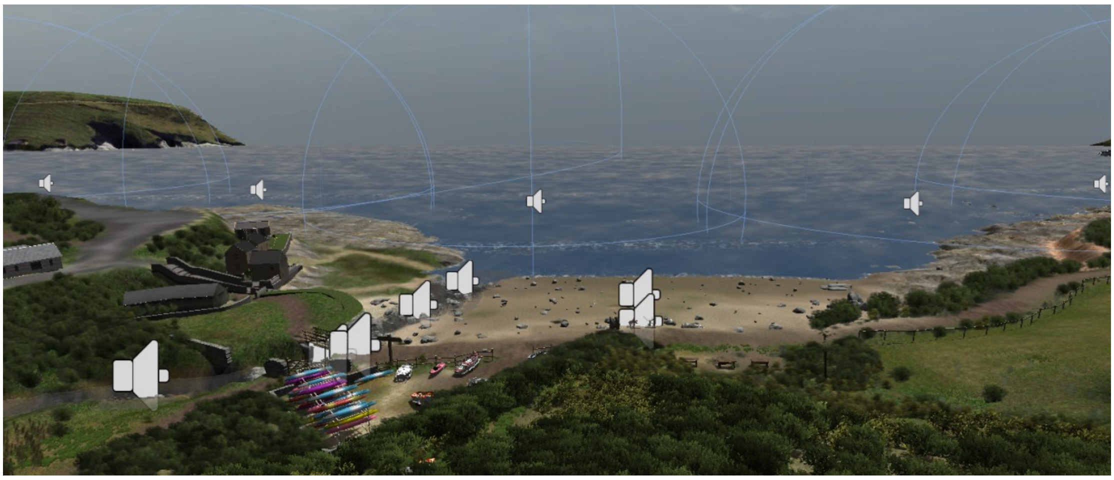

Figure 3.20 A Screenshot of the Sound Sources and their Effective Range in the Wembury Beach Area

3.7 Navigation in Virtual Scenes

In-game movement and control of the character defined the style of virtual navigation. A First Person Character (FPC) controller was used in order to simulate virtual walking experiences. Meanwhile, a method was developed and implemented for easier integration of different commercial off-the-shelf controllers, such as gamepads.

The FPC controller gives a user the ability to move around as well as look freely in the virtual world by using standard input devices (e.g. keyboard and mouse, Microsoft Xbox controller etc.). For example, the FPC detects the keystrokes (e.g. W-A-S-D keyboard inputs) and moves the user avatar forward, backward, left or right. The value alteration of the X and Y axes of the mouse input (i.e. mouse movement) controls the direction of the virtual view.

However, the input devices supported by Unity3D are very limited. Some functions of the desired input devices are not compatible with the Unity3D. A new version of FPC was, therefore, developed, which allows standard keystrokes to control the view angle instead of via the mouse (or the right-hand joystick of the Xbox controller). Together with a key-mapping software (Xpadder), the Virtual Wembury application is compatible with most of the mainstream gaming input devices.

3.8 Construction of a Small Scale Virtual Town Environment

In order to conduct early Pilot Studies (Section 4.2) comparing participants' psychological responses to virtual rural environments, it was decided that a good additional environment for comparison would take the form of a virtual urban scenario. To this end, a small, enclosed 3D townscape was developed.

Figure 3.21A shows the overview of the town model, comprising a rectangular road routing with buildings on both sides. The buildings were downloaded mainly from Google SketchUp Warehouse (where they exist in abundance, negating the need to build the assets from scratch), and included shops, restaurants, gardens, a gas station, car park, and even a train station.

Although the town model is imaginary, most of its components are constructed based on real scenes. Figure 3.21B, for example, shows a church model which was found in the Google SketchUp Warehouse and was developed to represent an actual church in the UK. Many similar 3D assets exist in this form and are often used to bring 3D features to such software packages as *Google Earth*.

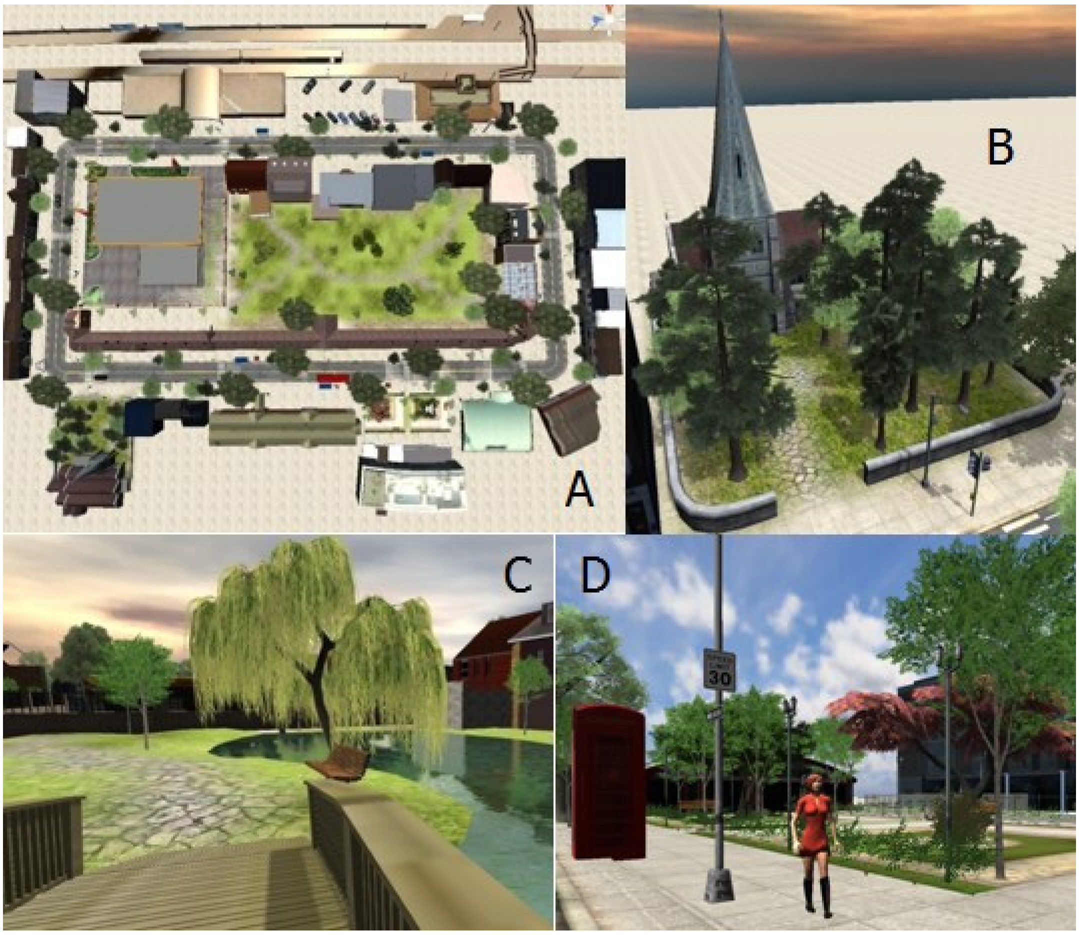

Figure 3.21 Image A: Overview of the Virtual Town Model; Image B: A Church Model; Image C: A Virtual Park with a Pool; Image D: A Pedestrian Walking on a Pavement.

Recent research findings by others indicate that built environments containing green space are rated more positively than those without, and aquatic environments are associated with higher preferences and more positive subjective reactions than both natural and urban settings without water (Sternberg, 2009). For the present research, therefore, the town was endowed with both green and blue features, the latter taking the form of a pond located in a quiet urban park – one view of this park area is shown in Figure 3.21C. Animations were implemented in this project not only for the vehicles but also for the characters (Figure 3.21D) to offer a dynamic scene to the participants. City sound effects were also widely used. Urban ambience with traffic sounds, people talking and walking was set as default audio source. Other sound effects were triggered if the participant entered a certain area. For instance, they could hear birds chirping with the traffic sounds in the background when they stepped into the city park, and they could even hear the church bells when they passed by the front of the church.

3.9 Conclusion

In this chapter, a detailed workflow describing the virtual reconstruction of the Wembury Bay terrain was introduced, including converting digital terrain data into greyscale heightmaps in Global Mapper, standardising digital heightmap in Photoshop and generating a 3D terrain model of Virtual Wembury in the landscape editors (i.e. Unity3D and 3DS MAX). After comparing these two editors, the terrain system in Unity3D was chosen for Virtual Wembury as it provided convenient terrain tools (e.g. height adjusting, textures painting and virtual vegetation planting tools), realistic wind effects and optimised rendering efficiency. A standard procedure for building 3D models with textures in virtual environments has been established. Different texturing shaders were compared to determine the appropriateness of using specific shaders for their corresponding types of surface, including general texturing shaders (e.g. Bumped Defuse and Bumped Specular) and special shaders for water and sky effects. A "white edge" issue for textures has been resolved by using edge padding. Different types of lighting and shadows have been adopted in the Virtual Wembury scene, resulting in a more natural, dynamic and effective lighting effect. 3D spatially distributed sound effects, such as walking and environment-specific soundscapes were added to the coastal scene offering an extra sensory modality for the end user. A modified first person controller was developed for easier integration of different input devices.

The development of a small-scale town environment has also been presented in this chapter. Streets with buildings, traffic, pavement, natural elements, and 3D urban sound effects were included in this scene.

The next chapter evaluates different aspects (e.g. urban and coastal scenes, sound and smell) of the two environments introduced in this chapter, and the results of pilot studies investigating their possible effects on human well-being.

Chapter 4 Pilot Studies: Evaluating Scene, Sound and Smell in Virtual Environments

4.1 Introduction

Early work in the development of Virtual Restorative Environments has been presented in the previous chapter. The present chapter focuses on pilot research investigations, aimed at addressing some of the key sensory issues raised in the literature and how these might be represented in virtual environments targeting human well-being and restoration. Two early pilot studies evaluating different features of VEs - scene, sound and smell - have been discussed in this chapter. Some issues in terms of human factors and usability in VREs have also been addressed.

The review of previous studies based on static images indicates differences of impact on user preference, human health and well-being between natural and urban environments (Kaplan, 2001b; Berto, 2005; Hartig & Staats, 2005; Simonic, 2006; Hartmann & Apaolaza-Ibáñez, 2008; Berman et al., 2008). The first pilot study conducted as part of the present research set out to investigate if such differences could be replicated in a virtual world. In particular, the first study compared Virtual Wembury and a virtual town environment, both developed as described in previous chapter. As previous studies also presented that natural soundscapes had restorative effects (de Kluizenaar et al., 2007; Gidlöf-Gunnarsson & Öhrström, 2007; Fyhri & Klæboe, 2009), this first pilot study also investigated any similar effects related to the background sounds provided in both VEs.

The second pilot study considered the methodological issues during integrating smell or odours into a VE (Virtual Wembury). The results of previous research (as described in Section 4.3.1) have suggested that odours such as essential oils have significant effects on human performance (Gidlöf-Gunnarsson & Öhrström, 2007; Herz, 2007), pain reduction, relaxation (Cooke & Ernst, 2000; Villemure et al., 2003; Lee et al., 2012). In previous studies, olfactory displays were experienced by patients or participants (Herz, 2007; Krijn et al., 2007; Kortum, 2008). However, it may still be worthwhile for a clinical researcher or a designer to be aware when an odour has been sensed by a user. This is useful for future studies with VREs in which more than one odour may be present or when odours may be located in multiple places. Previous studies used physiological measures (e.g. heart rate, skin conductance/electrodermal activity, skin temperature, skin blood flow and respiratory frequency) to examine autonomic nervous system function and arousal to odours, as using subjective measures, such as questionnaires, interviews, or self-reports may cause distraction of attention and affect the level of presence (Alaoui-Ismaili et al., 1997; Robin et al., 1999). Therefore, the second study also sought to examine if such smells would evoke a physiological response that could be detected, logged and measured objectively and inconspicuously in real time.

4.2 Pilot Study 1: Scene and Sound

4.2.1 Background

Restorative environments have been used in the form of static images, such as posters, large-scale photographs, artwork (e.g. murals, frescos, etc.), high definition slide shows of natural environments and "Green" or "Blue" restorative elements in interior design (e.g. forest, lake or ocean settings). A study was conducted to investigate individuals' interests or preferences for nature-related products, and suggested that consumer exposure to photographs of forest, coast and waterfall in green energy product advertising may lead to emotional consumption benefits that were similar to those in "real" nature (e.g. Hartmann & Apaolaza-Ibáñez, 2008). Other studies addressed the restorative effects of windowed views from residences, commercial apartments or hospitals as described in Section 2.2 (e.g. Tennessen & Cimprich, 1995; Kaplan, 2001a). By measuring the rating of participant's preference for use during exposure to a selection of images of natural or urban settings, Simonic (2006) suggested images with green areas such as grass, trees and gardens, or "blue" features such as lakes and coastal areas were more likely to be chosen. Research since the early 2000s has shown that individuals who are shown images or views of REs (e.g. forests, lakesides, costal settings, etc.) are more likely to restore attentional capacity and, hence, increase performance in attention tasks over and above than those involving walking in urban settings which lack of natural elements (Kaplan, 2001b; Berto, 2005; Hartig & Staats, 2005; Berman et al., 2008).

The auditory stimuli of the surroundings can also have impact on human health and well-being. As some studies suggest, many health problems, discomfort and diseases such as irritation, fatigue, headaches and sleep disorders are closely linked to the level of participant's sensitivity to urban traffic noise (de Kluizenaar et al., 2007; Fyhri & Klæboe, 2009). Conversely, other research demonstrates the importance of having the possibility of regular access to nearby green environments within urban settings with positive soundscapes (e.g. birdsong, wind in trees, and sounds from water). Such soundscapes have the ability to arouse pleasant feelings, and thus, may improve the well-being of urban residents (Gidlöf-Gunnarsson & Öhrström, 2007).

4.2.2 Aim

The aim of this first pilot study was to compare the differences of influence on anxiety and relaxation between two VEs – a virtual coastal environment (Virtual Wembury, described earlier) and a smaller-scale urban enclave possessing some natural features (also described earlier and shown in part in Figure 4.1). Additionally, this study also aimed to investigate any potential restorative effects related to the use of realistic background sound in both VEs.

Figure 4.1 A Screenshot of the Virtual Town Environment

4.2.3 Methods

4.2.3.1 Participants

Fourteen undergraduate students and staff at the University of Birmingham participated in the study (12 male, 2 female, mean age = 20, age range: 18 - 34).

4.2.3.2 Conditions

There were two independent variables for the experiment. These were the virtual scene and the presence of sound. The participants were asked to roam around two scenes: an urban city scene and a natural coastal scene. Each scene was presented with two sound conditions. One condition had no sound present, the other included appropriate background sounds (e.g. traffic noises for the urban scene, natural coastal sounds for the coastal scene). Therefore, there were four overall conditions in this study.

4.2.3.3 Procedure

In the city condition, the participants walked along the pavements around the town (see Figure 4.2). Moving traffic was present (e.g. cars and buses), but there were no pedestrians other than the participant. Whilst in the coastal condition, the participants walked along the coastal path within Virtual Wembury as shown in Figure 4.3. Both conditions were hosted on a Dell Alienware Area-51 PC (Intel Core i7-930 processer, ATI Radeon HD 5870 graphics card, 6GB system memory) and displayed on a Viewsonic 28” LCD monitor (1920 x 1080 resolution, 32-Bit colour), displaying scenes that were rendered higher than 30 frames per second.

Figure 4.2 An Overview of the Virtual Town Environment (NB. The red lines indicate the force fields – see text for description.)

During the experiment, the participants sat on a comfortable height-adjustable chair in front of the monitor. A wireless handheld thumbstick controller (Zeemote™ JS1™) was chosen for the participants to "walk" in the VEs for the two pilot studies described in this chapter as opposed to an Xbox controller or keyboard and mouse, as the second pilot study needed one hand free for the pulse oximeter. The participants were directed to simply navigate in the scenes through a first person view. Two maps of the VEs were shown to the participants in order to give them a brief idea of the area and the direction they were following (see both Figure 4.2 and Figure 4.3). In the city condition, they were directed to keep to the pavement areas and walk anti-clockwise from the starting point around the town. In the costal scene, they were requested to follow the coastal path from the starting point to the end. No special task was given to the participants - they were free to stop and look around at any point in the experimental session. Therefore they were not under any pressure of time while exposed to the VEs. Invisible "force fields" were activated in both scenes to keep the participants on the path or pavement and not to venture towards or "off" the limit of each virtual scene.

Figure 4.3 An Overview of Virtual Wembury (NB. The white lines indicate the virtual coastal path.)

At the beginning of each condition with sound, the participants donned wireless on-ear headphones (Sony™ MDR-RF4000K). The sound effects in the town scene included moving traffic, background noise, birdsong in city parks and footsteps of the participant himself/herself. In the coastal scene, sound effects of ocean waves, birds, wind and footsteps were provided.

All of the participants completed all of the four conditions in this study. A Latin-square method was used to control the order of the conditions that each participant followed, in order to minimise any order effects (Kirk, 1982). After familiarising themselves with the controls, the participants were instructed to start, and to stop in 5 minutes. There was a 20-minute break between conditions.

4.2.3.4 Measures

4.2.3.4.1 Anxiety and Relaxation

As described in Section 4.1, previous studies based on static images indicate differences of impact on stress level, human health and the feeling of well-being between natural and urban environments. Therefore, subjective measurements including questionnaires of anxiety and relaxation in 10-point rating scales (see Figure 4.4) were designed to investigate if such differences could be replicated in a virtual world. For a rating of anxiety, the participants rated from "Low" to "High" to the question "How, uneasy, tense, nervous, worried or anxious do you feel anxiety". For a rating of relaxation, the participants rated from "Low" to "High" to the question "How calm and relaxed do you feel?" The measures were administered prior to interacting with the virtual scene and after cessation of each trial.

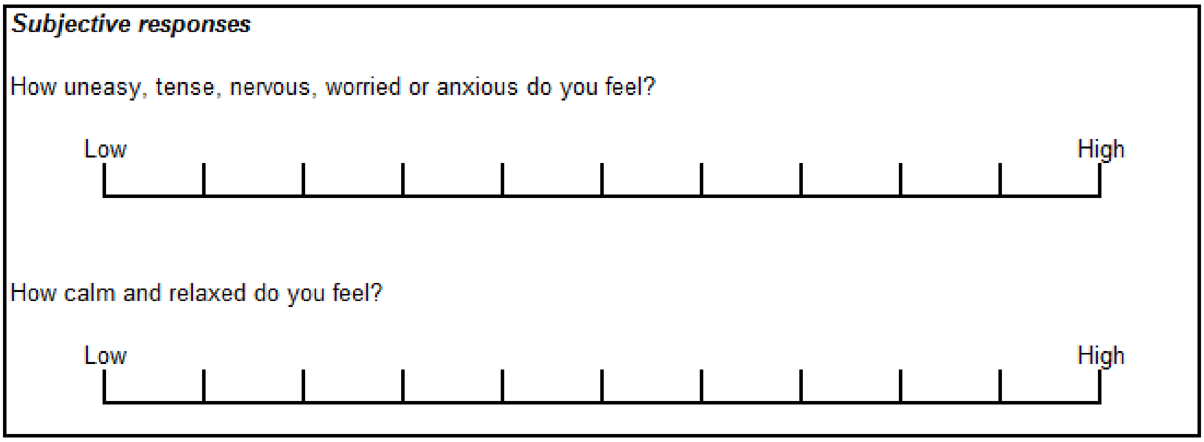

Figure 4.4 Anxiety and Relaxation Questionnaire

4.2.3.4.2 Arousal ratio

Arousal Ratio value has been designed in order to associate anxiety and relaxation ratings. The value is the ratio of the rating of anxiety to relaxation (Anxiety / Relaxation). For example, it would result in a lower arousal ratio, if the rating of anxiety decreases and relaxation increases.

4.2.3.4.3 Usability

After the end of the experiment, each participant was also asked to rate the usability of the ease of navigation and ease of use of the controller. These measures were recorded using 10-point scales rating from "Very difficult" to "Very easy" (see Figure 4.5).

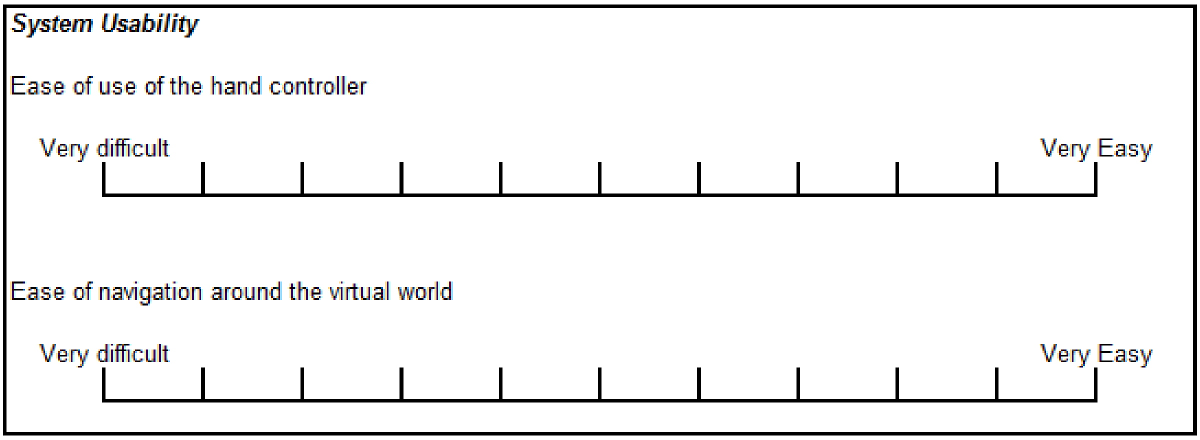

Figure 4.5 Usability Questionnaire

4.2.4 Results

4.2.4.1 Anxiety & Relaxation Ratings

Table 4.1 demonstrates the measures of Anxiety and Relaxation before and after each condition. Total mean Anxiety ratings which were generated by combining pre and post ratings for both sound and no sound conditions for each scene conditions suggested that the Town scene condition was rated higher than the coastal condition (Town = 2.48, *STDEV* (Standard Deviation) = 1.16; Coastal = 2.16, *STDEV* = 1.20). Correspondingly, the relaxation rating of the coastal condition appeared to be greater than the Town condition (Town = 7.95, *STDEV* = 1.01; Coastal

= 8.32, *STDEV* = 1.09). However, Paired-Samples t-Tests showed the differences were not statistically significant (p > 0.05). There was no obvious change to the Anxiety and Relaxation ratings before and after completing the conditions without sound. Conversely, ratings of anxiety increased and relaxation declined in the Town condition; but in the Coastal condition anxiety dropped and relaxation increased in the conditions with sound. Finally, three-way Analysis of Variance (ANOVA) test showed that the changes of ratings related to sound were not significant for anxiety, but they were for relaxation [F (1, 13) = 6.449; p = 0.025].

			Anxiety		Relaxation		Arousal Ratio	
			Mean	*STDEV*	**Mean**	*STDEV*	**Mean**	*STDEV*
Town	**No Sound**	*Pre*	2.50	1.09	7.86	1.79	0.36	0.20
		Post	2.29	1.59	8.07	1.21	0.31	0.24
	Sound	*Pre*	2.21	0.89	8.21	0.80	0.28	0.13
		Post	2.93	2.13	7.64	1.34	0.42	0.32
Coast	**No Sound**	*Pre*	2.21	2.01	8.21	1.63	0.32	0.37
		Post	2.36	1.69	8.29	1.64	0.33	0.30
	Sound	*Pre*	2.29	1.07	7.86	1.51	0.32	0.21
		Post	1.79	0.89	8.93	0.62	0.20	0.11

Table 4.1 Ratings of Anxiety and Relaxation

4.2.4.2 Arousal Ratio

Arousal Ratio values (Anxiety / Relaxation, see Section 4.2.3.4.2) were also shown in Table 4.1 in order to associate anxiety and relaxation ratings. A three-way ANOVA test indicated that the interaction between scene and sound was statistically significant [F (1, 13) = 5.033; p = 0.043]. There was little difference in Arousal ratio between the Town and Coastal conditions when no sound was presented, whereas it was significantly larger in the Town conditions than the Coastal conditions (Figure 4.6). As in the Town conditions, Anxiety rose while Relaxation dropped; whereas in the Coastal conditions the opposite was apparent, Anxiety levels dropped while

Relaxation increased.

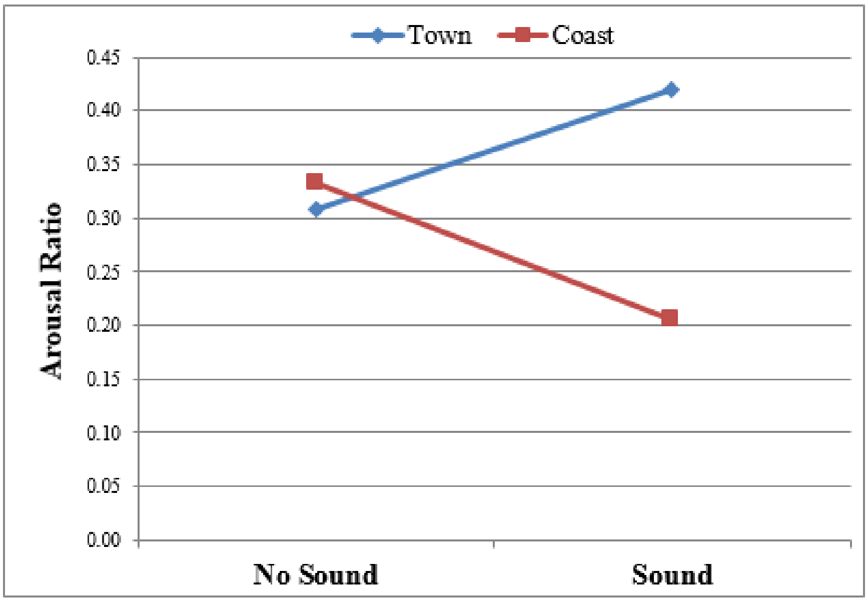

Figure 4.6 Interaction Between Scene (City versus Coast) and Sound on Ratios of Ratings of Anxiety and Relaxation Post Testing

4.2.4.3 Usability Ratings

Usability ratings for the VE system are shown in Table 4.2. The overall rating of ease of navigation in the VEs was 8.34, *STDEV* = 0.75. A two-way ANOVA showed that there were no main effects on ratings of navigation due to the scene or sound ($p > 0.05$). Conversely, a two-way ANOVA revealed a significant main difference due to sound on ratings of usability of the controller [$F (1, 13) = 7.654$; $p = 0.016$], though no difference from scene. The result of these analyses suggests that the presence of sound may reduce the difficulty of using the hand controller in VEs.

		Mean	*STDEV*
Navigation			
Town	**No sound**	8.64	1.08
	Sound	8.00	1.84
Coast	**No sound**	8.21	1.58
	Sound	8.50	1.56
Hand controller			
Town	**No sound**	7.50	2.03
	Sound	8.21	1.58
Coast	**No sound**	7.86	1.92
	Sound	8.64	1.45

Table 4.2 Usability Ratings of VE System

Correlation analysis indicated a significant correlation between scores of ease of use of the hand controller and ease of navigation of the VEs. However this connection was weak [$r = 0.265$; $p = 0.048$]. The analysis also revealed correlation between the usability variables and the ratings of anxiety and relaxation. Negative relationships were found between ease of navigation and ease of use of the hand controller with anxiety [Navigation: $r = -0.390$, $p = 0.003$; and Hand controller: $r = -0.352$, $p = 0.008$]; while positive relationships were showed with relaxation [Navigation: $r = 0.418$, $p = 0.001$; and Hand controller: $r = 0.318$; $p = 0.017$].

4.2.5 Discussion

No significant difference in ratings of anxiety and relaxation post-testing were found in the conditions without sound. This finding does not match with those of previous studies which have reported a difference of those ratings between natural and urban scenes using static images (e.g. Kaplan, 2001b; Berto, 2005). This may because the subjective measurements used in the present study, which only have two scores directly related to anxiety and relaxation on simple scales, were not sufficiently sensitive to determine an effect. Objective measurements of arousal (e.g. heart rate and skin conductance) were adopted in the second pilot study and will be reported later in this thesis (see Section 4.3.3.4). These studies will also attempt to evaluate the restorative effects of VEs directly, by raising the stress levels of the participants in advance of an experimental session as implemented in previous studies (Kaplan & Kaplan, 1989; Kaplan, 1995; Berto, 2005; Berman et al., 2008)

The presence of sound in VEs was accompanied by significant differences in ratings of anxiety and relaxation between the town and coast conditions. When urban sound, such as moving traffic, was included to the virtual town scene, the ratings of anxiety increased while those for relaxation dropped. In contrast, with the sound of the coastal area, such as lapping waves and gentle wind, a reduction of anxiety and an increased rating of relaxation were revealed. These results confirm the findings from previous studies that urban traffic noise increases ratings of self-reported hypertension (de Kluizenaar et al., 2007; Fyhri & Klæboe, 2009) and rural sounds increase those ratings (Gidlöf-Gunnarsson & Öhrström, 2007). Therefore, when compared to the cited sensory stimulation of static images, VEs have an advantage in that they can also deliver dynamic soundscape conditions to accompany already-strong visual scenes, and this feature may enhance restorative effects on observers' feelings of well-being. Additionally, the level of immersion and presence when exposed to the virtual scenes may be boosted by integrating soundscapes, as suggested by previous studies (Serafin & Serafin, 2004).

The "Blue" space or water expanse in the coastal scene may also have therapeutic potential. The research conducted by White et al. (2010) measured ratings of participants' preferences such as attraction and willingness to visit city and rural settings containing an element of water. They showed that water significantly increased the level of positive affect and perceived restoration in both settings.

In terms of usability, adding the sound effects to the scene also played an important role, especially for the ease of use the controller, as revealed by the results. This effect may be that the sound of footsteps and the spatial effects of background sounds during exploration enhanced the participants' sense of motion in the VEs. Recent studies have suggested the audio cues have significant effects on the perception of self-motion and presence in VR applications (Larsson et al., 2004; Nordahl et al., 2010; Nordahl et al., 2011). In particular, when the monitor was displaying a scene of a long-distance view without close-range references or objects (which provide important motion cues such as flow and perceived size changes), the sense of motion delivered from that view was very small. In this case, adding sound to the VEs may offer the participants an additional and strong sense of motion. This may also assist the participant with providing immediate feedback that the 'move-forward' button on the hand controller has been pressed, therefore increasing the ratings of usability.

The ratings of usability were strongly connected with the ratings of arousal. This suggests that usability issues may be one of the aspects that could actually weaken the restorative effect of virtual natural environments. Human ratings of well-being may decline not only as a result of the VE itself, but also because it is difficult - and frustrating - to use the system. Davis (1989) proposed that usability factors (e.g. the ease of use) had a significant impact on the level of acceptance of technologies. It cannot be taken for granted that users will naturally adapt to master the interface components provided with VR applications. Therefore, it is crucial that the usability of those applications – including each display and control interface element - be pre-tested to diminish any negative effects.

4.3 Pilot Study 2: Smell

4.3.1 Background

Previous research results have suggested that odours have significant effects on human performance. Recently, Johnson (2011) reported a series of studies that demonstrated how essential oils and other off-the-shelf odours can affect alertness, expectation, product marketing and memory. Herz (2007) has also demonstrated that odours have a relationship with long-term memory, and a particular scent can stimulate a strong memory recall of a previous experience. Furthermore, Herz believes that the feelings and recalls prompted by odours are unique, and the correlation between "olfaction, emotion and memory makes scent-evoked memories so special".

Other research, in terms of the medical value of odours, has been reported since the late 1990s. In recent studies, evidence has been found that appear to prove the therapeutic effects of aromatherapy (Cooke & Ernst, 2000; Lee et al., 2012), including pain reduction, the lowering of blood pressure, dementia and relaxing muscular pressure and associated stress/fatigue symptoms by using essential oils extracted from vegetation. However, those studies also warned that there were many precautions which indicated that the validation of the therapeutic effectiveness of aromatherapy remained indeterminate. Research studies have also investigated the relation between olfaction and emotion (Alaoui-Ismaili et al., 1997) and the consequent effect which evokes a cognitive reaction such as cues to pain (Villemure et al., 2003) and general anxiety (Robin et al., 1999). Some odours that have the connection with traumatic memories can cause anxiety disorders such as Post Traumatic Stress Disorder flashbacks, and those predominantly psychological disorders are suggested to be treated in systematic desensitisation therapies (Herz, 2007).

Olfactory interfaces are relatively novel devices (Yanagida, 2008). So far, these technologies only capture a small portion of the market share in the VR world, yet there are still specific areas in which olfactory displays are developing quickly. Research conducted by Herz (2007) describes an olfactory device (the "Scent Collar") used by the US military to familiarise soldiers with their future destinations. In addition, other trials report that this technology may still have its own value in certain areas, regardless of the insufficient studies conducted, such as post-traumatic stress disorder, and cue-exposure therapy for drug abuse and anorexia (Krijn et al., 2007).

4.3.2 Aim

This pilot study had two main aims. The first was to investigate the methodological issues of integrating smell into a VE (Virtual Wembury). The second aim was to discover if such smells would evoke a physiological response that could be detected, logged and measured objectively and inconspicuously in real time.

4.3.3 Method

4.3.3.1 Participants

Fourteen (mean age = 19, age range: 18 - 21) male undergraduate students at the University of Birmingham participated in the study.

4.3.3.2 Conditions

The same VE (Virtual Wembury) was used as described in the previous pilot study. The soundscape and sound of footsteps were presented by wireless headphones (Sony^{TM} MDR-RF4000K) in all conditions. During the participants' navigation along the coastal path, there were two conditions of different odours and a control condition in which no odour was released.

4.3.3.3 Procedure

During the exposure to the VE, the participants were instructed to simply navigate from one end of the coastal path to the other, which took about 3 minutes. The participants had no pressure on time usage as they were not given any task during the test.

An olfactory device (ScentScape™ by Scent Sciences Corp) was used to release smells. The ScentScape™ system consisted of a unit that connected to a PC via a USB cable and generated odours using a removable tray of scent cartridges with 20 pre-loaded odours. A "Wizard-of-Oz" protocol (Kelley, 1984) was applied to control the release of the smells. The experimenter manipulated the ScentScape™ user interface (Scent Player) on the PC to generate the odour approximately 90 seconds from the start of virtual walk, once the participant had completed around half of the coastal path. By heating the contents of one of the 20 wells in the cartridge mounted inside the ScentScape™ for 30 seconds, the odour was forced out of the device by a small fan and released to the participants. The exact time that the smell was released and the conditions started and ended were logged, in order to match the physiological measures.

The selection of smells for the study was narrowed by the capacity of the cartridge of the ScentScape™. Each smell in the cartridge could be reused up to approximately five times.

Seven different odours were selected. They were: two odours of the forest (“Damp Forest” and “Balsam Fir”), four odours of the flowers (Floral, Jasmine, Lavender and Lilac) and one odour simulating an electrical component burning smell. Six of these were used to simulate natural aromas. The electrical burning scent was used to simulate a smell that would be inconsistent with the VE, but may prompt a cautionary reaction or response on the part of the participant. The labelling of each smell was provided by the producer of the smell system (i.e. Scent Sciences Corporation). Because the availability of the selected scents was limited, the odour presented to each participant varied. It was controlled so that each participant would complete one condition with a flower-based odour, and then, for the other odour condition, with either burning electrical or one of the woodland scents (as far as they were available to reuse). Eventually, 13 participants finished the experimental sessions; one participant had to be presented with two different flower-based odours. A Latin-square method was use to disrupt the order of the conditions that each participant followed, in order to minimise any order effects (Kirk, 1982).

The participants were informed that an odour *might* be released during the condition. However, for any one of the three conditions, the participants were not aware whether they would be presented with an odour or not, nor were they told what the odours actually were (or were meant to represent). The participants were told not to focus on, or search for a scent, but instead, focus their attention on roaming within the VE.

4.3.3.4 Objective Physiological Measures

Physiological measures (e.g. heart rate, skin conductance/electrodermal activity, skin temperature, skin blood flow and respiratory frequency) were employed in previously reported studies in the literature in order to examine autonomic nervous system function and arousal to odours (Alaoui-Ismaili et al., 1997; Robin et al., 1999). For the present study, physiological measures were also used, specifically, pulse rate and electrodermal activity (EDA). The choices of physiological measures were made based on the availability of devices within the School at the time the research was undertaken.

A pulse oximeter (Contec OLED CMS-50E) worn on the fingertip of the index finger was used to measure the pulse rate. A ThoughtStream galvanic skin response (GSR) device with electrodes strapped across the surface of a palm pad was used to measure EDA. The sample rate of recorded data was 1Hz for pulse rate and 20Hz for EDA. Both the pulse oximeter and the electrodes were attached to the left hand, which was rested on a table so that the forearm was supported horizontally at waist height. Both physiological measures were recorded uninterruptedly during each condition.

Qualitative analysis was employed to investigate whether the data indicated any particular characteristics which may be indicative of a response to the scent. For the pulse rate data, such a response was confirmed as a noticeable variation in pulse rate during the stimulus. For EDA data, a response was identified by a discernible increase in skin conductance response (SCR) of > 0.5μS (Cacioppo et al., 2007).

4.3.3.5 Subjective Measures

After each condition the participants were required to complete a questionnaire. A simple 7-point scale of odour intensity was used to measure the strength of the scent (see Table 4.3). A 9-point Hedonic tone scale (Snaith et al., 1995) was used to measure the pleasantness of the smell as shown in Table 4.4. Additionally, whenever an odour was confirmed, if the measure of

Odour intensity scale scored more than 1 – ‘No odour’, the participant was required to try to match the odour with one of the odours in the list of 20 odours (see Table 4.5) provided.

No odour	Very faint odour	Faint odour	Distinct odour	Strong odour	Very strong odour	Extremely strong odour

Table 4.3 Odour Intensity Scale

Dislike extremely	Dislike very much	Dislike moderately	Dislike slightly	Neither like nor dislike	Like slightly	Like moderately	Like very much	Like extremely

Table 4.4 Hedonic Tone Scale for Odour Pleasantness

Flowers	Geranium	Lavender	Jasmine	Balsam fir
Apple	Roses	Lilac	Pine	Cinnamon
Damp forest	Chocolate	Baked bread	Burning rubber	Dung
Bacon	Burning electrical	Gun smoke	Campfire	Cut grass

Table 4.5 A List of Odours Provided to Participants

4.3.4 Results

4.3.4.1 EDA

An example of skin conductance trace with a discernible SCR is shown in Figure 4.7. The trace demonstrates an obvious surge of conductance when the participant was instructed to start walking. This slowly returned to pre-test resting levels during exposure to the VE. There was a delay on the trace between the triggering of the smell and the second SCR, as it took approximately 10 seconds for the odour to reach the participant. Table 4.6 shows that approximately two-thirds of conditions in which odours were released to the participant evoked SCRs that were discernible with a > 0.5 µS jump in skin conductance after initial perception.

Burning electrical scored the highest ratio of discernible SCRs (5:1). The odours based on natural aromas (forest and flowers) scored an overall ratio of approximately 2:1.

Smell Stimulus		Discernible SCR	
	N	Yes	No
Burning electrical	6	5	1
Balsam fir	5	3	2
Damp forest	2	1	1
Floral	3	2	1
Jasmine	4	2	2
Lavender	3	2	1
Lilac	5	4	1
Total	***28***	***19***	***9***

Table 4.6 The Number of Discernible SCRs for Each Odour

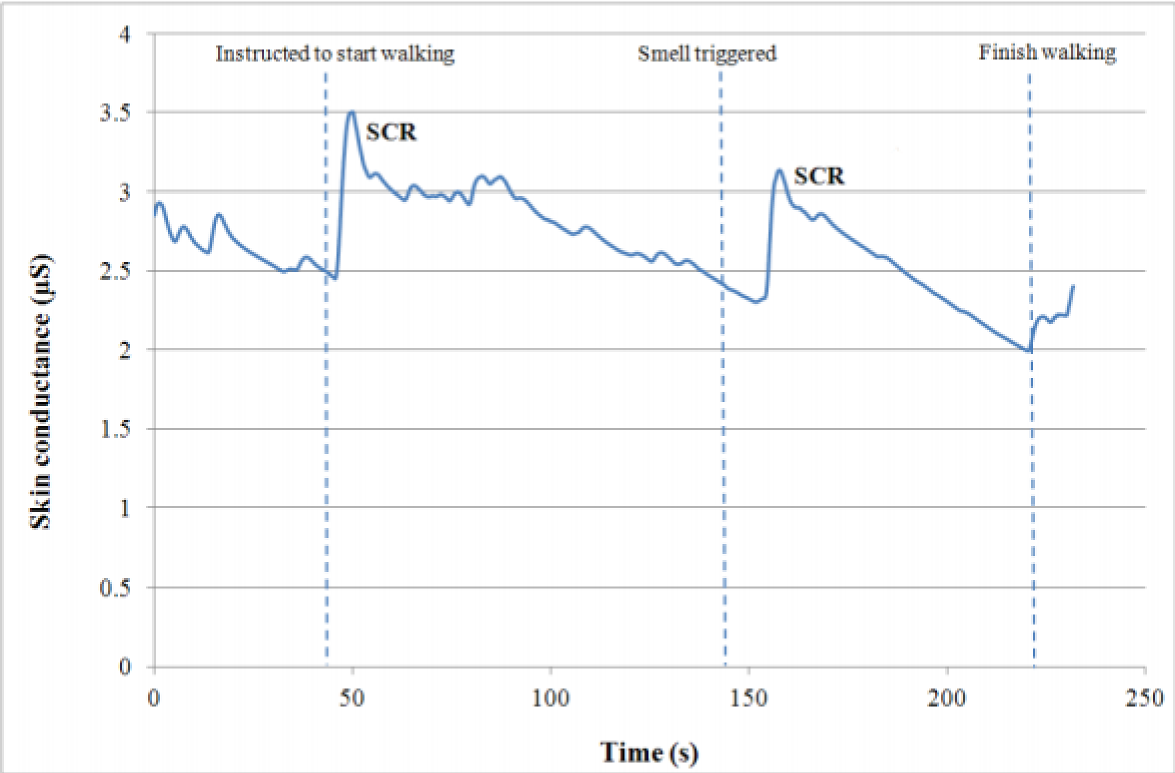

Figure 4.7 Example Trace of Skin Conductance for a Condition with an Odour Presented to the Participant

For all conditions where an odour was released, all participants successfully detected it. Therefore, after each test the rating of intensity and pleasantness section was recorded. Table 4.7 demonstrates the amount of discernible SCRs with respect to the subjective ratings of intensity of the odour presented. For example the table shows that out of the 19 SCRs that were descernible 3 were rated as possessing a "Very faint" intensity.

	Very faint	Faint	Distinct	Strong	Very strong	Extremely strong
Yes	3		2	7	3	4
No		2	2	2	2	1

Table 4.7 Discernible SCRs with respect to Subjective Rating of Intensity of Smell

Table 4.8 displays the amount of SCRs with respect to its pleasantness rating For example the table shows that out of the 19 SCRs that were descernible 1 was rated as possessing being "Disliked very much".

Whether an SCR was determined or not, most of the odour conditions produced subjective intensity ratings at Strong or higher (n=19). In these 19 runs, 14 produced SCRs, which reflects a ratio of just over 3:2. But for the odours that produced intensity ratings at Distinct or lower, the ratio of discernible SCRs was approximately 1:1 (Yes = 5, No = 4). This finding suggests a possible relationship between the production of an SCR and the associated subjective rating of intensity, where higher intensity odours are more likely to produce SCRs.

	Dislike extremely	Dislike very much	Dislike moderately	Dislike slightly	Neither like nor dislike	Like slightly	Like moderately	Like very much	Like extremely
Yes		1	2	3	2	7		4	
No						3	3	3	

Table 4.8 Discernible SCRs with respect to Subjective Rating of Pleasantness of Smell

The data in Table 4.8 also suggests a possible relationship between the subjective rating of pleasantness of the odour and the objective measure of SCRs. However, as most of the odours were rated as being pleasant (i.e. like slightly or higher, n = 20), the ratio of SCRs produced for them was just above 1:1 (Yes = 11, No = 9). In contrast, for odours rated as being unpleasant (Dislike slightly or lower, n = 6), all produced discernible SCRs. This suggests that unpleasant odours are more likely to produce discernible SCRs.

4.3.4.2 Heart Rate

Figure 4.8 shows an example trace of heart rate (HR) data. The graph shows no change in HR due to triggering of te odour. This was typical for all conditions. This result shows that HR response was not affected by the odour released during the study. Therefore, the data were not analysed further.

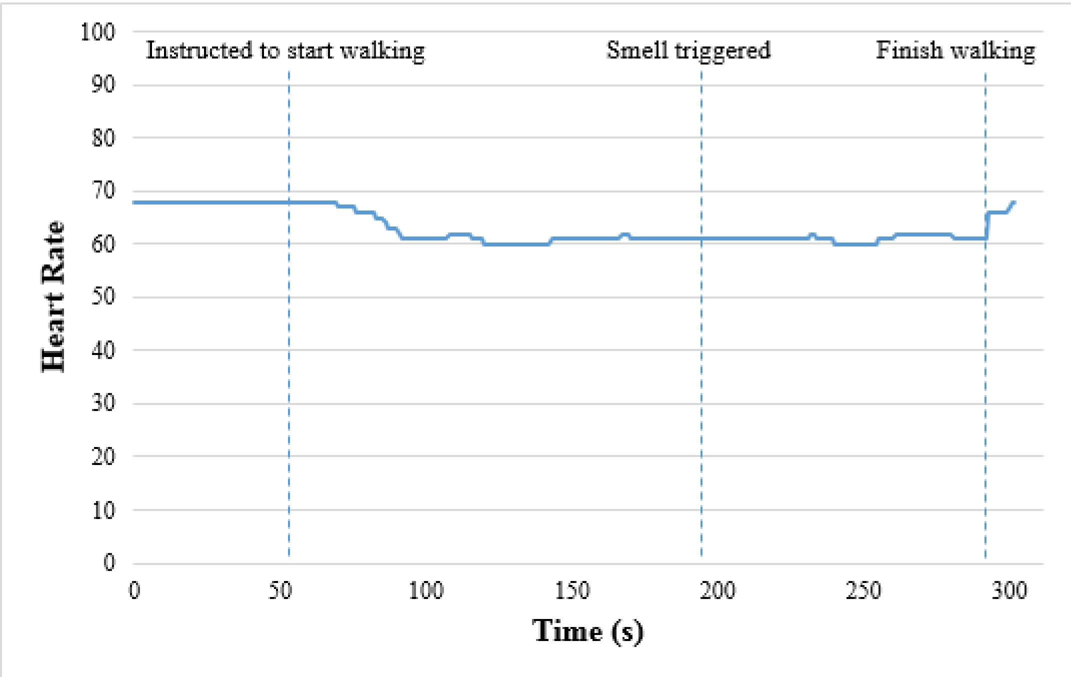

Figure 4.8 Example Trace of Heart Rate for a Condition with an Odour Presented to the Participant

4.3.5 Discussion

The therapeutic value of using odour in VREs still remains indeterminate. However, devices like ScentScape that attempt to produce scents reminiscent of nature must continue to attract interest from the VR community as, suitably developed into a mature display technology, it has the potential to enhance the fidelity of virtual worlds and the sense of presence therein. As mentioned before, the aim of the present study is not to determine the therapeutic ability of odours in VEs. The main aim of this study is to evaluate if the presentation of an odour within a VE can evoke a physiological effect that could be detected objectively and unobtrusively. Therefore, the outcome of this study offers a basis on which future studies would be based.

The results of this study demonstrated that approximately 2/3 of the conditions with odours could be recognised as indicated by the generation of a discernible SCR, while there were no significant changes in pulse rate. Similar results were also shown by the smell study conducted by Robin et al. (1999) that found strong skin conductance responses, but not heart rate responses, to odours. In addition, other researchers have suggested that electrodermal responses declined greatly during testing with VEs, whereas no distinct alteration in heart inter-beat intervals were discovered (Valtchanov et al., 2010). This recommends that, for studies related to VRE, electrodermal response may be more suitable to detecting sensory responses to novel stimuli than heart rate.

The results also show that on most occasions, the EDA measures employed can objectively determine that the participant has sensed the presence of an odour during exposure to a visually dominant VE. This finding may benefit future studies with VREs in which more than one odour may be present or odours may be located in multiple places.

A range of methodological issues were uncovered during this study. Sometimes it was impossible to detect any SCR after the release of an odour because of noise in the EDA data. This, of course, increased the possibility of incorrect alerts. For example, an SCR was detected in the EDA trace during one of the control conditions, but was not associated with the release of any odour. As claimed by Andreassi (2007), EDA can have significant correlations with physical, sensory (e.g. visual, auditory) and emotional stimuli. Consequently, those SCRs detected due to "system noise" may actually be triggered by other stimulus reactions or conditions, such as unfamiliarity with the controller or navigation style, or other external stimuli (i.e. external to the VRE and immediate participant workspace). Therefore it is essential that the experimenter carefully observers the participant throughout the conditions, determining all of the SCRs when they appear, in order to minimise the possibility of such errors.

In the present study, the experimenter controlled the release of the smell using a Wizard-of-Oz protocol which was a manual procedure. Further development of the VE will attempt to integrate some software tool capable of recording the navigational activities of the end users and automatically triggering odours into the VE. Therefore, for example, when a participant steps onto a lawn, the odour of grass will be triggered. In this and other similar examples, the time of triggering will be recorded automatically by the "embedded" software tool and used to "time-stamp" the EDA data. In addition, this tool could be used to assist the evaluation of a user's performance and subjective reports, including usability feedback. For example, during exposure to the VE, some participants stopped to adjust the grip of the hand controller. The duration, location and number of times could be recorded by the software tool for VE system usability study.

An associated issue in the present research was that it was difficult to record the timing of identifying the odour, as the delay between the triggering and an SCR was found to be variable. This issue increased the difficulty of determining whether such delays were caused by the physiological variances between participants or the strength and the spread of the odour.

In addition, there was the important issue of odour removal or dispersal. Previous research reported that it was less difficult to control the conditions with just one or a moderately altering odour in a relatively larger time scale (Yanagida, 2008). However, there are real-world issues involved in eliminating odours from the environment and, in conditions that demand a rapid removal of odours, today's olfactory display technologies fail dramatically.

Another issue related to the validity of the artificial odours. Most of the participants were not able to correctly recognise the odours. They were guessing or roughly categorising the odours as trees, flowers or "air freshener". Improvements have to be implemented by the producer, in order to precisely associate the odour to what they are stated to be. However, this may be an extremely difficult goal to achieve, as it is well known that one culture will label an odour completely different to another (Chrea et al., 2004).

It may also be an issue related to the persistence of the intensity of the odour. In the conditions where the intensity of the odour was rated as strong, SCRs were triggered more frequently. Future work will attempt to classify standards for the odours to guarantee that they are not unreasonably overpowering. Additionally, future work will try to discover the difference between pleasant and unpleasant odours. In the present study, SCRs occurred subsequent to the triggering of an odour that was later rated as unpleasant.

The finding that high intensity and unpleasant odours produce a measurable physiological fight response (in terms of a SCR) may have implications for virtual therapeutic environment applications where such a response may be unwanted. For example, for possible PTSD applications (as discussed in Section 2.3.2) the therapist may wish to increase "presence" by use of smell but not stimulate a physiological response. This supports the findings of Herz (2007) who discovered/suggested that unpleasant odours may trigger a flight-or-fight response, alerting the participants to risks, unpleasant experiences or dangers (e.g. burning, toxic fumes).

Therefore, for the integration of odours into any Therapeutic VE it may be essential to confirm that all odours embedded are *pre-rated* as pleasant, in order to ensure that they do not adversely impact on the VRE's otherwise restorative powers. However, unpleasant odours could be beneficial for desensitising therapies, or for applications where they may be associated with danger (such as the use of burning electrical odours in aircraft or submarine emergency situation simulators, for instance). In the case of desensitising therapies, it has been claimed that slow-release unpleasant odours may assist the recovery of patients presenting with post-traumatic stress disorders (Emmelkamp, 2005).

4.4 Conclusion

The pilot studies described in this chapter are initial surveys using the early versions of restorative VEs, exploiting gaming technologies in a novel application of virtual reality techniques supporting restorative therapy. These studies have built strong foundations on which subsequent research reported in this thesis has been built.

In order to address the advantages of VE's over imagery in the form of static images or videos, it will be necessary to conduct studies that compare the restorative effects of VEs with different media. One of the advantages of using VE over images and videos is that the virtual scenes can be easily operated in real-time and can be manipulated or changed with relative ease and at low cost. For example, the same scene can be effortlessly changed to feature different lighting conditions, different times of the day (e.g. night, midday or dusk) or different weather conditions. The ability to control these settings may deliver valuable understandings of ambient effects on health restoration.

In the first two pilot studies, exposure to the VE was limited to 5 minutes. This was relatively shorter than the 15-to-20-minute periods in other research (Tsunetsugu et al., 2007; Park et al., 2007) which showed an effect with real-world exposure to natural environments. Longer periods of exposure may improve the possibility of achieving more significant restorative effects from the VEs. A recent study presented major responses even after 10 minutes (Valtchanov et al., 2010). An associated issue was that the size of the area for exploration in the VEs was limited. For example, walking from one end of the coastal path to the other only took approximately 3 minutes in the early version of Virtual Wembury. Therefore, an extension of the area of Virtual Wembury is required for further studies.

The study of scene and sound indicated that the participants who found the controller very hard to use also had greater anxiety ratings. Therefore usability factors of the VE can be very important for studies that aim to lower anxiety and improve well-being. Future research will evaluate different controllers for VEs to maximise usability.

The results of the smell study suggested that the presence of smell could be detected and reported by participant, and most of the electrodermal activities due to the existence of olfactory stimuli were discernible in the skin conductance response data. However, a number of methodological issues were discovered, such as the uncontrollable and inconsistent delay between triggering and the detection of smells, the slow removal and dispersal of odours, and mismatch between the odours and their labelling. In addition, the capacity of the cartridge of the ScentScape system is very limited. The replacement of this cartridge is, at the time of writing, inconvenient and expensive (requiring the cartridge to be returned to its US supplier). Therefore, the technology of olfactory displays is still very immature and smell will not be used in the further development of VREs described within this thesis.

Future work will also try to address the therapeutic effects of VRE systems. These systems may be used for patients recovering from traumatic surgery, with associated applications for rehabilitation centres, care homes and housebound individuals.

Chapter 5 Further Development of Virtual Environments

5.1 Introduction

The previous chapters have described the early stages of research focusing on the development of VEs of appropriate fidelity, including visual, auditory and olfactory qualities. Whilst new techniques and resources are continuously being developed and applied to improve (predominantly) visual and auditory fidelity, the present project also exploits the existing virtual environment, by seeking potential features that can be added, thus enhancing the end users' navigational experiences and preserving the longevity of the virtual experience. Such features include time-of-day effects, adding new assets (e.g. vegetation, virtual animals, etc.), developing interactive and more dynamic, motivational activities (e.g. operating a virtual *pedalo*) and offering end users additional interaction methods, including easier selection of viewpoints via single button clicks and the use of non-contact motion sensors such as Microsoft Kinect.

In addition, it became clear from the earlier pilot studies (as discussed in Section 4.3.5) that some form of "embedded" or minimally invasive software tool capable of recording the navigational activities of the end users would also be of significant use, especially if the results of such software could be used – in part – to explain or theorise about the reasons underpinning some of those users' objective performance indicators and subjective reports, including usability feedback. Previous studies have attempted to create various evaluation tools and methods of usability and user experience in VEs (e.g. Mourouzis et al., 2003; Chittaro & Ieronutti, 2004). However, no tools supporting the collection of end user navigation behaviours were discovered, especially for the current real-time software development environment (i.e. Unity3D). To be able to support quantitative and qualitative analyses of usability and user behaviour in the planned VRE related studies, an integrated cross-application user exploration tracking/logging system has been developed and is described in more detail in this chapter. Additionally, to meet other requirements of further studies, such as longer testing periods, a second virtual restorative environment, representing a different geographical location, was implemented. The development of this VRE will be described in Section 5.8.

5.2 Extension of Virtual Wembury

In the pilot studies reported in Chapter 4 of this thesis, the duration of exposure of participants to the VE was restricted to less than 5 minutes, as the coastal path, which the participants were directed to walk from one end to the other, was not long enough. This test time is noticeably shorter than the 15 to 20 minutes that Tsunetsugu et al. (2007) and Park et al. (2007) discovered to have an effect with real-world exposure to natural environments. Longer periods of immersion may, therefore, provide greater opportunity to respond to the restorative environment. Considerable responses were found after 10-minute exposure to VE (Valtchanov et al., 2010). Consequently, an extension of the current VE was completed with the aim of generating longer exposure periods during experiments and subsequent real-world use.

As shown in Figure 5.1, the spatial area of Virtual Wembury was effectively doubled. The extension area, represented by the area within the red square in Figure 5.1, was approximately

9 km^2, covering a square area from St Werburgh's Church overlooking Wembury Bay and following the coastal path west to the Noss Mayo Ferry Landing on the River Yealm. A Digital Terrain Model with a horizontal accuracy of 5 metres and a vertical accuracy of 1 metre was imported into Unity3D game engine as a second terrain object. An aerial photo at 12.5cm resolution was applied to this terrain as a base map texture.

Figure 5.1 The Overview of the Extended Virtual Wembury with a Selection of Labelled View Points

In parallel with the terrain data conversion efforts, additional high-resolution terrain textures and different species of plants were “painted” and “planted” onto the terrain areas. New coastal wind effects were employed to match the distinct feature of the extended terrain. In particular, as the elevation of the extended area was higher than the region around Wembury beach, the added wind effects were stronger and associated with higher frequency turbulence (i.e. bush and plant motion). A new sound source of strong and continuous costal wind was also added to the extended area to enhance such an environmental contrast.

5.3 Virtual Animals

Historical evidence of the value of human-animal relationships has been reviewed, such as life-prolonging effects for pet owners with cardiovascular diseases, relaxing effects of short-term animal contact, and long-term health improvements (Serpell, 2000). In recent years there has been increasing interest in the importance of introducing virtual wildlife to digital entertainment and health care sector. For example, virtual pets (e.g. puppies, kittens, birds etc.) can be adopted online and taken care of in "Adopt a Pet" games (Hallpassmedia, 2014). The interactive virtual companion (e.g. a dog or a penguin) invented by Wang & Deng (2014) was claimed to be capable of forming a personal emotional connection with the end users, elderly people in particular, to provide them with company and potentially improve their mental health. VR applications of virtual dolphins have been developed for future clinical trials which will determine if such a virtual approach can help stroke patients to recover faster than traditional therapy (Team, 2014).

Verbal feedback received from patients following the early VE trials staged within QEHB (as described in Section 6.2.5), suggested that the Virtual Wembury scenario was somewhat sterile, in effect suffering from an absence of life (both human and wildlife). Some even described the virtual scenario as "post-apocalyptic", as a result of this sterility! As a result, it was decided to experiment with the addition of virtual wildlife in the first instance, using, where possible (and to save time), "animation-ready" assets from online resource sites. Consequently, six different species of fully animated virtual animals were introduced to the virtual world, including horses, rabbits, seagulls, owls, butterflies and dolphins. Once procured from online resource sites, the animations were then processed in 3DS MAX and Unity3D to meet the requirement of Unity's embedded animation system. A virtual path-following system was also developed for some of these virtual animals. The virtual animals and their “behaviours” can be summarised thus:

- A small number of virtual rabbits at various locations of the coastal scene (e.g. in the bushes or on and around the main area of fenced-off meadow), as shown in Figure 5.2. The animation of virtual rabbits includes walking and idle.

Figure 5.2 A Screenshot of Virtual Rabbit

- Virtual horses with different colours and animations. Using the path-finding system described in Section 5.3.1., the horses were introduced into the VE with walking, grazing and resting “behaviours” within the fenced-off meadow.
- Virtual seagulls were included (with appropriate sound effects), flying over different areas of Virtual Wembury in flocks (see Figure 5.3). Two animation types were used: soaring (passive) and active flying.

Figure 5.3 A Screenshot of Virtual Seagulls

- Virtual butterflies with flying animations were scattered around the coastal area (see Figure 5.4). Their flying routes were randomised, so that no repeated visual patterns of flight trajectory could be recognised.

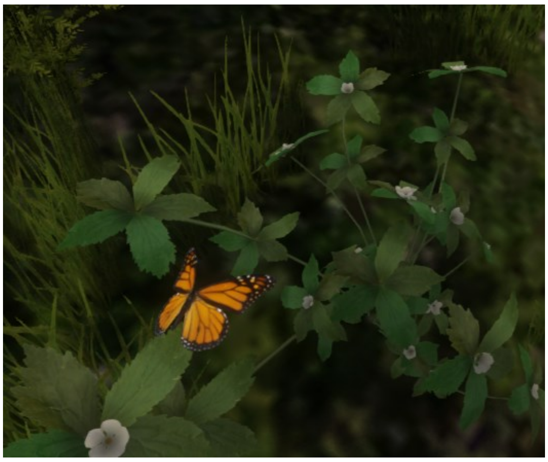

Figure 5.4 A Screenshot of a Butterfly in Virtual Wembury

- Virtual dolphins were also included, swimming in Wembury Bay and leaping out of the water occasionally (Figure 5.5).

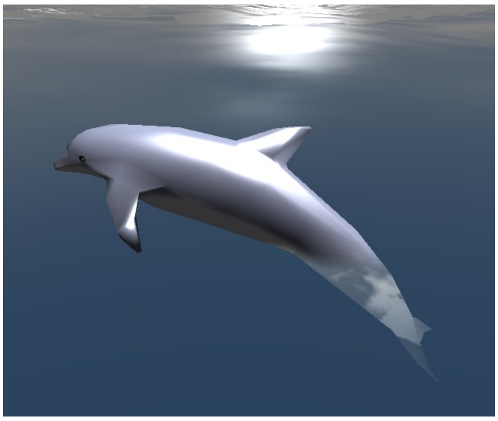

Figure 5.5 A Screenshot of a Dolphin in Virtual Wembury

- Virtual owls were also included, exhibiting a random circular flight-rest pattern between a wooded area and a finger post on the coastal pathway. Animations included gliding, active flying, taking off and landing. The animations were managed by the path-following system described in Section 5.3.1.

Figure 5.6 Screenshots of Virtual Owls at Night Time. Left: An owl landed on a fingerpost; Right: An owl gliding towards nearby woods.

The appearance of each or all of the virtual animals listed above can be selected manually through a graphical user interface (GUI). As shown in Figure 5.7, if the "Auto Switch" function is switched off (i.e. not highlighted in the box in front of it), individual species of the virtual animals can be turned on/off manually. Alternatively, the entire virtual animal system can be switched on/off by toggling the function “Zoo Mode!” on/off. When the “Auto Switch” function is on, the presence of the virtual animals is automatically controlled by the 24-hour day-night cycle system which will be described later.

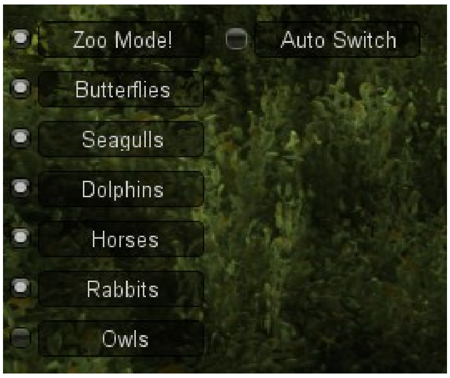

Figure 5.7 Graphical User Interface for Activating the Virtual Animals

5.3.1 Virtual Path-Following System

The virtual reality path-following system developed for the VREs reported here was designed to create virtual paths that were followed by specified objects, in this case, the virtual animals. As shown in Figure 5.8, a number of waypoints (the green spheres) were pre-set and distributed over an area. The path was a combination of these waypoints and green lines generated automatically between the waypoints. Such paths and waypoints were invisible to the end users.

Figure 5.8 A Screenshot of the Path-Following System for a Virtual Rabbit

During runtime, a pre-assigned virtual animal moved along the path with pre-set speed and animations. For example, as shown in Figure 5.9B, the horse would walk along a path between two waypoints using the walking animation until it reached a waypoint. Then, an animation was randomly selected and played from a list, such as grazing (Figure 5.9A), idling or even bucking. After a moment, which was also randomised between a certain range (e.g. from 20 to 60 seconds), the horse would start to walk towards the next waypoint. The system can manage multiple animals with different animations simultaneously (Figure 5.9B).

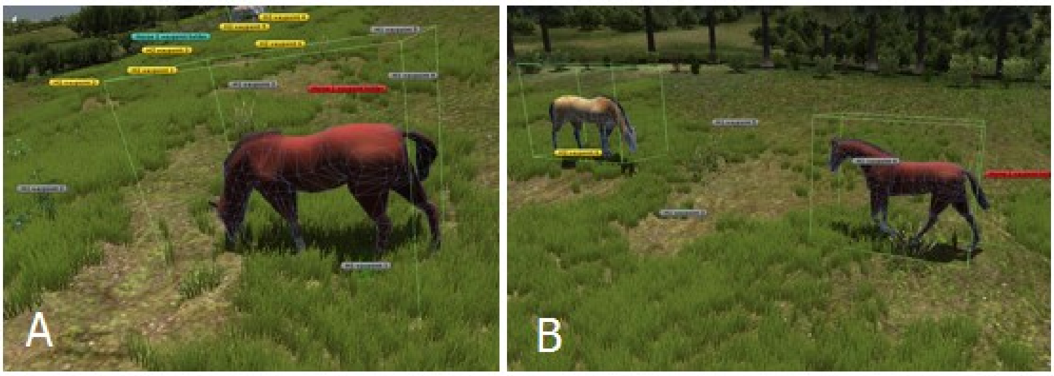

Figure 5.9 Screenshots of Animations Played by the Path-Following System. Image A: a virtual horse grazing animation; Image B: management of multiple objects with different animations

5.4 24-Hour Day-Night Cycle System

In a real-world study of the importance of windows in an Intensive Care Unit (ICU), Keep et al. (1980) suggested that patients treated in windowless units had poorer memory of the length of their stay, worse orientation for the time of day, greater reported sleep disturbance and a much higher incidence of hallucinations and delirium than those who were treated in ICUs with windows. In order to support the ongoing sleep study in the ICUs at QEHB (as reported in Chapter 7), to refresh and extend the earlier VRE experience and to improve the visual fidelity of the VE, a 24-hour day-night cycle system was developed.

In virtual environments, the simulation of different times of the day is accompanied by a wide range of alterations to almost every element in those environments, such as lighting, sound and the presence of natural and man-made objects (e.g. sea mist in the morning, rocks, benches, boats, etc.). In order to simulate such effects, a commercial Unity package called UniSky (Morris, 2011) was integrated within the Virtual Wembury scenario. This system includes a 24-hour day-night cycle with sun, moon and stars. The position of the sun, moon and stars are changed as the time of day or night progress. A cloud/sky system was also delivered with the UniSky system. The cloud cover (e.g. partly cloudy, overcast), colour (e.g. light blue, dark) and cloud motion speed are controllable to alter the appearance of the cloud effects. A number of modifications and functions have been made or added to this system, including:

- A graphical user interface for the 24-hour day-night cycle system (Figure 5.10). The "TIME" text box indicated the time in the virtual scene in a 24-hour format. This time has been synchronised with the real-world time and can be changed either using the slider bar or the four buttons of pre-set time of day. These are Dawn (06:30 AM), Midday (12:30 PM), Dusk (18:00) and Night (23:00 AM).

Figure 5.10 Graphical User Interface of the 24-Hour Day-Night Cycle System

- The directions of the sun and the moon, adjusted to match the real world.
- A Unity3D procedural system to control the presence and condition of virtual natural and man-made elements during different times of the day, as follows.
  - ❖ Day time (06:00 – 18:00)
    1. During the early morning (06:00 –0 9:00) only, a sea mist is presented at the mouth of River Yealm using a particle effect (Figure 5.11). The mist particles are small mist textures that are displayed and moved in large numbers by the Unity3D particle system. All the particles together create the impression of sea mist effect.
    2. All the models and animations of ferries, yachts, sailing boats, and so on are shown.
    3. All the virtual animals are enabled except the owls.
    4. Day time sounds, such as birdsong are enabled.

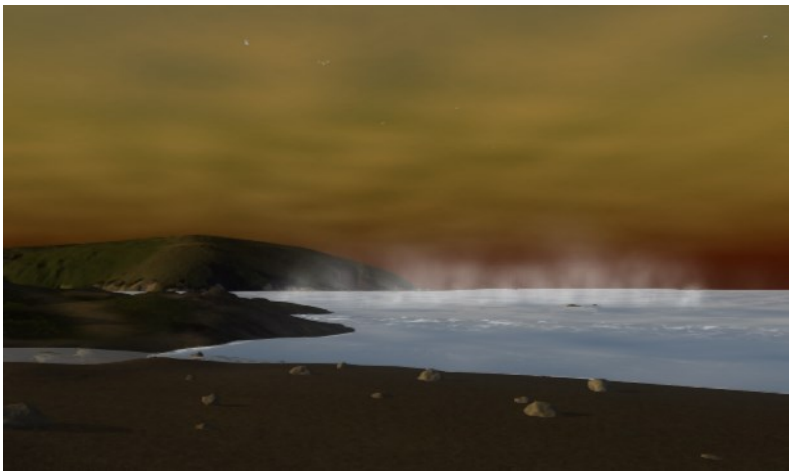

Figure 5.11 A Screenshot of Virtual Sea Mist

- Night time (18:01 – 05:59 Next day)

    1. All the models and animations of ferries, yachts, sailing boat etc. are disabled.
    2. Only the virtual owls are shown. All other virtual animals are disabled.
    3. A new night time sound is turned on. This sound effect includes the "chirping" of crickets, owl calls and general night time coastal ambient sounds.
    4. The distant light of the Eddystone lighthouse model (purchased online) is presented. As shown in Figure 5.12, the Lighthouse was just above the horizon, approximately 15 km from Wembury. The light beam was animated so that it rotated around the lighthouse.

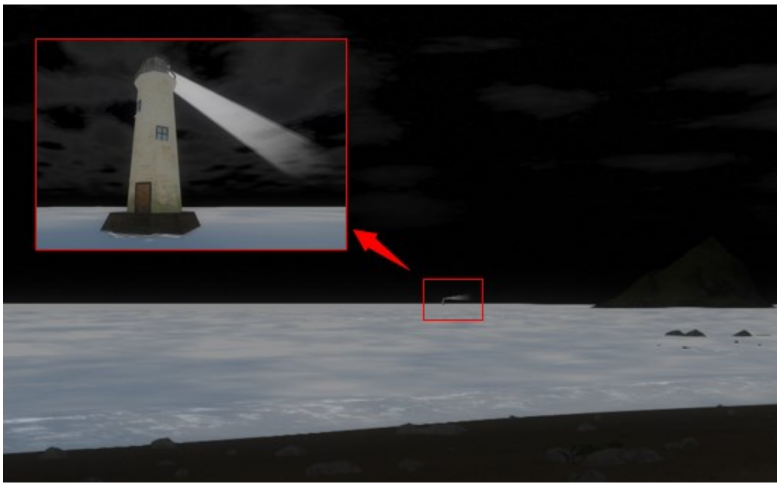

Figure 5.12 A Screenshot of the Virtual Eddystone Lighthouse

5. Virtual Campfires (commercially available from the Unity Assets Store) were added to the night time scene of Virtual Wembury (Figure 5.13). 3D sound sources of campfires with crackling sound effects were also attached to the campfire models. The Campfires can be switched off via the GUI.

Figure 5.13 Screenshots of Virtual Campfires

6. A night time version of the St Werburgh's Church has also been created. As shown in Figure 5.14, point lights and light flares were used for the stained glass of the church windows, in order to achieve a weak lighting effect. The point lights are light sources that shine from a location equally in all

directions, and the light flares simulate the effect of lights refracting inside camera lens (Unity3D, 2014).

Figure 5.14 A Screenshot of the Virtual St Werburgh's Church at Night

By including the 24-hour day-night cycle system, end users, and hospital patients in particular (especially those with no visual reference to the outside world) can become more aware of the real time of day, or are free simply to navigate within the virtual world in a time of day of their choice. For example, they can change the virtual time to 17:30 and enjoy the sunset on Wembury Beach (Figure 5.15).

Figure 5.15 A Screenshot of the Sunset in Virtual Wembury

5.5 Development of Virtual Window View

Again, as a result of feedback from patients following early VE trials staged within QEHB (as reported in Sections 6.2), requests were received relating to the provision of improvements to the control of the VE systems. Some users experienced difficulties using standard input devices, such as patients with severe hand injuries. Some experienced simulator sickness during navigation in VEs, and stated that they would simply prefer to sit back and "enjoy the view". Some patients requested much more basic levels of interaction. Therefore, to improve the usability and wider acceptance of the VE system, and to minimise and avoid the incidence of simulator sickness during user exposure, a virtual "window view" was developed.

5.5.1 Virtual Curtains

As part of the virtual window view concept, "virtual curtains" have been developed using the interactive cloth method (which is a Unity3D standard asset simulating a "cloth-like" behaviour on a mesh) of Unity3D physics system (Figure 5.16). This effect was also implemented following discussions with QEHB medical personnel following earlier trials and awareness sessions. Not only was it suggested that some means should be provided for the patient to end a VRE session, for example when they became sleepy or when relatives were visiting, it was also implemented as a means of actually recording the timing and duration of use of the VRE. The curtains are fully animated and affected by the virtual wind (e.g. moving gently in the sea breeze). The curtains can be set to three states: open, closed and 80% open (i.e. partially in view at both sides of the monitor frame, thereby simulating a virtual window effect). In addition, and when the curtains are fully closed, all VRE sound effects are muted. Therefore, the end users or their hospital carers do not have to turn off the system completely prior to sleep. Instead, by using a single keystroke on the input device, the curtains will close.

Figure 5.16 A Screenshot of Opening Virtual Curtains

5.5.2 Virtual Viewpoints

Different viewpoints have been selected across the extent of the Virtual Wembury scenario. In addition, a new viewpoint – a virtual cabin cruiser - was “anchored” near the Great Mewstone to provide an offshore viewing option for the end users. (Figure 5.17).

Figure 5.17 A Screenshot of the Viewpoint on the Virtual Cabin Cruiser

Two techniques were implemented to all end users to change their viewpoints within the Virtual Wembury scenario:

1. A graphical user interface was developed as a convenient visual way to switch between viewpoints (see Figure 5.1 at the beginning of this chapter). This interface offers the end users a map-like overview for Virtual Wembury, from which they can simply mouse-click on one of a number of viewing locations to launch the virtual view at that location.
2. A "Jump-and-Watch" function. This function was developed to provide a simple interface for those patients who were considered to be too frail to use more substantial hand controllers, such as the Xbox. By using a simple keypress on an input device (e.g. a keyboard or function keypad, or a special finger-mounted input device such as the Genius Ring Mouse or Ring "Presenter" etc.), the user's view "jumps" to the next viewpoint in a sequence. Once at the viewpoint of choice, the user can then simply "watch" and enjoy the view. Or, in the case of the Genius Ring Mouse, they can use light stroking thumb movements over the device's sensitive central touch pad to in order to pan the view left or right. This data input method was specially designed to benefit people with hand injuries or those who might otherwise present with symptoms of simulator sickness when undertaking more extensive movements through the VRE, as discussed in Sections 6.2.5 and 6.4.5.

5.6 User Navigation Tracking/Logging System

Although some generic guidelines (e.g. Charitos & Rutherford, 1996; Vinson, 1999; Stone, 2012) have been proposed in the past for designing interactive VEs, significant challenges still exist in developing robust methods of evaluating such features as usability, presence and user experience for VE technologies. Since the early 2000s, some attempts have been made by researchers to develop their own metrics and evaluation methods for evaluating usability and user experience in VEs. In 2002, the concept of 'Virtual Prints', in effect the patterns of virtual footprints that users leave behind, was proposed for tracking user navigation in Virtual Environments (Grammenos et al., 2002). Mourouzis et al. (2003) developed an integrated tool not only for supporting the main functions (e.g. navigation, orientation and way-finding in VEs) evident in the traditional Virtual Prints concept, but also for logging interaction history and for replaying the Virtual Prints. The following year, a visual tool for detecting user behaviour in a 3D indoor VE was proposed (Chittaro & Ieronutti, 2004). This tool was designed to record the user's path, to chart a 2D representation of the areas visited and to display the area seen by users, for ultimate 2D replay of users' navigational behaviours in VEs. A framework of measures and techniques for evaluating usability and user experience in VEs were also introduced to ensure valid, reliable and meaningful measures.

To support early usability trials in the QEHB, experiments addressing the fidelity of the virtual coastal environment and the further VRE-related studies that required evaluation of usability and user experience (as reported in Chapter 6), an integrated cross-application user exploration tracking/logging system was developed. The aim of this prototype system was to assist in the analysis of user objective and subjective data records, specifically addressing the questions: (a) how do users actually use virtual restorative environment; and (b) how interactive do the VEs need to be, based on an early understanding of the user's physical and psychological conditions; and (c) what are the most appropriate interface technologies to support that interaction for specific types of end user physical and psychological conditions? Additionally, it was felt that, by recording such features as direction, walking times, dwell times and direction of gaze, the exploration data could be used to infer user behaviour, engagement or usability during their navigation in VEs.

5.6.1 User Tracking System

The user tracking system developed in support of the present research automatically records two types of data:

1. The user's movement - the detailed path that the user “leaves behind” in the VE from start to finish of the session. As shown in Figure 5.18, the red line is a path describing a user’s navigation in the VE. The recorded path can be loaded in-game for path tracing in real-time or be exported as high definition image for post analysis and archiving purposes.

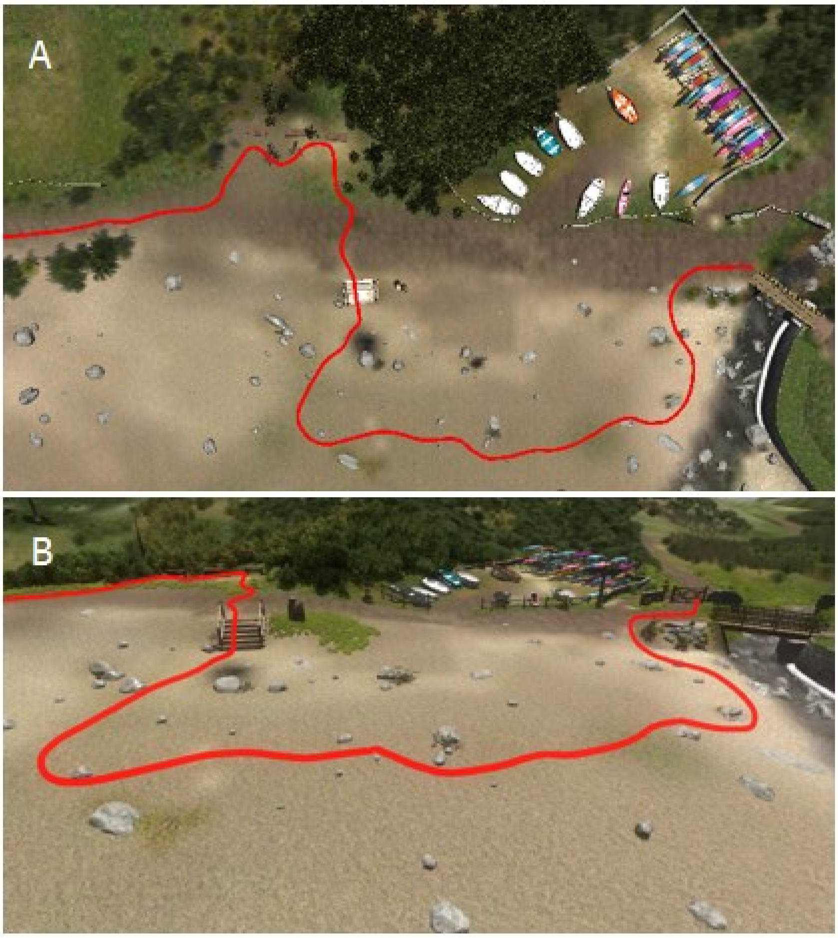

Figure 5.18 Screenshots of a Recorded User Path. Image A: a screenshot of the user path captured from top view; Image B: a screenshot of the in-game user path

2. A 3D in-game replay of user's movements and the view of the virtual camera are used to represent the user's head position (and, roughly speaking, the direction of gaze) during first-person navigation. The replay can be saved for later analysis and be loaded in-game for a detailed qualitative analysis using the GUI shown in Figure 5.19. This GUI can be used to open a replay file with a specified extension name (e.g. ezr) in different locations of local storage (e.g. internal hard drive, external hard drive, USB flash drive etc.).

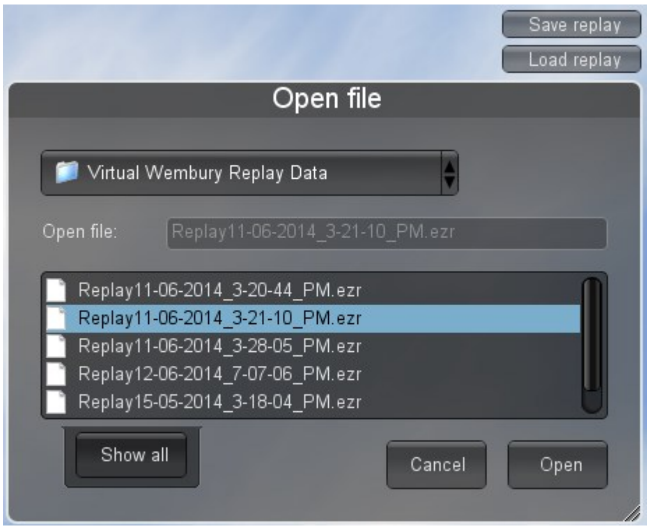

Figure 5.19 GUI of the Save and Load Functions for the Replay System

The in-game replay system has a range of conventional video-like functions such as load/save, play/stop, and forward/back (as shown in Figure 5.20). The replay speed can be adjusted from 4 times slower to 4 times faster.

Figure 5.20 The GUI of the Embedded Replay System

5.6.2 User Logging System

The user logging system records a timestamp for any game event trigged by user inputs. For example, the logging system will become active whenever a session is started, after a period of inactivity or at first start-up. Also the system will record a timestamp whenever the user walks past a virtual object, such as a bridge, bench or other feature. A list of tracked in-game events is shown in Table 5.1. The recorded data are saved in a comma-separated text file that can be imported into data analysis software such as Microsoft Excel or IBM SPSS for further analysis.

Interaction Function	Interaction Variable
General view status	Curtains open / closed
Location selection	Number of location changes
	Choice of location
	Time spent at each location
View panning	Number of view direction changes
	Preferred view for each location
Free-roam	Time spent in free roam
	Location of resting spots
	Duration of resting

Table 5.1 Events Tracked by User Logging System

5.7 Interaction with Virtual Activities Using A Non-Contact Motion Sensor

As well as the restoration of feelings of well-being and general health, VR has the potential to be exploited across a wide range of healthcare applications, including physical rehabilitation. For example, at the time of writing, there is considerable interest on the part of trauma clinicians, physiotherapists and occupational health specialists within QEHB in using interactive activities within existing VREs to offer high motivational exercises for, again for example, amputees awaiting the fitting of prosthetic limbs. In what has been termed “Preparing for Prostheses”, dynamic and motivational rehabilitation procedures may be able to help prevent or minimise muscle atrophy and loss of residual limb capabilities (Stone et al., 2014). Since 2010, non-contact motion sensors, such as Microsoft's Kinect and the ASUS Xtion, have been increasingly used in physical therapy and rehabilitation applications (e.g. Mousavi Hondori & Khademi, 2014; Antón et al., 2014). The present research introduces the results of early investigations into methods for translating limb movements into on-screen activities, such as "walking" or "driving" a virtual pedalo, within VREs using motion sensors. As an aside, the re-use of existing VREs in developing novel prototype solutions for a range of cross-hospital applications has met with considerable support within the VR stakeholder community in QEHB, not least because this represents a potentially huge saving of costs by avoiding the need to develop new or bespoke simulation scenarios to meet the needs of different medical applications.

A free middleware product called Flexible Action and Articulated Skeleton Toolkit (FAAST) was employed to provide communication between skeletal representations of human limb positions and orientations, tracked in real time using Microsoft's Kinect, and VE applications. FAAST can recognise user-defined body gestures and postures and translate them into emulated standard keyboard inputs (Suma et al., 2013). For example, as shown in Figure 5.21, the action "left hand to the right of neck by at least 10 cm" (as captured by the Kinect systems and displayed as a skeletal overlay in the top, right-hand window segment) can be set to trigger a keyboard input, "D", which results in moving the first person character controller to the right for a short distance in Virtual Wembury.

Figure 5.21 Navigation in Virtual Wembury Using Kinect and FAAST

As well as using non-contact gesture/posture recognition technologies such as Kinect, to achieve an additional goal of providing more motivational exercises, a virtual *pedalo* simulator was developed using the same technologies together with a real-world pedal exerciser (see Figure 5.22). To “drive” the pedalo at the seaside or on a lake, the user simply sits in front of the motion sensor and pushes the pedals. The virtual scene comprises a pedalo model with fully animated 3D lower limb models, and the sound of pedalling and water splash effects. The left or right virtual limb animations were programmed to be triggered by emulated keystrokes translated from the corresponding real-world limb movement of pedalling.

Figure 5.22 Virtual Pedalo Simulation. Upper left: 3D model of a pedalo and lower limbs; Upper right: operation a pedalo in Virtual Wembury; Lower: a pedal exerciser.

During the development of this system, an issue was identified relating to the resolution of the Kinect's inbuilt depth sensor. To recognise any body gesture, FAAST needs to receive skeletal position data from the skeleton tracking software, such as OpenNI or Microsoft Kinect for Windows. Such tracking software detects and highlights the user's body in the depth images captured by the depth sensor, and then maps a skeleton-like framework onto the detected body in the on-screen depth image (as can be seen in Figure 5.21). However, when users – and particularly hospitalised users – are sitting in a high-back chair or lying in a bed, the body of the user cannot be distinguished from the background surface (e.g. the back of the chair or bed sheets). Consequently, FAAST failed to generate suitable inputs for the VE. Future work will seek to find possible solutions to overcome this issue, such as using motion sensors with higher depth resolution (e.g. Microsoft Kinect v2), or using other motion capture systems as substitutions (e.g. OptiTrack, Leap Motion, etc.).

5.8 Further Development of A Virtual Forest Environment - Virtual Burrator

In order to provide the end user population of VREs with some variation in imagery and virtual experiences, it was decided that a second VE should be developed and modified to present similar functions (including underlying experimental recording software) as described earlier in this chapter. During the development of the Virtual Wembury scenario, an additional VE became available, courtesy of another postgraduate student project. The nature of this VE suggested that it would not require significant effort to modify and add to its contents in order to deliver a second VRE. In this case, the VE was a large-area representation of the area around the man-made lake of Burrator Reservoir, a forest environment with a vast expanse of water, located on the south side of Dartmoor National Park in the county of Devon. Previous studies suggest that forest environments can improve human well-being and offer restorative effects (e.g. Tsunetsugu et al., 2007; Park et al., 2007; Valtchanov et al., 2010).

A Digital Terrain Model with a horizontal accuracy of 5 metres and a vertical accuracy of 1 metre was imported into the Unity3D game engine as the main terrain model. An aerial photo at 12.5cm resolution was applied to this terrain as a base map texture (Figure 5.23).

Figure 5.23 High Definition Aerial Photograph for Burrator

Another motivation for developing the Virtual Burrator scenario further relates to an experiment described later in this thesis, which investigates the navigation styles and environment awareness of individuals when presented with virtual representations of scenes local to their place of residence (in this case Wembury Village) and with virtual scenes of a non-local environment. Virtual Burrator is the perfect choice for this experiment, as it is a) developed in the same game engine as Virtual Wembury, which offers the similar VE experience in terms of VR techniques, and b) represents a large area (approximately $5km^2$) which is sufficient for the 15-minute test time, as discussed earlier. Therefore, to meet the current research requirement and offer an additional option to the selection of virtual restorative environments for future research in healthcare, a number of modifications were made to Virtual Burrator project.

5.8.1 Repairs and Modifications to the Burrator Terrain Model

As shown in Figure 5.24, it can be appreciated that the scale of the Burrator model is enormous. Consequently the entire area has been divided into 16 separate terrains or "zones" for easier management of rendering performance (such 'zoning' helps to manage level of detail processing by, for example, only rendering those zones that are close to the current position of the user in the VE and no others, until they are approached). However, as a result of such zoning, faults such as polygon and texture tearing appeared at most parts where the terrain components were supposedly joined.

Figure 5.24 A Screenshot of the Overview of Virtual Burrator

As can be appreciated from the example shown in Figure 5.25, such tears could be highly distracting during user's exposure to and navigation through the environment.

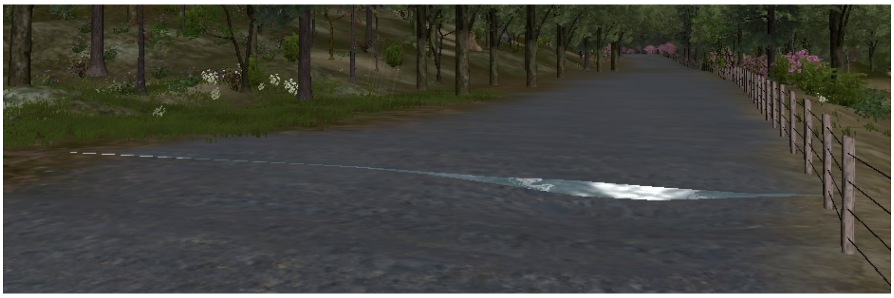

Figure 5.25 A Tear Issue between Two Terrain Zones

Modifications using Unity's embedded terrain tools such as Raise/Lower, Paint Height and Smooth Height tools were been applied to the edges of these problematic terrain zones. The result was a seamless or continuous visual connection between adjacent zones (see Figure 5.26).

Figure 5.26 Fixed Area of the Tear in Figure 5.25.

In addition, issues due to the inaccuracy of terrain textures have also been fixed. For example, some of the paths and roads were either too wide or too narrow compared to those in the real world. Terrain texture painting tools and Unity embedded measurement tools were used to correct the width of these paths and roads. In most cases, this dramatically improved the visual realism of the environment.

5.8.2 Development of Visual Details in Virtual Burrator

As shown in Figure 5.27, 3D representations of known local vegetation were added to the original selection of virtual plants provided in Virtual Burrator, such as gorse and rhododendron. Additional man-made objects (e.g. fences and stone walls) were also built alongside roads and paths.

Figure 5.27 Virtual Gorse, Rhododendron, Fences and Stone Walls in Virtual Burrator

Virtual animals were also introduced to the forest scene, such as rabbits, horses and butterflies. The path-following system used in the Virtual Wembury scenario was also integrated into this project.

The water shader of Virtual Burrator reservoir was updated to Unity's 'Water 4' with real-time reflection and specular lighting effects. For example, Figure 5.28 shows a dusk scene of Virtual Burrator – note that the setting sun is reflecting off the reservoir.

Figure 5.28 Virtual Burrator Reservoir Sunset

5.8.3 Experimental Modifications for Virtual Burrator

The in-game settings, visual effects and related factors in the Virtual Burrator project were modified to ensure that these factors were equivalent to those in Virtual Wembury. The level-of-detail settings (i.e. the gradual fading in and out of object detail depending on the visual range and approach speed of the user) for vegetation and detailed objects (e.g. rocks) were modified to maintain a consistent and higher visual quality. Other settings, such as texture quality and shadow quality were also adjusted.

The 24-hour day-night cycle system and the user tracking system with complete graphical user interface (described in Sections 5.4 and 5.6) were also imported into Virtual Burrator. Those systems were initially developed for Virtual Wembury, but further modifications were necessary, and are described below.

For the 24-hour day-night cycle system, changes were mainly applied to the procedural time control module. All of the virtual animals in this scenario were only programmed to be present during the day time (i.e. 06:00 – 18:00). The settings of the sky/cloud system, such as alteration of sky colour during different times of day, cloud colour, level of coverage and movement speed were set to the same parameters and values as those implemented in Virtual Wembury.

The user tracking and logging system was modified so that it was able to track the user's movement in Virtual Burrator. The in-game replay system was also integrated into the forest/lake scenario.

5.9 Conclusion

In this chapter, two virtual environments have been developed. The area of Virtual Wembury has been expanded to twice as large as its predecessor to offer a wider region for user exploration and, possibly, a longer testing time for the later studies. The Virtual Burrator project has been significantly modified to support an experiment to evaluate user navigation styles and feedback, comparing local vs. non-local VEs. Visual fidelity in the Burrator forest and lake scene has been improved by fixing terrain elevation and inter-zonal "tearing" issues, upgrading the water shader and adding representations of local vegetation. The ability to conduct rapid modifications to the Virtual Burrator scenario based on "lessons learned" from the development phases of the earlier Virtual Wembury project provide much confidence that the tools and techniques are highly transferrable and, as such, will be able to support the conversion of a range of Unity-compatible VR scenarios to match the "standard" requirements defined throughout the present research for experimentation and healthcare application.

A number of new features have been developed for both the coastal and forest environments. One of these features is the 24-hour day-night cycle system, which procedurally controls the presence of natural and artificial objects with regard to the time of day. Other features include two new methods allowing users to choose their locations to watch environmental changes, a simulation of a "virtual window" using virtual curtain material effects, the driving of a virtual *pedalo* representation using non-contact motion sensors and a suite of fully animated virtual animals. Additionally, GUI systems have been developed to control these features and to actuate and examine other experimental functions.

A user exploration tracking/logging system has also been created and integrated into the two virtual settings. During exposure to the VEs, the users' movement and on-screen views are recorded, while user interaction functions such as the number of location changes and time spent in navigation are logged. Quantitative parameters recorded by this system for the post-session analysis of ease of navigation and use of the controller are currently limited. Future work will seek to introduce appropriate factors to support more detailed usability studies. For example, the distance that users deviate from the path that they are instructed to follow may be sampled at a certain frequency. Greater deviation from the path may indicate poorer usability of controller or navigation in a VE.

The next chapter will present the results of experiments focusing on the human factors analysis of VEs including usability, visual and auditory fidelity and the impact of real-world based VE on local participants.

Chapter 6 Experiments with Virtual Natural Environments

6.1 Introduction

In previous chapters, the appropriateness of multisensory display (e.g. visual, auditory and olfactory) within virtual natural environments has been investigated. Whilst the visual and auditory quality of the VEs are constantly being improved (courtesy of rapid technological developments in, for example, the gaming industry), new, relevant and important features (e.g. time-of-day effects, the user tracking system, interactive activities, etc.) have also been developed and added as a result of the research described herein and as a result of close engagement with QEHB stakeholders and subject matter experts.

In order to determine the principles for the development of virtual natural environments for future bedside and clinical applications, and as part of the present research, two studies were undertaken to investigate the impact of visual and auditory fidelity (Section 6.3), and the accuracy of representation of a localised VE (i.e. the sense of presence and acceptance on the part of end users of a VE based on a location in the vicinity of their town or village, Section 6.4). Additionally, as presence is significantly associated with usability in VEs (e.g. Sylaiou et al., 2010; Busch et al., 2014), usability issues of a number of input devices have also been addressed (Section 6.2).

6.2 Usability Study of Commercial Off-The-Shelf Input Devices and Displays for Virtual Natural Environments

6.2.1 Background

Many studies have addressed different factors of usability for computer systems, especially input devices. An earlier study (Bates & Istance, 2003), for example, focused on pointing technology by comparing usability scores of eye- and head-based controllers, and the results suggested that, although eye-based pointing devices were not "mainstream", in a marketing sense, they can be rated higher than head-based device by increase the user proficiency. In addition, recent studies have compared the usability of controllers in VEs. By comparing users' navigation from one coordinate to another in a VE, Lapointe et al. (2011) found that a mouse had a main effect on improving the user performance, using less time to finish the task, than the three other controllers (a keyboard, a joystick and a gamepad).

Although most of the input system design and evaluation studies have addressed usability related issues, there were, however, different choices of usability testing methods. A study conducted by Lange et al. (2009) examined the usability factors of three off-the-shelf game controllers, (e.g. Nintendo Wii, Nintendo WiiFit and Sony PlayStation 2 EyeToy) for VR rehabilitation. A Computer System Usability Questionnaire (CSUQ) was chosen for the evaluation. Patients with disabilities such as spinal cord injury, traumatic brain injury and stroke participated the study and rated the Sony PlayStation 2 EyeToy as easiest to use, describing the product to be more intuitive than other controllers. Such usability tools have been designed for computer systems in general, whereas VR systems have a range of unique characteristics (e.g. the feeling of being there during exposure to a VE) that traditional usability tests might well struggle to determine. Therefore, a specially designed questionnaire (VRUSE) has been proposed to dedicatedly measure the usability of VR systems (Kalawsky, 1999), as described in Section 2.7.1.

6.2.2 Aim

As described in Section 5.7, at the time of writing, there is special interest in using interactive activities within existing VREs to offer high motivational exercises for amputees awaiting the fitting of prosthetic limbs. A highly important human factors activity within this study is to investigate appropriate technologies supporting interaction with VREs. Therefore, the aim of this first study reported here is to identify usability issues with four different COTS (commercial off-the-shelf) control devices selected for potential use by a range of patients (and amputees in particular) who may present with differing perceptual, cognitive and residual motor capabilities when interacting with virtual restorative environments. In particular, data input devices for upper limb amputees (or lower-limb amputees with significant additional damage to upper limb areas) demand close attention, as even some of the most popular products (such as the Xbox controller or the Wii Nunchuk Controller) could cause serious problems for some patients in their attempts to maximise benefits from the VEs.

6.2.3 Methods

6.2.3.1 Participants

15 male patients within 412 (Military) Ward of the QE Hospital participated in the experiment. For each participant, a description of their condition was required, which, it was felt, might help to identify and explain subsequent and specific usability issues between the participant and the

control device. This description was provided by the medical partners on the project, who determined the appropriate level of releasable detail of information relevant for the study. Specially, three participants were identified as having hand injuries, which, at the time, was felt may affect their performance.

6.2.3.2 Conditions

The experiment determined usability issues for four types of input control device. Therefore there is one independent variable, which is type of controller. This means that there are four conditions. These are (see also Figure 6.1):

I. Keyboard and mouse (Logitech wireless combo MK260)
II. One-handed handheld gaming controller (Nintendo Wii Nunchunk thumb controller)
III. Two-handed handheld gaming controller (Microsoft Xbox wireless controller)
IV. Joystick (Speedlink)

Figure 6.1 Four Input Devices Used in the Usability Studies. (Upper left: Nunchuk thumb controller; Upper mid: Joystick; Upper right: Xbox wireless controller; Bottom: Keyboard and mouse)

There was a single display device for all conditions. This was a large-screen (50-inch LG, 1920 x 1080 resolution) TV display. The most up-to-date version of Virtual Wembury (as described in Chapter 5) was used. The soundscape and walking sounds were presented by wireless headphones (Sennheiser) in all conditions.

6.2.3.3 Procedure

The experiment employed a repeated measures design. All participants were asked to undertake all four conditions. To avoid fatigue effects, participants were advised to complete each condition on a separate day (i.e. over 4 days). Note that this did not have to be 4 consecutive days, and could be spread out over a longer period if necessary. If a period of four separate days was not possible, some participants were asked to complete two or more conditions in one day, and to be provided with at least 5 minutes rest period between conditions.

The input devices (and specifically for the Keyboard & Mouse and Joystick conditions), were positioned in front of the participant on a height-adjustable table, which was set at a level most comfortable for the participant. The devices were sterilised before each trials to comply with to hospital health and hygiene regulations. Prior to each condition, the participants were given time to familiarise themselves with the input device. Most participants either sat at an angle of 90 degrees or 45 degrees, reclining back in a hospital bed, depending on their physical conditions. However, one participant was lying down during the full testing process, as this particular patient could not sit up because of a coccyx injury.

During the exposure to the VE, the participants were instructed to simply navigate from one end of the coastal path to the other as quickly as possible. The participants were asked to stay centrally on the path, following a route identified by flags. Invisible “force fields” or barriers were activated approximately 1 metre away from both sides of the virtual path to keep the participants on the path and prevent undesirable incidents (e.g. falling off the cliffs alongside the path). For each condition, participants were asked to complete three attempts. Completing one route takes approximately 3 minutes. The order in which the participants undertook different conditions was varied using a cascaded Latin-square method for control of order and learning effects (Kirk, 1982).

6.2.3.4 Objective Measures

The objective data collected by the integrated user tracking system (as described in Section 5.6) measured navigation performance, comprising the time for completing each condition and the percentage of time of moving forward (i.e. holding down the forward button). The trajectory of navigation in the VE (see Figure 6.2) and a full in-game replay were both recorded.

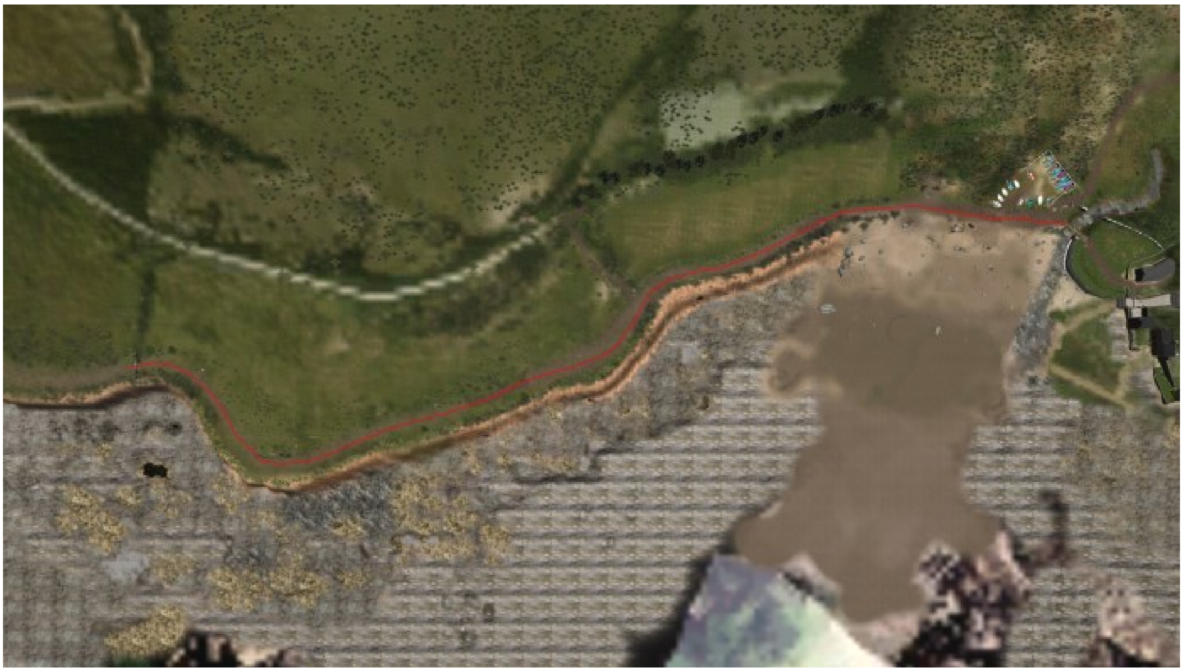

Figure 6.2 An Example of a Recorded User Path

6.2.3.5 Subjective Measures

Subjective data were collected following the completion of the third attempt for each condition, and consisted of questionnaires (see Appendix A) to measure:

I. Usability of the input device and display (VRUSE). As discussed in Sections 2.7 and 2.8, the VRUSE questionnaire (Kalawsky, 1999) has been chosen, as it is a complete, systematic and flexible measure, specifically designed for VR systems. Only the questions related to "User input" and "System Output (Display)" factors in VRUSE were included. As described in Section 6.2.4, the reliability of the results of usability of the input device is excellent, and the reliability of the results of usability of the display is acceptable.

II. Ratings of workload (NASA-TLX). The National Aeronautical and Space Administration Task Load Index (NASA-TLX) (Hart & Staveland, 1988) was selected to measure workload based on average ratings on six Likert-scale items: mental demand, physical demand, temporal demand, performance, effort and frustration.

III. Rating of Strain or Discomfort Using the Controller (Borg CR10). The Borg CR10 scale (Borg, 1982) is a numerical scale ranging from 0 (nothing at all) to 10 (very, very, strong) and has been widely used to measure exertion and pain (Borg, 1990; Persson et al., 2006).

The participants were guided through the questionnaires by the experimenter, and were encouraged to explain their responses, or to add qualitative statements to their ratings. After completing the fourth and final condition, the participant was asked to rank their order of preference of the four control input devices.

Participants were also asked about their computer gameplay experience. This involved completing a background data questionnaire (see Appendix A). This information may help classify or correlate usability data in terms of previous experience.

6.2.4 Results

Only 12 participants completed all conditions. One participant only completed the Keyboard & Mouse condition before being discharged from the ward. One participant only completed two trials of the Microsoft Xbox condition before the session terminated as the patient was unfit to continue. The third participant felt nauseous and was withdrawn from the study after completing two conditions (Thumb Controller and Joystick).

Reliability tests of internal consistency were used to evaluate the consistency of results across items within a questionnaire (Gliem & Gliem, 2003), and can be measured with Cronbach's alpha (α), a statistic calculated from the pairwise correlations between items (Knapp, 1991). Table 6.1 showed a commonly accepted rule of thumb for describing internal consistency (Field, 2013).

Cronbach's Alpha	Internal consistency
$\alpha > 0.9$	Excellent
$0.8 < \alpha < 0.9$	Good
$0.7 < \alpha < 0.8$	Acceptable
$0.6 < \alpha < 0.7$	Questionable
$0.5 < \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

Table 6.1 A Commonly Accepted Rule for Describing Internal Consistency Measured with Cronbach's alpha (α) in a Reliability Test (Field, 2013)

Only the records of the 12 participants who completed all four conditions were analysed. The reliability tests show that the user input usability reliability (i.e. internal consistency) is excellent (α = 0.939). The display usability reliability is questionable (α = 0.644), as shown in Table 6.2. However, if questions 5 and 6 of the display usability questionnaire (which were "The quality of the image affected my performance" and "There were no glitches in the display") are removed, the reliability of the remaining data is then acceptable (α = 0.769). In addition, the overall reliability of workload is questionable (α = 0.561), but it is good after question 4 (i.e. performance question) is removed (α = 0.851). Finally, the overall reliability of pain and discomfort is good (α = 0.888).

Condition	N_1	Cronbach Alpha (N_2=8)	Q5 removed (N_2=7)	Q6 removed (N_2=7)	Q5 & Q6 removed (N_2=6)
All	48	0.644	0.751	0.713	0.769
Joystick	12	0.467	0.665	0.663	0.783
Keyboard + Mouse	12	0.628	0.869	0.521	0.828
Thumb	12	0.803	0.765	0.834	0.787
Xbox	12	0.622	0.71	0.732	0.789

Table 6.2 Results of Display Section Reliability Test (N_1 indicates the sample size. N_2 indicates the number of items tested. Q5 indicates question 5. Q6 indicates question 6.)

The total time spent by hand injured patients using keyboard and mouse (see Figure 6.3) is longer than any other conditions. Correspondingly, as can be seen clearly in Figure 6.4, the percentage of the total time that the hand injured patients were navigating forward in VE using keyboard and mouse is significantly lower than any other conditions. However, two-way Analysis of Variance (ANOVA) tests showed that both these two results are not statistically significant (time: [$F(1.635, 16.347) = 1.941$, $p > 0.05$]; percentage: [$F(2.480, 24.802) = 1.531$, $p > 0.05$]). Whilst there are no apparent differences of both total time and percentage of forward movement time between the remaining conditions, the hand injured patients spent a little more time to complete the task and had less percentage of time triggering the forward function when compared to patients with no hand injury in all conditions.

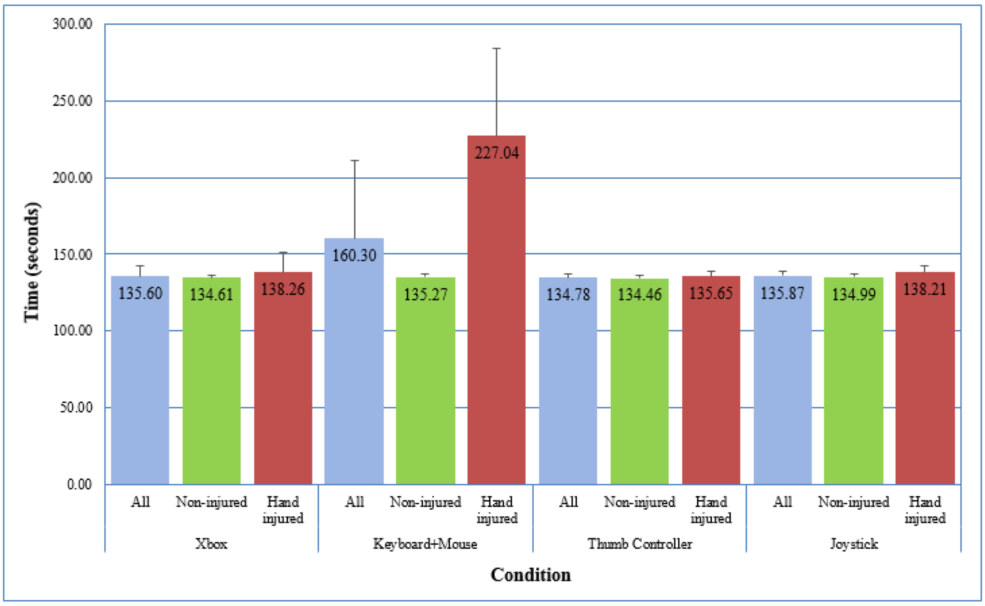

Figure 6.3 Average Time Spent from the Start Point to the End in Each Condition for All Patients, Non-Hand Injured Patients and Hand Injured Patients (Y-bars indicate standard deviation of the average value.)

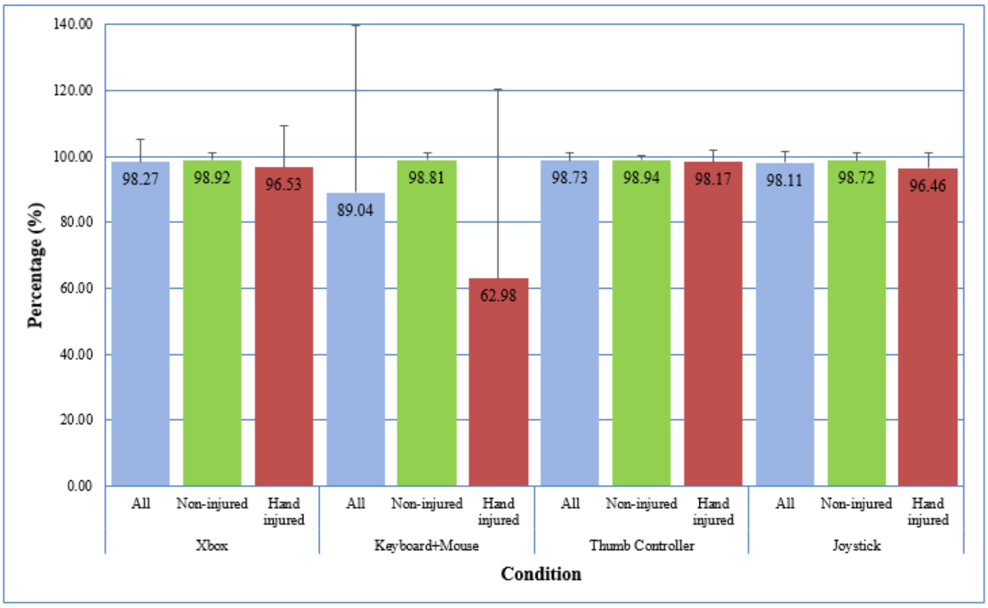

Figure 6.4 Average Percentage of the Total Time the Forward Motion is On-Going for All Patients, Non-Hand Injured Patients and Hand Injured Patients (Y-bars indicate standard deviation of the average value.)

Meanwhile, the navigation data of user path taken from hand injured patients in keyboard and mouse condition appear to be less smooth and show more sharp turns when compared to the data from non-hand injured patients (Figure 6.5).

Figure 6.5 A Screenshot of a Zoomed Trajectory of Hand Injured Participant Using Keyboard and Mouse

Table 6.3 shows the ratings of usability for participants with and without hand injury (the higher the score, the better the usability is). The Xbox controller rating is highest for all participants and the non-hand injured participants out of all four input devices (all participants = 5.93, *STDEV* = 1.65, non-hand injured = 6.04, *STDEV* = 1.83). The usability rating for the joystick is lowest on non-hand injured participants (3.86, *STDEV* = 0.70), while it scores highest on participants with hand injuries (6.69, *STDEV* = 2.31). Additionally, keyboard and mouse have the lower rating than the other three controllers (4.02, *STDEV* = 1.19) for all participants and hand injured patients.

	All Participants		Non-hand injured		Hand injured	
	Mean	*STDEV*	Mean	*STDEV*	Mean	*STDEV*
Joystick	4.57	0.71	3.86	0.70	6.69	2.31
Keyboard + Mouse	4.37	0.76	4.49	0.82	4.02	1.19
Thumb	4.51	0.81	4.40	0.91	4.86	0.98
Xbox	5.93	1.65	6.04	1.83	5.61	1.81

Table 6.3 Ratings of Controller Usability

A one-way ANOVA test was used to address any differences of the usability ratings between the four conditions of all participants. There was a significant main effect on ratings of usability due to input devices [F (3, 33) = 4.177, p = 0.013]. Furthermore, Table 6.4 shows that there were significant differences on ratings of usability between the Xbox and each of the three other devices (Joystick: p = 0.018; Keyboard and Mouse: p = 0.033; Thumb controller: p= 0.002). However there were no main effects between the other three controllers (p > 0.05).

	Joystick	Keyboard + Mouse	Thumb	Xbox
Joystick		0.757	0.889	0.018
Keyboard + Mouse	0.757		0.771	0.033
Thumb	0.889	0.771		0.002
Xbox	0.018	0.033	0.002	

Table 6.4 p Values of the Differences on Ratings of Usability Between Four Input Devices

The user preference results (Table 6.5) show that the Xbox controller was overall the most popular input device (8 votes), while 5 participants thought that the joystick was the worst controller. However, for the hand-injured participants, 2 out of 3 participants preferred the joystick whereas all three of them did not like the keyboard and mouse.

	All		Non-hand injured		Hand injured	
	Best	Worst	Best	Worst	Best	Worst
Joystick	2	5	0	5	2	0
Keyboard + Mouse	1	4	1	1	0	3
Thumb	1	3	0	3	1	0
Xbox	8	0	8	0	0	0

Table 6.5 Result of User Preference of Controller

A one-way ANOVA demonstrated no significant main effects on display usability due to the controllers [F (2.207, 24.279) = 1.753, p > 0.05]. As shown in Table 6.6, the workload ratings associated with the keyboard and mouse were the highest in four conditions, although a one-way ANOVA test demonstrated that the difference was not statistically significant [F (1.445, 15.899) = 2.246, p > 0.05].

	Mean	*STDEV*
Joystick	3.88	2.18
Keyboard + Mouse	6.22	5.63
Thumb	4.53	2.64
Xbox	3.01	1.61

Table 6.6 Ratings of Workload

A one-way ANOVA test showed there were no significant effects on ratings of strain or discomfort due to controllers [F (1, 11) = 0.519, p > 0.05]. However, the participants with hand injuries rated strong pain or discomfort on a number of limb areas, from fingers to the upper arm.

6.2.5 Discussion

There are no significant main effects for either the time used for each navigation attempt or the percentage of time moving forward, even though the keyboard and mouse scored much higher on time usage and much lower in forward movement percentage. This could have resulted because of the very large standard deviations as shown in Figure 6.3 and Figure 6.4, as the participants with hand injuries had different issues using controllers. For example, in the keyboard and mouse condition, all hand injured participants were only able to use one hand. They had to switch between keyboard and mouse using that single hand. Specifically, when pressing the forward button on the keyboard and reaching a corner of the path, the hand-injured participant had to release the button (i.e. stop moving forward) in order to use the mouse to change direction, and then had to switch back to the keyboard again to continue navigation. Therefore the trajectories of hand- injured participants consisted of long straight lines and sharp turns at the corners. This also explains why the percentage of moving forward for the keyboard and mouse is lower than the others, as the keyboard and mouse represent the only input method that requires a two-handed operation in order to achieve good performance. All of the other controllers can be used to move forward and change direction simultaneously. In addition, the workload ratings show that Xbox scored lowest overall, whilst the keyboard and mouse scored highest, especially for hand-injured participants.

There is a significant main effect on overall usability ratings due to the type of controller, although only the ratings of Xbox are significantly different than other conditions. As shown in Table 6.3, the Xbox average usability score was 5.93, *STDEV* = 1.65. For the non-hand- injured participants this score is higher (6.04, *STDEV* = 1.83), and the joystick rating is really low (3.86, *STDEV* = 0.71). However, once the hand-injured patients are included (who scored 6.69, *STDEV* = 2.31 on the joystick condition), the overall average score of joystick is increased. This may because the participants with hand injuries cannot use the Xbox, but they can use the joystick. As shown in Table 6.5, two of the hand-injured participants preferred the joystick, because they found it easy to push forward even with hand and finger injuries (e.g. arm in sling, hand in cast or heavily bandaged). Therefore the rating of the joystick would be really low if not for the hand-injured participants. However, it would be inappropriate to break down the data to this level, as the participant number size is too small (i.e. less than 10 participants).

Fifteen participants volunteered for this experiments at the outset. However, as mentioned earlier, three of them did not complete. One was discharged and one session was terminated, as the participant was deemed unfit to continue by the experimenter. The third participant felt nauseous during exposure to VE and was advised to withdraw from study. Previous researchers reported that a delay between user input and the corresponding change in the VE could cause symptoms such as nausea sweating, vomiting, dizziness, headache etc. (Krijn et al., 2004). This delay could be triggered by a number of reasons, such as low display refresh rate, low frame rate of the VR application, or even difficulties in using a particular controller (Hoekstra, 2013). However, this particular participant was on self-administered morphine. Hoffman et al. (2011) have suggested that nausea might be one of the side effects of opioids. Therefore, the feeling of nausea experienced by the participant may be caused by the VE, medication or a combination of the two. The effects of different medications on patients' acceptance of, immersion within and interaction with VEs is an important topic for future research consideration, especially in terms of how different VEs may need to be designed for hospital deployments (with regard to such features as audio-visual fidelity, colour, dynamic motion, field of view of presentation, etc., etc.).

There were no significant effects on display usability due to the controllers used. This may simply be because the settings for display were unaltered throughout the whole procedure. However, in terms of future system design, there are some display usability ratings that are worth considering here. Four participants strongly agreed with the Likert statement "I was aware of distortion in the image". Three of them were moderately in agreement that the delay in the image affected their performance. The participant who was withdrawn from studies because of nausea, rated an average score of 3 in the two conditions which were completed, although, as mentioned above, this may be indicative that the sickness was likely to be a result of side effects of the medical treatment.

Future work will also seek to develop the user tracking system to become more of an objective end user performance capture system, providing (for example) observable and measurable deviations from an ideal path, and will be able to output such data for quantitative analyses. In terms of display quality, future work will attempt to find more efficient methods to optimise the VE system for higher frame rates and lower delay, in doing so possibly helping to reduce the incidence of VR sickness.

6.3 The Influence of Visual and Auditory Fidelity on Presence in Virtual Natural Environments

6.3.1 Aim

According to Stone (2012), fidelity is, in general terms, "a term used to describe the extent to which a simulation represents the real world, including natural and man-made environments, systems and, increasingly, participants or agents." However, when applied to simulation, the definition above is linked to "physical fidelity", or "engineering fidelity". In contrast, "psychological fidelity" can be defined as "the degree to which simulated tasks reproduce behaviours that are required for the actual, real-world target application" (Stone, 2012). A number of studies have investigated the relationship between visual or auditory fidelity and presence in VEs. Higher reported degrees of presence were shown to be associated with higher shadow quality (e.g. Slater et al., 1995a; Slater et al., 2009a), higher image realism (e.g. Welch et al., 1996; Kwon et al., 2013), spatialised sound effects (e.g. Hendrix & Barfield, 1996b; Bowman et al., 2000). However, some studies have suggested there was no significant main effect on presence due to shadow, texture and lighting quality (Zimmons & Panter, 2003; Mania & Robinson, 2004). Additionally, with the development of visual and dynamic qualities in today's VR simulation and games engine software, there may be too much, too little or inappropriate sensory detail in a VE which may be unnecessary for the task. Stone (2012) uses the terms "hypo- and hyper-fidelity" to describe such detail.

Therefore, the aim of this part of the PhD research was to investigate fidelity related elements of a virtual coastal environment (Virtual Wembury), and its effects on presence, quality and realism. In particular, this part of the study aims to determine the impact of levels of image quality (e.g. the quality of texture, lighting etc.), quality of virtual natural motion (movements of the natural elements, e.g. waves, grass, trees, etc.) and sound (e.g. sound of waves, river water, wind, birds, etc.) on reported presence, quality and realism. Furthermore, this part of the study addresses the importance of different factors of fidelity in VEs, in order to deliver methodological suggestions for further VE design and optimisation in terms of balancing VE system performance and user experience, thereby supporting future developments in the design and implementation of low-cost, effective and believable VE systems for supporting healthcare restoration and rehabilitation.

6.3.2 Methods

6.3.2.1 Participants

19 undergraduate and postgraduate students (15 males and 4 females, mean age = 21, age range: 18 – 26) participated in the experiments.

6.3.2.2 Conditions

The experiment consisted of three independent variables with five conditions. The independent variables were level of image quality/fidelity (low, medium and high, as shown in Table 6.7), the presence of motion (movements of the natural elements, e.g. waves, grass, trees, etc.) and sound within high image quality setting. Therefore the five conditions were, (1) low image quality without motion and sound, (2) medium image quality without motion and sound, (3) high image quality without motion and sound (as shown in Figure 6.6), (4) high image setting with motion and without sound, and (5) high image setting with both motion and sound. The technique terms within the left-most column of Table 6.7 are explained as follows:

- Texture quality: The quality of the details including images or colours that are added to the surface of a 3D model (as described in Section 2.4.3). In a "Flat-shaded" model, only one colour, no images, is added to its surface (see the upper image in Figure 6.6). "Half" texture quality refers to the reduced texture resolution. For example, if a 3D model has "full" texture quality of a 1024×1024 resolution texture, the resolution for half texture quality is 512×512.
- Shader quality: Quality of the shaders that affect the level of lighting and colour of textures (as described in 3.4.2.1).

- Anti-Aliasing: a technique used in computer graphics to combat the issue of aliasing (Jimenez et al., 2011). In a multisample anti-aliasing method, which is a type of anti-aliasing, the higher the multi-sampling, the better the image quality is.
- Shadow distance: the maximum distance from the virtual camera at which shadows is visible (Unity3D, 2014).
- Pixel error: the accuracy of the mapping between the terrain maps (i.e. heightmap and textures) and the terrain (Unity3D, 2014);
- Base map distance: the maximum distance at which terrain textures is displayed at full resolution (Unity3D, 2014).
- Billboard start: the distance from the virtual camera at which 3D tree meshes are replaced by billboard images (Unity3D, 2014).
- Max mesh trees: the maximum number of visible trees that are displayed as 3D models. Beyond this limit, trees models are replaced with billboards (Unity3D, 2014).

	Low	Medium	High
Texture Quality	Flat-shaded	Half	Full
Shader Quality	Diffuse	Diffuse	Bumped Diffuse
Sea	Flat-shaded	Simple	Complex
Sky	Flat-shaded	Skybox	Unisky full
Buildings	Flat-shaded	Textured	Textured
Rocks	Flat-shaded	Textured	Textured
Grass	Flat-shaded	Textured	Textured
Trees and bushes	Flat-shaded	Textured	Textured
Beach-side artefacts (fences, seats, boats, steps, footbridge)	Flat-shaded	Textured	Textured
Anti-Aliasing	Off	4x multi-sampling	8x multi-sampling
Shadows	Off	On	On
Shadow distance	Off	100	1000
Terrain settings			
Pixel Error	200	50	1
Base map dist	0	300	2000
Billboard Start	5	200	2000
Max Mesh Trees	0	500	5000

Table 6.7 Settings in Different Image Quality/Fidelity Levels

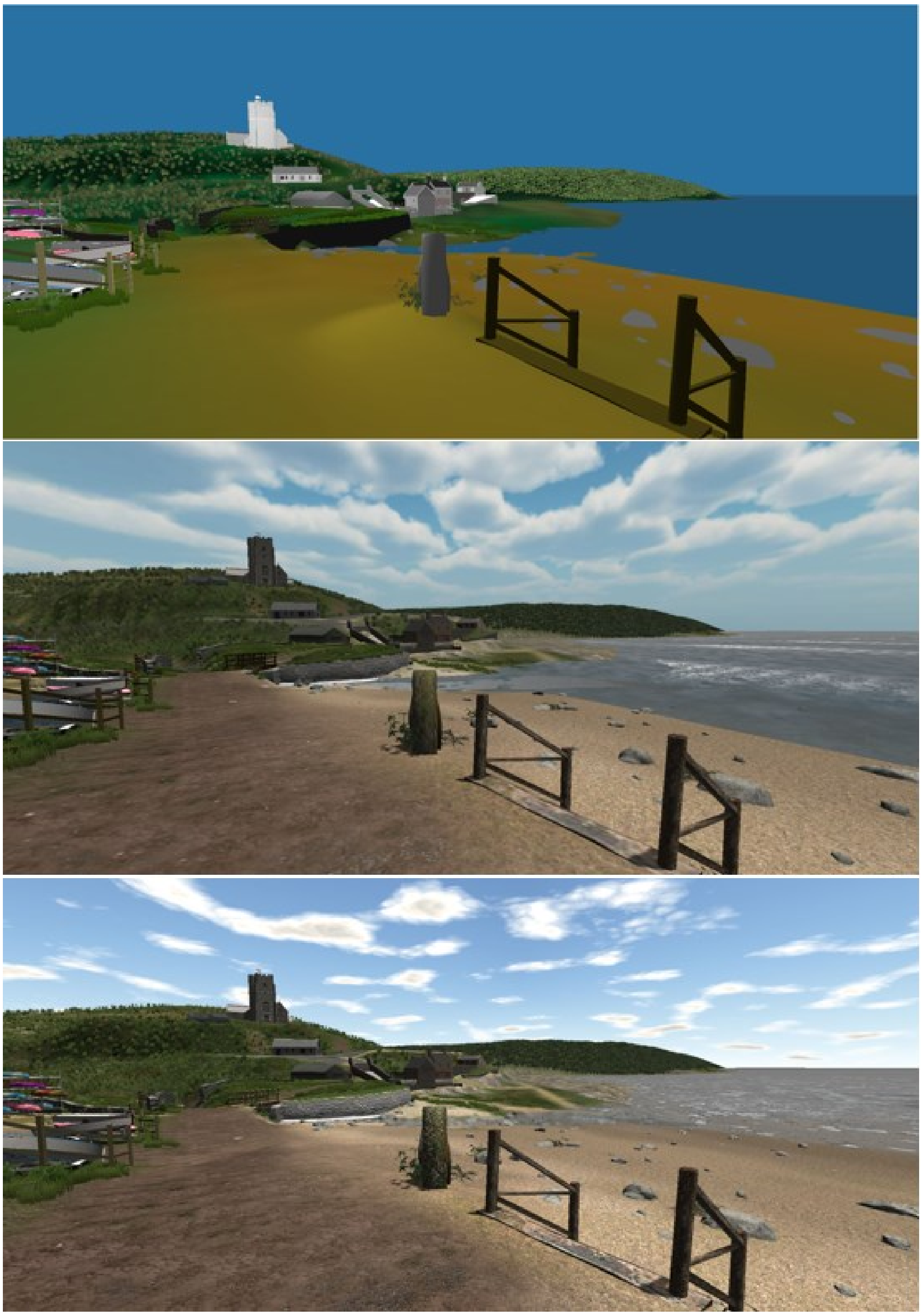

Figure 6.6 Screenshots of Three Image Quality Levels. Upper: low image quality; middle: medium image quality; lower: high image quality.

6.3.2.3 Procedure

The experiments took place in a secluded, quiet room. Only the participant and the experimenters were present. Following the explanation of the research, all participants were required sign an informed consent form. The participants sat on a standard office chair with height adjusted to a comfort level directly in front of a large-screen (50-inch LG^{TM}, 1920 x 1080 resolution, and 60 Hz refresh rate) TV display. On the display the virtual coastal scene (Virtual Wembury) was presented at 25 frames or more per second in all conditions. In conditions with sound (i.e. conditions 4 and 5), the participants wore wireless headphones (Sennheiser^{TM}) which presented virtual context-specific ambient sounds (e.g. waves and birdsong).

Prior to testing the participants were given the opportunity to practice using the system, specifically navigating the environment with the Microsoft Xbox wireless controller (which has been shown to possess the highest usability rating among the four chosen controllers in the usability studies, as described in Section 6.2). Then, the experimenter described the general layout of virtual scene (e.g. buildings on the hill, coastal path along the coast line etc.), as there were questions about quality of models such as the quality and realism of manmade objects, trees, water etc. in the questionnaires to be administered later. After the beginning of data collection, the participants were directed to roam around the virtual environment using the controller provided. The participants were not given any specific task or goal; instead they were simply asked to explore the environment freely. After a period of 15 minutes, the participant was directed to cease roaming.

With five conditions, to assess the effect of each on the participant, a repeated measures design was implemented. As such, each participant undertook all five conditions. To minimise any learning effect, the order of the three conditions were mixed between participants using a Latin square protocol. Participants were given a minimum 5-minute break between each condition to minimise any fatigue effects between conditions.

6.3.2.4 Objective Measures

The objective navigation data were recorded by the user exploration tracking/logging system (as described in Section 5.6) including the detailed user path and the replay data during the user's navigation in VE.

6.3.2.5 Subjective Measures

After each condition the participants were asked to complete three different types of subjective rating measure, capturing their responses to presence, quality and realism. The presence measurements were based on the Slater-Usoh-Steed questionnaire (Usoh et al., 2000), the only difference was that the phrase "in a VE" was changed to "on the coast". The question of primary interest was a rating question on overall presence - "I had a sense of "being there" on the coast", rating from "Not at all" to "Very much". The quality questionnaire designed by the author (see Appendix B) consists of similar questions on visual elements in the coastal scene, such as sky, lighting, water, ground cover, plant, buildings and man-made objects. A typical question was "How would you rate the quality of the sky?" An example question from the realism questionnaire designed by the author (see Appendix B) was "Overall, how realistic was the landscape?" The word "landscape" was replaced by other parameters from the scene, such as man-made objects, movement, sound of walking, movements of the natural elements and ambient sounds. There was also a question of overall realistic rating of the virtual world in the realism measure.

The presence and realism measures were recorded on Likert rating scales. Each measure consisted of 5 to 7 questions, requiring the participants to complete 19 questions in all. The participants were guided through the questionnaires by the experimenter, and the experimenter encouraged the participants to explain their response or to add qualitative statements to their ratings when necessary.

6.3.3 Results

The reliability analysis (as described in Section 6.2.4) demonstrated that the overall reliability of the presence, quality and realism ratings was excellent (presence: α (Cronbach's alpha) = 0.962; quality: α = 0.938; realism: α = 0.913).

As shown in Figure 6.7, the overall average score of presence for low image quality (10.26, *STDEV* = 4.33) was lower than the rating for medium setting (18.73, *STDEV* = 6.38). As shown in Table 6.8, a one-way ANOVA was used to address any differences of the overall presence ratings between the five conditions. There was a significant main effect on ratings of presence due to fidelity levels [$F(4, 72) = 31.512$, $p < 0.001$]. In addition, the difference of presence ratings between low and medium quality was statistically significant ($p < 0.001$). There were no significant main effects between the medium and high quality levels ($p > 0.05$), and between the high quality levels with or without natural motions ($p > 0.05$). However, the presence rating of the medium level (18.74, *STDEV* = 6.38) was significantly lower than the condition with high image quality and motion (22.53, *STDEV* = 6.42, $p = 0.01$). Presence in the high quality level with motion and sound was reported significantly higher than all of the conditions without sound ($p < 0.001$).

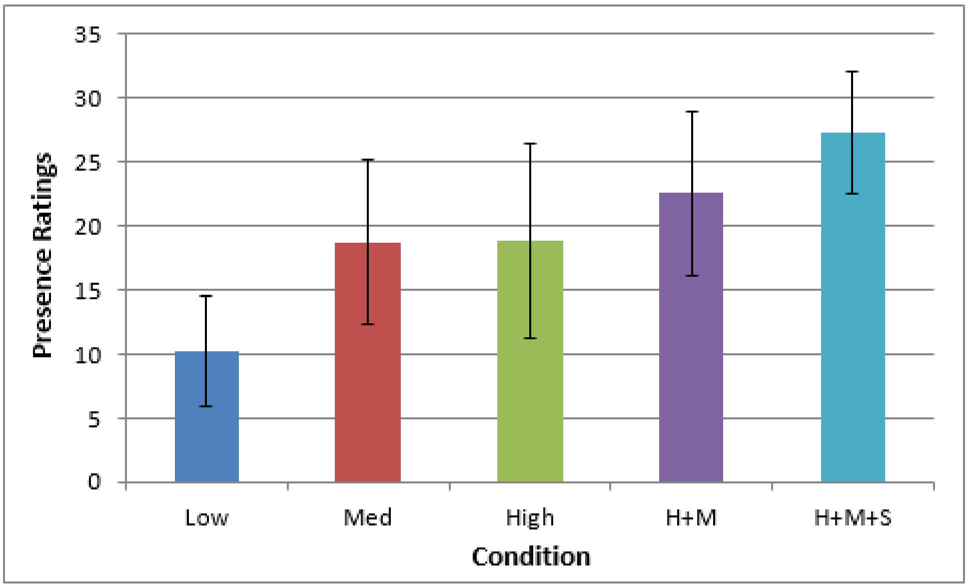

Figure 6.7 Average Total User Rating of Presence (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound. Y-bars indicate standard deviation of the average value.)

	Low	Med	High	H+M	H+M+S
Low		0.000	0.000	0.000	0.000
Med			0.976	0.010	0.000
High				0.085	0.000
H+M					0.000
H+M+S					

Table 6.8 p Values of The Differences on Ratings of Presence (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound)

As demonstrated in Figure 6.8 and Figure 6.9, the ratings of quality and realism had similar tendencies (i.e. the ratings increased from low to medium quality condition, decreased slightly from medium to high quality condition, and increased gradually from high quality, through the condition of high quality with motion, to the condition of high quality with motion and sound) as presence ratings. As shown in Table 6.9, there was a significant main effect on ratings of quality in terms of fidelity [F (4, 72) = 40.385, p < 0.001]. The difference of quality ratings between low quality (13.53, *STDEV* = 4.35) and medium quality (24.63, *STDEV* = 4.42) was statistically significant ($p < 0.001$). The difference of quality scores between medium and high levels was not significant ($p > 0.05$). There was also no main effect between high settings with and without motions, nor between high quality with motion and sound or no sound.

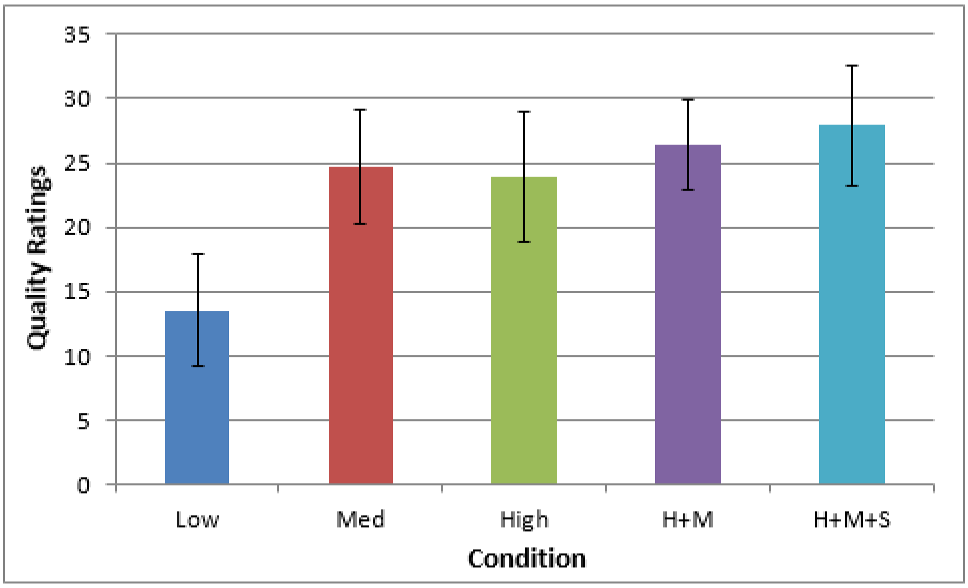

Figure 6.8 Average Total User Rating of Quality (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound. Y-bars indicate standard deviation of the average value.)

	Low	Med	High	H+M	H+M+S
Low		0.000	0.000	0.000	0.000
Med			0.586	0.144	0.009
High				0.081	0.012
H+M					0.154
H+M+S					

Table 6.9 p Values of the Differences on Ratings of Quality (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound)

There was also a significant effect on realism ratings due to fidelity as shown by the results of a one-way ANOVA [$F(4, 72) = 32.785$, $p < 0.001$]. As shown in Table 6.10, only the differences of realism between medium and high settings, and between the high setting with or without sound were not statistically significant ($p > 0.05$).

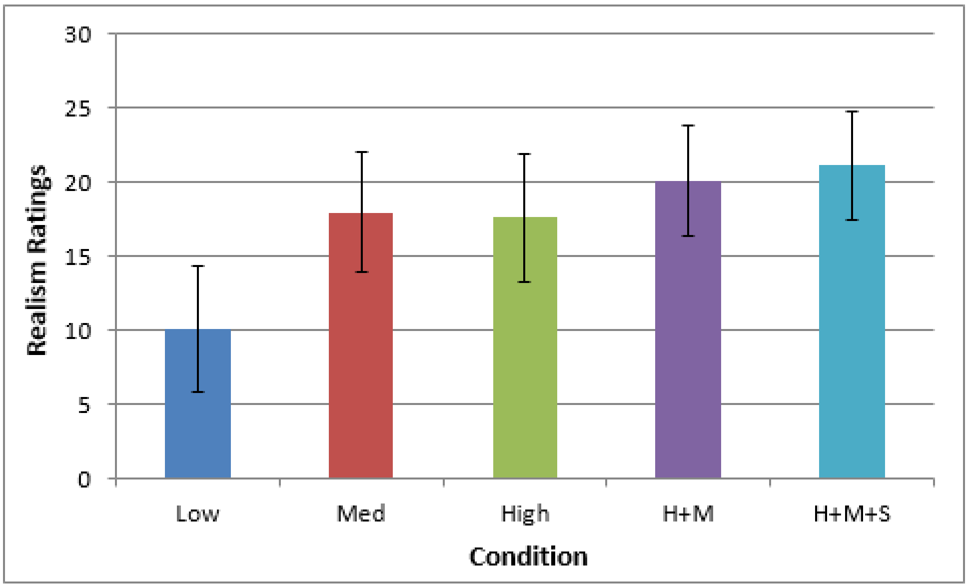

Figure 6.9 Average Total User Rating of Realism (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound. Y-bars indicate standard deviation of the average value.)

	Low	Med	High	H+M	H+M+S
Low		0.000	0.000	0.000	0.000
Med			0.732	0.029	0.001
High				0.033	0.007
H+M					0.131
H+M+S					

Table 6.10 p Values of the Differences on Ratings of Realism (Med: medium image quality; H+M: High image quality + Motion; H+M+S: High image quality + Motion + Sound)

Based on Dancey and Reidy's (2007) categorisation in Table 6.11, a correlation analysis (as shown in Table 6.12) indicated a significant correlation between scores of presence and quality, and this correlation was “moderate” [$r = 0.581$; $p = 0.009$]. The analysis also revealed moderate relationships between presence and realism [$r = 0.636$; $p = 0.003$]. In addition, There was a strong relationship between quality and realism [$r = 0.802$; $p < 0.001$].

Value of the Correlation Coefficient	Strength of Correlation
1	Perfect
0.7 - 0.9	Strong
0.4 - 0.6	Moderate
0.1 - 0.3	Weak
0	Zero

Table 6.11 Dancey and Reidy's (2007) Categorisation of Strength of Correlations

		Presence	Quality	Realism
Presence	Pearson Correlation	1	0.581**	0.636**
	Sig. (2-tailed)		0.009	0.003
	N	19	19	19
Quality	Pearson Correlation	0.581**	1	0.802**
	Sig. (2-tailed)	0.009		0.000
	N	19	19	19
Realism	Pearson Correlation	0.636**	0.802**	1
	Sig. (2-tailed)	0.003	0.000	
	N	19	19	19

N.B. **. Correlation is significant at the 0.01 level (2-tailed).

Table 6.12 Correlations of the Overall Ratings of Presence, Quality and Realism

6.3.4 Discussion

There were significant differences of overall presence, quality and realism ratings between the low and medium quality levels. This suggests that the image settings from low to medium level may increase a sense of actually being at a coastal setting. However, as shown in Table 6.7, there were approximately 20 quality settings, including texture, shader, image effect (e.g. anti-aliasing) and lighting, changed from the low quality setting to the medium. The reported quality and realism scores of the sky, lighting, sea, landscape and buildings all increased from the low to the medium fidelity condition. Any of those factors could contribute to the difference of presence. Therefore, the overall improvement of quality settings from low to medium appear to contribute to an increase in users' sense presence, and this may be mainly because of the enhancement of textures, as the comments added to the ratings by the participants reported that the changes of textures from low to medium quality settings were "quite obvious". Future work will seek to compare specific factors of the quality settings in terms of presence, in order to assist the design and optimisation of virtual restorative environments.

There were no main effects on overall presence, quality and realism ratings between medium and high quality settings. In addition, the overall quality rating even decreased slightly from medium to high level. The difference of texture quality between the medium and high levels was a result of changing the texture shader from Diffuse to Bumped Specular. As shown in Figure 6.10, the trajectory data from the software logging system showed that some participants did not demonstrate any periods of close observation, or "dwelling" in the vicinity of those man-made objects which had been the focus of the shader improvements listed above. This may have an effect on their ratings. In addition, a t-test revealed that the reported quality of the sky in the high quality condition was significantly lower than in the medium condition [$t(18)= 2.272$, $p = 0.036$]. The reported quality rating of the sea and water also declined in the high quality condition, although this difference was not statisticly significant ($p > 0.05$). As stated in Table 6.7, the sky changed from standard Unity skybox to the Unisky. The main purpose of integration of Unisky system (as described in Section 5.4) was to introduce a 24-hour day/night time system with motion of the clouds and atmospheric scattering for different sky colours at any time of day. The results suggested that the participants prefer the traditional skybox to that provided by the Unisky package. Meanwhile, the sea model was changed from simple Unity Water 3 to a "complex mode" of Unity Water 4 which was a newer version, claimed by the developers to delivery better visual quality (Unity3D (2014). The results indicate that use of the older version of the Unity ocean asset has little impact on user presence, and will certainly help to improve the system performance (e.g. increase frame rate) and reduce the need for a more powerful (and potentially expensive) VE computer system.

Figure 6.10 A Screenshot of a Trajectory of a Participant's Navigation in the Condition of High Quality Level

Although the overall difference of presence and quality ratings between high-quality level with and without motion is not statistically significant, it is statistically significant in terms of realism. However, the difference in presence ratings was significant between the high quality condition with motion and the medium quality setting. The objective measures of the user trajectory showed that some of the participants went straight to areas mainly consisting of static man-made objects (e.g. buildings, bridges), whilst those areas consisting of elements with motion were not observed. The ratings of motion from these participants were lower than others. Future studies of in-scene motion should ensure that participants are encouraged to explore as many areas of the VE as possible, by means of a guided path, for example, thus exposing them to as many of the VE features of interest in the study of fidelity as possible.

Figure 6.11 A Screenshot of a Trajectory of a Participant's Navigation in the Condition of High Quality Level with Motion

There were no significant effects on the ratings of quality and realism in the high quality level with and without sound. This was because the two questions relating to sounds in the realism questionnaire were not included in the ANOVA analysis, as these were not applicable for other conditions without sound. The rating of the realism of sound of walking was average (4.53, *STDEV* = 1.88) and ambient sound was rated as high (6.13, *STDEV* = 1.06). Consequently, the presence ratings increased dramatically due to sound. This result supported the outcome of the early pilot study, which discovered that the presence of sound may contribute to effects in the VEs that improve human well-being, as displayed by a reduction in anxiety and a promoted sense of relaxation. Future work will improve the fidelity of the walking sound effects in the restorative environment. For instance, the use of high-fidelity sound effects which correspond to the contact surface on which the user is "walking" (e.g. wooden floor, muddy coastal path, sand, water in a stream or brook).

6.4 User Exploration Tracking and Presence within Real-World-Based Virtual Natural Environments

6.4.1 Background

In the pursuit of attempting to replicate similar restorative effects on humans to those demonstrated in real-world settings, a number of factors have been investigated. In previous studies, VE system usability issues that were felt to have an impact on presence have been investigated. A significant influence of visual and auditory fidelity on reported presence rating has also been revealed. But are there any other factors that may be related to user experience in virtual natural environment? In December 2012, one year before a more formal experiment was conducted in the village of Wembury, a “Virtual Wembury Evening” event was held in the village hall by the Human Interface Technologies (HIT) team (see Section 8.4.1 for more detailed information of the event).

The villagers were able to explore Virtual Wembury displayed either on a 50-inch TV display or a Sony HMZ-T1 HMD using an Xbox controller. The sound effects were delivered using Sennheiser wireless headphones. There were no time limits or specific tasks given to the participants. Some of the participants did not use the headphones, whilst others were simply spectators who watched the virtual view of others’ navigational attempts on the screen. Questionnaires about user background (age, gender, place of residence, use of computers, etc.) and on the Virtual Wembury project itself were given to the participants. 44 participants (19 male, 25 female) returned the questionnaires in the end of the event. Approximately 3/4 of the participants were over 50 years of age. Only 5 of them were not actual Wembury residents, yet still lived in Devon around this region.

As shown in Table 6.13, almost all of the participants showed great interests in the Virtual Wembury project, especially for “creating a virtual version of Wembury”, virtual heritage and using VR in hospital care. Perhaps unsurprisingly, the participants reported higher interests in the creation of VE based on the local area than on virtual natural environments in general.

	No. of responses	Not at all interesting	Slightly interesting	Somewhat interesting	Considerably interesting	Very interesting
Using latest gaming technology	*35*		3	6	13	13
Using VR	*35*		2	5	15	13
Using computers to create virtual natural environments	*35*	1	1	4	16	13
Creating a virtual version of Wembury	*35*			4	14	17
Local history	*35*			6	12	17
Using VR for local history	*35*			5	13	17
Using VR in hospital care	*34*			5	9	20

Table 6.13 User Interest in the Virtual Wembury Project

In general, highly positive feedback was given by the participants following their experience of Virtual Wembury (see Table 6.14). One participant commented that she “very much enjoyed it”, and “felt like Alice in Wonderland” during the exposure. Others suggested that the VR experience was enjoyable and should be extended to a larger coastal area for wider choices and experiences.

	No. of response	Mean rating	Distribution of rating (1 = poor, 10 = excellent)									
			1	2	3	4	5	6	7	8	9	10
Virtual Wembury (Overall)	*30*	8.0		1	1		1	1	3	11	5	7
Realism of Virtual Wembury	*28*	7.5			1		2	5	6	6	3	5
Sound effects in Virtual Wembury	*15*	7.2			2		2		3	4	1	3
Use of games controller	*20*	7.9			2		2		1	5	5	5
Use of Head Mounted Display	*12*	6.7	1		1	1	1		2	3	1	2

Table 6.14 The Ratings of User Experience in Virtual Wembury

The high ratings of reported interest in this project and satisfaction of the VR experience from the local community suggest a possible high level of user engagement in using the VR system. Lepper & Malone (1987) suggest that greater user engagement is associated with more time spent on learning activities, better learning efficiency and more sustained interest in educational content. Lessiter et al. (2001) argue that engagement is one of the four factors for measuring presence level during user exposure to VEs. Therefore, user behaviour and a sense of presence may vary depending on the different levels of user engagement on the part of local and non-local participants. It was decided, therefore to conduct a short experiment involving the Virtual Wembury scenario, but using both local and non-local participants.

6.4.2 Aim

The aim of this study was to determine whether or not there were differences in navigation and engagement of participants who were asked to navigate a virtual natural environment based on an area local to their place of living (in this case Wembury), in contrast to navigating a VE based on a non-local area (a large-scale virtual natural forest scene with lake). Specifically, this study aimed to determine if such differences could be distinguished by the total time of exposure and the rating of presence.

6.4.3 Methods

6.4.3.1 Participants

Fifteen local villagers in Wembury (Devon) participated the study (male = 7, female = 8; mean age = 68, age range: 45 – 78).

6.4.3.2 Conditions

There was one independent variable for this experiment - the virtual scene itself. The participants were asked to roam around two scenes: a natural coastal scene (Virtual Wembury) and a natural forest scene with lake (a modified version of Virtual Burrator, as described in Section 5.8). Therefore, there were two conditions in this study.

As described in Sections 5.2, 5.3 and 5.6, this extended version of Virtual Wembury includes a 24-hour day-night cycle system, a variety of virtual animals (e.g. rabbits, seagulls, dolphins etc.), and a user navigation tracking system. Virtual Burrator was specially modified for this study. All of the natural features (e.g. a ravine next to the main Burrator dam) and man-made objects (e.g. two dams of the Burrator reservoir) that would identify the area to those who may have visited it in the past were removed completely and replaced by general forest features. Both coastal and forest scenes covered an area larger than $4km^2$.

6.4.3.3 Procedure

The experiments took place in a secluded, quiet room (in this case a meeting room in Wembury Village Hall – see http://wemburyvillagehall.org.uk/). Only the participant and the experimenters were present at any one time. Following the explanation of the research, all participants were required sign an informed consent form. The participants sat on a standard office chair with height adjusted to a comfort level directly in front of a large-screen (50-inch LG, 1920 × 1080 resolution, 60 Hz refresh rate) TV display. On the display the virtual natural scenes were both presented at 25 frames or more per second. In both conditions, the participants wore wireless headphones (Sennheiser) which presented virtual context-specific ambient sounds (e.g. waves, birdsong, sound of footsteps).

Prior to testing, the participants were able to practice using the system, specifically navigating the environment with a Microsoft Xbox wireless controller. There was no time limit, so that the participants could carry on practising until they had familiarised themselves with the controller. This freedom to become familiar and comfortable with the use of the Xbox controller was an important aspect this experiment, given the ages of most of the participants. The participants were made aware that they were not expected to undertake any specific task or goal during both experimental conditions. Instead, they simply explored the environment freely, at their own "pace". They were also instructed that the duration of navigation for both scenes was their choice, although there was a 10-minute limit. After a participant confirmed his or her readiness, the data collection began. After a participant stated that he/she had finished, or a period of 10 minutes had elapsed, he/she was directed to cease.

A repeated measures design was employed. Therefore, each participant completed both conditions. To minimise any learning effect, the order of the two conditions was mixed between participants using a Latin square protocol. Participants were given a minimum 15-minute break between each condition, to minimise any fatigue affects between conditions.

6.4.3.4 Objective Measures

The user tracking system records the participant's movement - the detailed path that the user leaves behind through the VE from start of session to the end. A 3D in-game replay of the user's movement and the view of the virtual camera are used to represent the user's head during first-person navigation. The recorded path can be loaded in-game or be exported as high definition image for post-experiment analysis. The in-game replay system has a range of conventional functions such as load/save, play/stop and forward/back, as reported in Section 5.6.1. The user logging system records the time (in seconds) spent by the participants during their exploration.

6.4.3.5 Subjective Measures

Both conditions used the presence and realism questionnaires employed in the previously-described fidelity experiment. In addition, five semantic differential scales of experience were modified from the Flow-Simplex Scale (Vittersø et al., 2000) for evaluation of satisfaction in the two scenes (see Appendix C). They were: Dull - Stimulating, Unpleasant – Enjoyable, Boring – Interesting, Unimpressive – Remarkable, Negative – Positive.

A questionnaire addressing "Fidelity and Accuracy to Wembury" was designed by the author and used only for the coastal condition (see Table 6.15 in the results section and Appendix C). The core question was "Do you think exploring a virtual environment that you recognised improved your experience?" which reflected the main aim of this study. The questions in all questionnaires took the form of 7-point Likert scales.

Participants were also asked about their computer gaming experience. This involved completing a background information questionnaire, which, it was felt, could help classify or correlate presence data in terms of previous experience.

6.4.4 Results

Thirteen participants finished the experimental trials. Two participants did not complete both trials. One participant (a male, aged 69) did not undertake the second (Wembury) trial because of sickness. Based on the participant's comment, there were initial feelings of queasiness when being hesitant (moving left and right, deciding which way to go to avoid a tree) when practising to use the controller. The participant was concerned that the effects might be exacerbated by wearing the wrong glasses (she had not, in the event, brought her computer glasses). The alternative suggested involved lowering the screen so that she could view through her bifocals. The participant also suggested that dense trees in the forest scene and the height differentials of off-the-path terrain caused such sickness, described as “being on a boat or rollercoaster”. The second participant who did not complete the experiment (a female, aged 69) experienced varying instances of nausea after 9 minutes in the coastal scene, despite showing very fine motion control at the beginning. With hindsight, this participant would prefer the Genius Ring Mouse “jump-and-watch” option (see Section 5.5.2). To use her words, she preferred to “move a little, then just watch and listen.” This participant only tolerated the second (forest) trial for 3 minutes because of unbearable discomfort.

A reliability analysis (as described in Section 6.2.4) showed that the reliability of the presence and realism datasets were good (Presence: $\alpha = 0.867$; Realism: $\alpha = 0.810$). The reliability of the satisfaction data was excellent ($\alpha = 0.944$).

As shown in Figure 6.12, the reported presence scores of the coastal condition were higher than those in the forest condition. The average rating of presence was 5.09, *STDEV* = 1.47 for coastal settings and 4.15, *STDEV* = 1.48 for forest settings. A Paired-Samples t-Test showed this difference was statistically significant [$t(12) = 4.037$, $p = 0.002$].

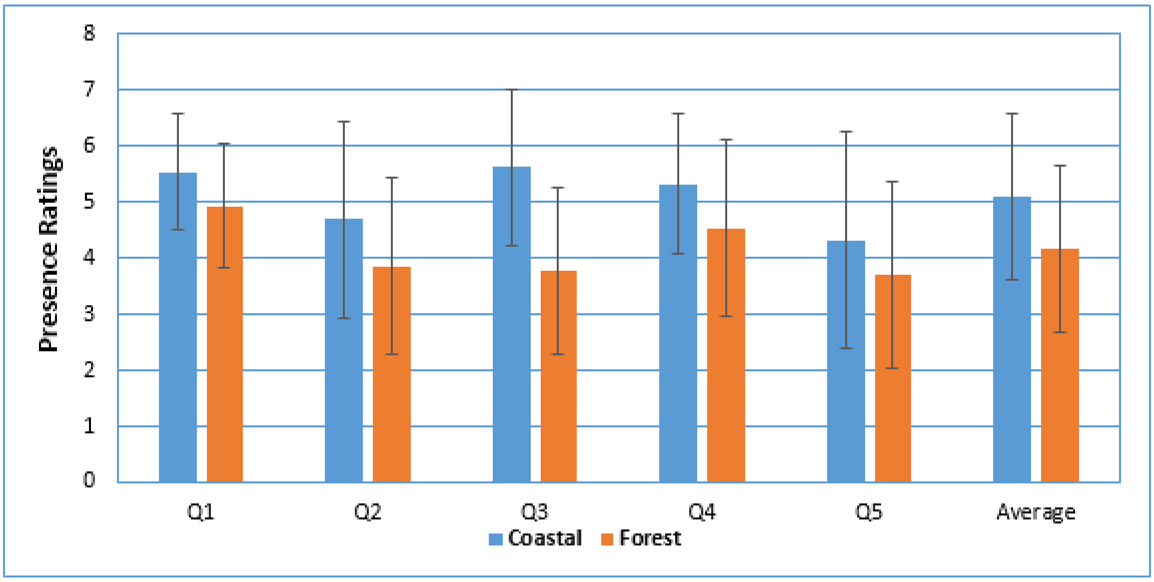

Figure 6.12 Average Ratings of Presence (Y-bars indicate standard deviation of the average value. Q1 to Q5 indicate question 1 to 5 in the presence questionnaire.)

Figure 6.13 shows that the ratings of realism of the coastal condition were higher than the forest condition. The average rating of realism was 4.93, *STDEV* = 1.12 for costal settings and 4.39, *STDEV* = 1.39 for forest settings. A Paired-Samples t-Test showed this difference to be statistically significant [t(12)= 4.277, p = 0.001].

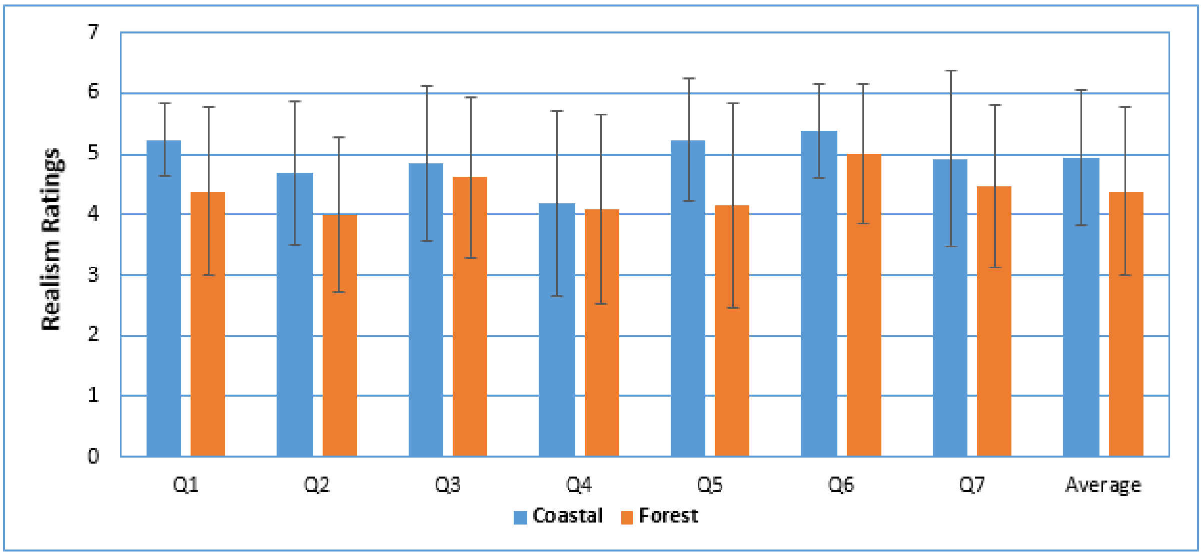

Figure 6.13 Average Ratings of Realism (Y-bars indicate standard deviation of the average value. Q1 to Q7 indicate question 1 to 7 in the realism questionnaire.)

The ratings of realism of the coastal condition were also higher than the forest condition (see Figure 6.14). The average rating of realism was 5.78, *STDEV* = 1.20 for costal settings and 5.35, *STDEV* = 1.10 for forest settings. However, a t-Test showed this difference not to be significant [t(12)= 2.018, p > 0.05].

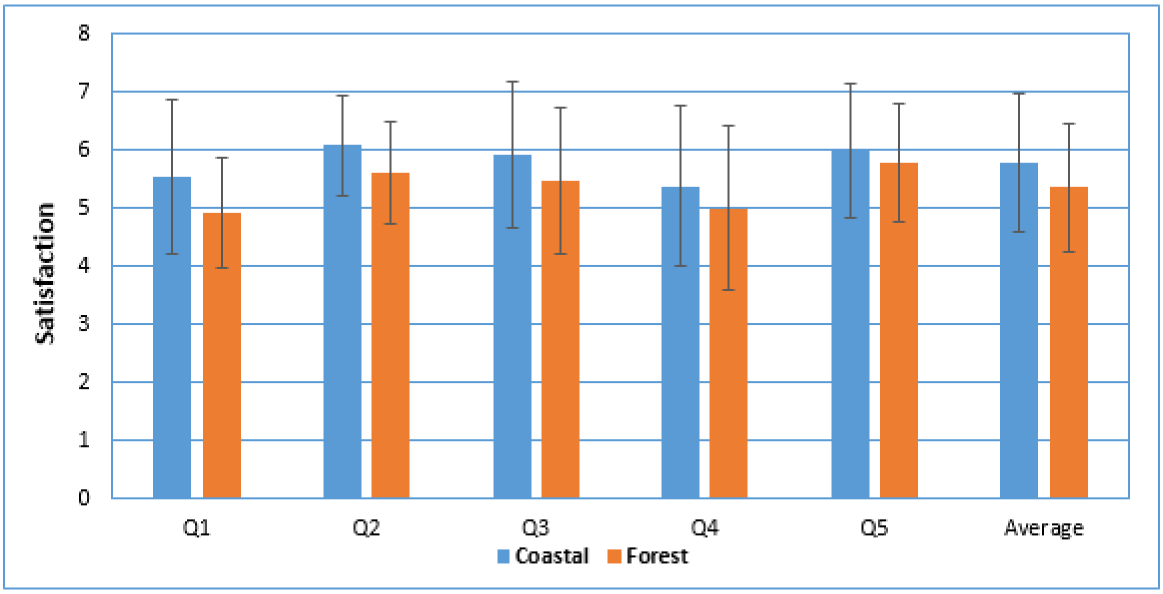

Figure 6.14 Average Ratings of Satisfaction (Y-bars indicate standard deviation of the average value. Q1 to Q5 indicate question 1 to 5 in the satisfaction questionnaire.)

As shown clearly in Table 6.15, the participants claimed that they knew the area on which Virtual Wembury based very well (6.25, *STDEV* = 0.92). The ratings of fidelity were slightly above medium. The overall rating of the fidelity of Virtual Wembury was 5.00, *STDEV* = 1.08. The rating for the impact of the inaccuracies in Virtual Wembury was 3.45, *STDEV* = 1.66. The question relating to how the exploration of a VE that can be recognised as a reconstruction of a real-world setting might improve the user's experience was rated 5.50, *STDEV* = 1.09.

Questions	1	7	Mean	*STDEV*
How well do you know with the area of coastline between Wembury Point and Gara Point?	Not at all	Very	6.25	0.92
Overall how would you rate the fidelity of **Virtual Wembury**? How accurate is it to the real place?	Low	High	5.00	1.08
How would you rate the fidelity of the **landscape**?	Low	High	4.77	0.83
How would you rate the fidelity of the **buildings and other man-made structures**?	Low	High	4.42	1.73
How would you rate the fidelity of the **plant life**?	Low	High	4.46	1.20
How would you rate the fidelity of the **animal life**?	Low	High	4.54	1.45
How would you rate the fidelity of the **sound content** (e.g. wind, waves, birds)?	Low	High	4.85	0.90
Do you think any inaccuracies in Virtual Wembury affected your experience?	Not at all	Very much	3.46	1.66
Do you think exploring a virtual environment that you recognised improved your experience?	Not at all	Very much	5.50	1.09

Table 6.15 Questionnaire and results of Fidelity and Accuracy to Wembury

Figure 6.15 shows the objective data of time spent (in seconds) in the virtual coastal and forest scenes (543.09, *STDEV* = 82.09; 468.26, *STDEV* = 111.61).

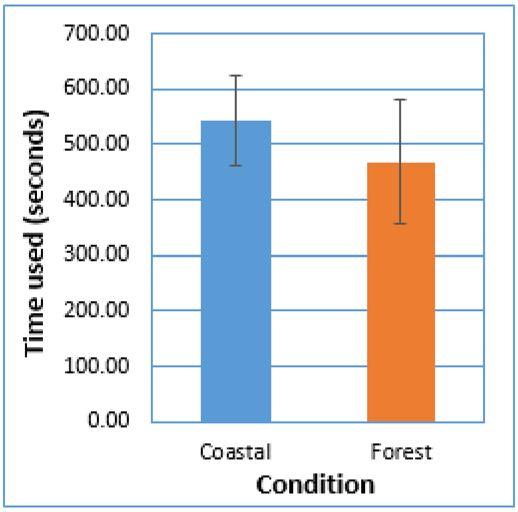

Figure 6.15 Average Time Used in Virtual Coastal and Forest Scenes (Y-bars indicate standard deviation of the average value.)

6.4.5 Discussion

The ratings of presence during exposure to Virtual Wembury was significantly higher than those for the forest setting. Also, the question “Do you think exploring a virtual environment that you recognised improved your experience?” had a relatively high score. This suggests that a real-world-based virtual natural environment is likely to be accompanied by a positive experience on the part of a local user, in contrast to that same user’s experience of a non-local VE. As noticed, the reported realism of the coastal scene was also significantly higher than the forest scene, which was based on how realistic the elements were in the VEs (e.g. grass, trees, motions, sound etc.). However, when developing those two natural settings, the techniques (e.g. software development toolkits, modelling processes) and quality were similar. For example, the two VE settings shared the same game engine (Unity3D), the same sky/lighting system, the same first person controller, and even the terrain representations used the same resolution of height maps and aerial photos. Additionally, the settings of these systems were adjusted to minimise discrepancies prior to the experiment. Therefore, it was likely that the reported realism of the coastal scene was also boosted because of the local regional factor. Furthermore, the participants believed that the inaccuracies in Virtual Wembury only affected their experience a little. This suggests that a real-world-based VE increases a local user’s presence even if it is not a 100% accurate representation of the real world.

However, based on the comments that were given during and post-trials, there were some suggestions for the possible improvement of the VREs that are worth recording here. For example, three participants thought that the harsh LOD (level of detail, which decreases the complexity of the 3D mesh of a virtual object as this object moves away from the virtual camera (Unity3D, 2014)) of the trees was distracting. One participant suggested that the virtual seagulls should, as is the case in reality, circle over the cliffs to the east of Wembury beach as opposed to over the beach area. It was also suggested that there should be “wild ponies” and “sheep” on the higher ground. Some participants even mentioned that some of the gates and fences were not accurate. Future development of the VEs will seek to improve the fidelity of the virtual settings based on such comments, in order to remove the distracting elements and further improve the users’ experiences.

The t-Test results showed that the time spent in the Virtual Wembury scenario, as logged by the user tracking system, was significantly higher than that of the forest settings [$t(12)= 2.787$, $p = 0.016$]. Most of the local participants were highly supportive and enthusiastic for the experiment - approximately half of them spent the full 10-minute period navigation in both conditions. Virtual Wembury was “very calming” as commented by one of the participants, who thought it was “like a 5-minute experience” as opposed to 10. Such support was very encouraging in terms of development of future virtual restorative environments. Additionally, the area covered by each of these two scenes is well over $9km^2$ ($3km \times 3km$). It was unlikely that participants could explore the whole area in less than ten minutes, not to mention that a number of participants stopped during their navigation to have a closer look at some of the objects (e.g. flowers, signs, fingerposts, etc.). In future studies, a longer period of exposure will be employed to investigate any time-related effects and to allow the participants themselves to choose when they wish the session to end.

There were some issues in terms of usability. It was remarked by some that the walking speed was “too slow” or “too fast”. One participant had problems with crossing the footbridge by using the Xbox controller (see Figure 6.16). One participant appreciated the usability and comfort of the Xbox controller, even with a significant right wrist and lower arm injury, commenting "I would not have appreciated any controller that would have required wrist rotation". As the results of the background questionnaire indicated that only 3 of the 15 participants played computer games, even their gaming experiences were very limited. In order to increase the ease of use by participants with various gaming backgrounds, further studies will make walking speed adjustable by users in future versions of the VEs.

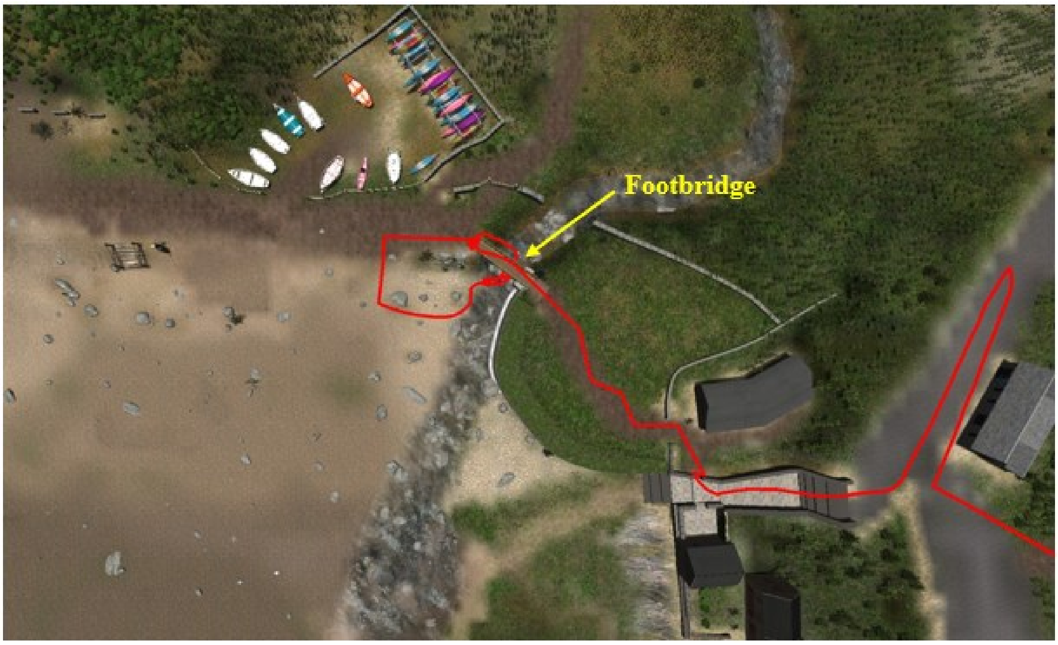

Figure 6.16 A Screenshot of the Trajectory of a Participant with Trouble Crossing a Footbridge

Another usability issue was that four (i.e. more than 25%) participants experienced different levels of sickness symptoms, such as nausea and disorientation. Two of them withdrew from the experiment after finishing one condition as reported in the results. The third participant ended the first condition (forest) early at 8 minutes because of slight simulator sickness, and stopped at 8 minutes into the second condition (Virtual Wembury), showing a strong manifestation of simulator sickness (in this case she actually vomited). Another participant enjoyed the first trial (Virtual Wembury), but felt "queasy" towards the end of the forest trial. As suggested in previous research, as many as 80% to 95% of users will experience some degree of disturbance during exposure to virtual environments (Stanney et al., 1998; Cobb et al., 1999), and 5% to 30% of such users will manifest symptoms severe enough to withdraw from exposure (DiZio & Lackner, 1997). Furthermore, and as discussed in literature review section, a higher simulator sickness score has been found for people over age of 50 than that of younger participants (Arns & Cerney, 2005). Therefore, future studies will seek possible solutions with respect to this issue, such as ensuring that the participants are aware that they can withdraw from the exposure at any time for any reason, including simulator sickness, and that experimenters are aware of the early symptoms of such sickness (e.g. general discomfort, sweating, nausea and burping). In addition, the "jump-and-watch" navigational function will be provided as a standard option, and users will be able to easily switch between pre-selected views within the VE and will, once choosing a desired viewpoint, be able to pan their viewpoint left and right freely as described in Section 5.5.2. Such functions will be recommended to participants with limited gaming background, over 50 years of age or with previous/regular experiences of simulator, vehicle or sea sickness.

Finally, in terms of experimental design, ideally, a group of non-locals with similar age, gender, gaming background, and work experience etc. would be preferred, in order to determine whether locals navigate a virtual environment based on a real place differently than non-locals. However, it would be rather difficult to find such group. If one was to use non-local with different personal backgrounds, these variables may have an effect on results, and unfortunately, could not be controlled.

6.5 Conclusion

This chapter described experiments that investigated a number of factors that were judged to have significant impacts on users' experiences of the virtual restorative environments.

Of the four commercial off-the-shelf input devices or controllers used in the research, the Xbox controller was rated highest overall in terms of usability ratings, while participants with hand injuries preferred using the conventional joystick. The Keyboard and Mouse combination scored the lowest ratings overall and for hand injured participants. Therefore, in the later applications of the VRET systems, the Xbox controller and joystick were chosen as the standard input devices for the end users.

The improvement of visual fidelity in the Virtual Wembury scenarios was accompanied by increases of reported presence, quality and realism, although this tendency appeared less obvious between the medium visual quality and high visual quality fidelity conditions. The inclusion of auditory stimuli, including ambient and context-relevant sounds, plus walking sound effects, had a significant positive impact on user presence ratings. Therefore, further development and creation of virtual natural environments will include high fidelity spatial sound and will investigate the use of walking sound effects based on different under-foot materials. Visual fidelity will also be improved using latest VR techniques and resources within budget limits, in order to maintain a balance of visual quality and system real-time rendering performance.

Real-world-based virtual natural environments were shown to increase the reported presence and realism ratings on the part of participants who live locally to the reconstructed scenes. This is quite an important finding and suggests that the participation of local inhabitants in the development of nearby VEs may be crucial for the subsequent acceptance and adoption of those VEs for local purposes, which could range from educational uses in local schools to the development of virtual heritage or historical scenarios.

There were some limitations discovered during the execution of some of the experiments introduced in this chapter. One of the most concerning was the incidence of a range of simulator sickness symptoms (from “queasiness” to actual vomiting), especially in the experiment conducted in collaboration Wembury villagers. A number of possible causes of such side effects have been discussed, including age, VR gaming background, visual display and the delay between user input and system response. Solutions including increasing the display frame rate, offering additional control means or a different level of interaction (e.g. free roam, “Jump-and-Watch”) and lowering the system delay. These have, since the Wembury experimentation, implemented to minimise the possibility of inducing simulator sickness in the future.

In terms of requirements for visual quality, although the results of the experiments showed in general that higher visual quality increased the reported sense of presence, the influences of individual visual settings (such as texture, shader, image effects, etc.) on presence still require systematic and detailed study. Future work will seek to compare specific factors of the quality settings in terms of presence, in order to assist in the design and optimisation of virtual restorative environments.

Chapter 7 Virtual Natural Environments for Rehabilitation: Sleep Study in an Intensive Care Unit

In collaboration with medical and nursing staff at the QEHB and the Royal Centre for Defence Medicine (RCDM), a series of sleep studies trials are, at the time of writing, being conducted within the hospital's Intensive Care Unit (ICU). The protocol (see Appendix D) of this study was designed by the lead clinical collaborator, ST5 Anaesthetist, Dr Charlotte Small, with inputs from the University of Birmingham's Human Interface Technologies Team. This study has actively involved the author of this thesis, and is exploiting all of the author's research findings in the form of the up-to-date virtual natural environment (VNE) – Virtual Wembury (as described in Chapter 5).

Many studies have investigated the factors related to the intensive care environment and a patient's personal condition that lead to sleep deficit. The environmental factors include high noise level, light, ambient temperature and lack of a clock (McCusker et al., 2001; Fontana & Pittiglio, 2010). The patient factors include anxiety, stress, pain and discomfort (Nicolás et al., 2008; Jones & Dawson, 2012). Poor sleep quality can cause both short-term and long-term negative influence on patient's mental and physical health, immune system and quality of life (Higuchi et al., 2005; McKinley et al., 2012). VR systems have been used for distraction therapy and exposure therapy in pain management and psychological therapies (as shown in Section 2.3). However, no study has used such systems for improving sleep quality.

7.1 Aim

According to the protocol of this study, the main aim is to investigate whether or not the use of VNE or Virtual Restorative Environment Therapy (VRET) system (see Section 6.2.1) could promote better levels of relaxation and improvements in sleep quality of intensive care patients. This study also aims to determine the modification based on feedback from intensive care staff and patients to improve the future development of VRET.

7.2 Methods

To date, 14 patients (more patients will be recruited, aiming at 30 completers) have been recruited for the experiment (10 male, 4 female, mean age = 57, age range: 23 – 79). There is one independent variable in this study, which is the level of interaction with the prototype VRET system. Participants are presented with a graduated level of interaction with the VRET system and undertake 5 conditions in sequence: on Day 1, the patient "receives" the "Control-Pre" condition which has no VRET, just his or her usual clinical care. On Day 2, the patient is offered level "VRET-A" in which they are unable to navigate within Virtual Wembury. The visual scene is a pre-recorded video of a fixed location within the VE. On Day 3, the patient is offered level "VRET-B" with a "Jump-and-Watch" function and a Genius ring mouse (see Section 5.5.2). On Day 4, the patient is offered level "VRET-C" with fully interactive VE scene (see Sections 5.2 to 5.5) and a selection of input devices (see Section 6.2.3.2). On Day 5, the patient receives the "Control-Post" condition which features no VRET, just his or her usual clinical care.

The main outcome metric for this study is the sleep quality measured by the Richards Campbell

Sleep Questionnaire (RCSQ), which is a survey designed for use in ICUs as shown in Table 7.1. The RCSQ includes 5 questions using 100mm (millimetre) visual analogue scale, in which a higher score is better, to evaluate sleep depth, time to fall asleep, number of awakenings, percentage of time awake and sleep quality (Kamdar et al., 2012). The RCSQ value indicates three levels of sleep quality: poor sleep (0 – 33mm), normal sleep (33-66mm) and optimal sleep (66 -100mm) (Nicolás et al., 2008). The other outcomes include the hours of sleep recorded by nursing staff, and patient and staff ratings of the usability of the VRET system recorded using System Usability Scale (SUS, see Appendix E (Brooke, 1996)). SUS scores have a range of 0 to 100. Based on a review of 50 studies, Tullis & Albert (2008) suggest that an average SUS score of less than 60 indicates relatively poor usability, whilst a score above 80 is relatively good. The data collection exercises included short interviews which recorded staff and patient feedback on usability, and were carried out each morning following each condition.

Measure	Question
1. Sleep depth	My sleep last night was: light sleep (0) ... deep sleep (100)
2. Sleep latency	Last night, the first time I got to sleep, I: just never could fall asleep (0) ... fell asleep almost immediately (100)
3. Awakenings	Last night, I was: awake all night long (0) ... awake very little (100)
4. Returning to sleep	Last night, when I woke up or was awakened, I: couldn't get back to sleep (0) ... got back to sleep immediately (100)
5. Sleep quality	I would describe my sleep last night as: a bad night's sleep (0) ... a good night's sleep (100)

Table 7.1 Richards Campbell Sleep Questionnaire (Kamdar et al., 2012)

Only three participants finished the 5-day trial of the sleep study (again, more patients will be recruited, as this experimental research is still in progress). All fourteen participants completed the “Control-Pre” condition in day 1. Twelve participants finished the VRET-A condition in day 2, as two participants were discharged from the ward. For the VRET-B condition in day 3, one participant was sedated during the day and withdrew from the study. One participant was discharged from the ward. The remaining ten participants undertook this condition. Only five participants were able to finish the VRET-C condition in day 4. Four more patients were discharged, while one patient experienced delirium during daytime and was unable to complete the trial. For the final "Control-Post" condition in day 5, another two participants were discharged from the ward, which left three participants to complete this condition.

7.3 Results and Discussion

As shown in Figure 7.1, the overall average score of RCSQ was highest in the fully interactive condition (VRET-C), accompanied with the longest average hours of sleep (see Figure 7.2). The RCSQ score increased with the level of interaction with the VRET system. Paired-Samples t-Tests showed significant differences in RCSQ score between the Control-Pre and VRE-A conditions [$t(11) = 2.437$, $p = 0.033$], and between Control-Pre and VRET-B conditions [$t(9) = 2.474$, $p = 0.035$]. However, there was no significant difference in RCSQ between VRET-A and VRET-B conditions ($p > 0.05$). Paired-Samples t-Tests showed that there were no significant differences in hours of sleep between any of the Control-Pre, VRET-A and VRET-B conditions ($p>0.05$). Analysis with VRET-C and Control-Post conditions has not been carried out because of the small group sizes. Results from patient interviews indicated that approximately 80% of participants fell asleep using VRET, and felt relaxed whilst using this system. Patient comments to date have included "Very relaxing and pleasant", "Calm watching the waves and the coastline", and "Distracting from surroundings, good for anxiety".

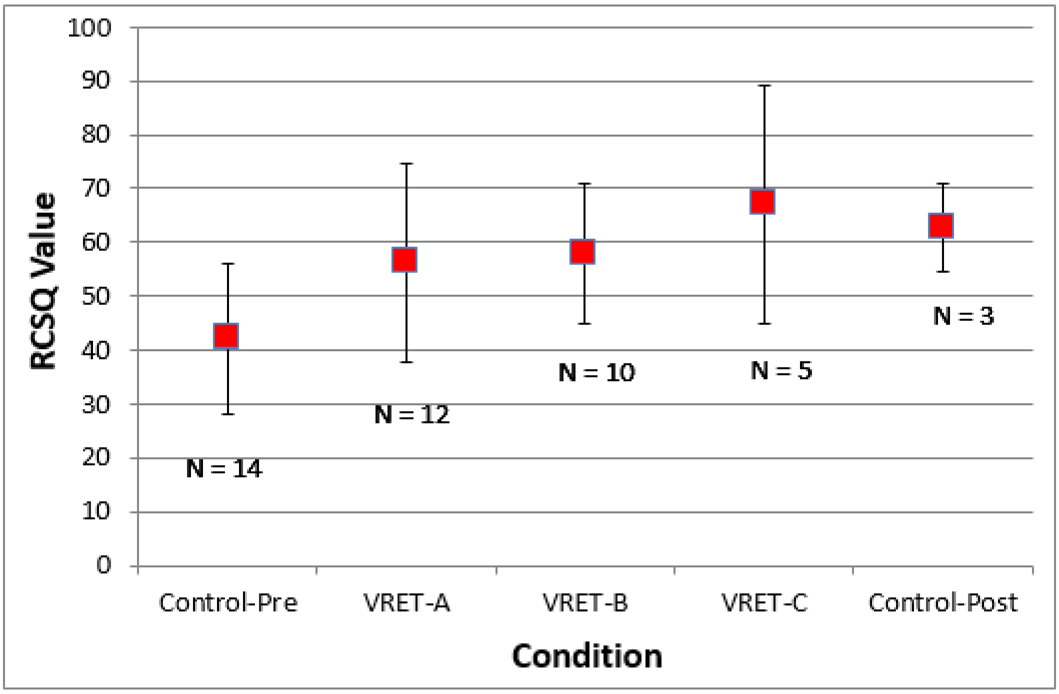

Figure 7.1 Average Ratings of RCSQ (Y-bars indicate standard deviation of the average value. N indicates the number of participants in each condition.)

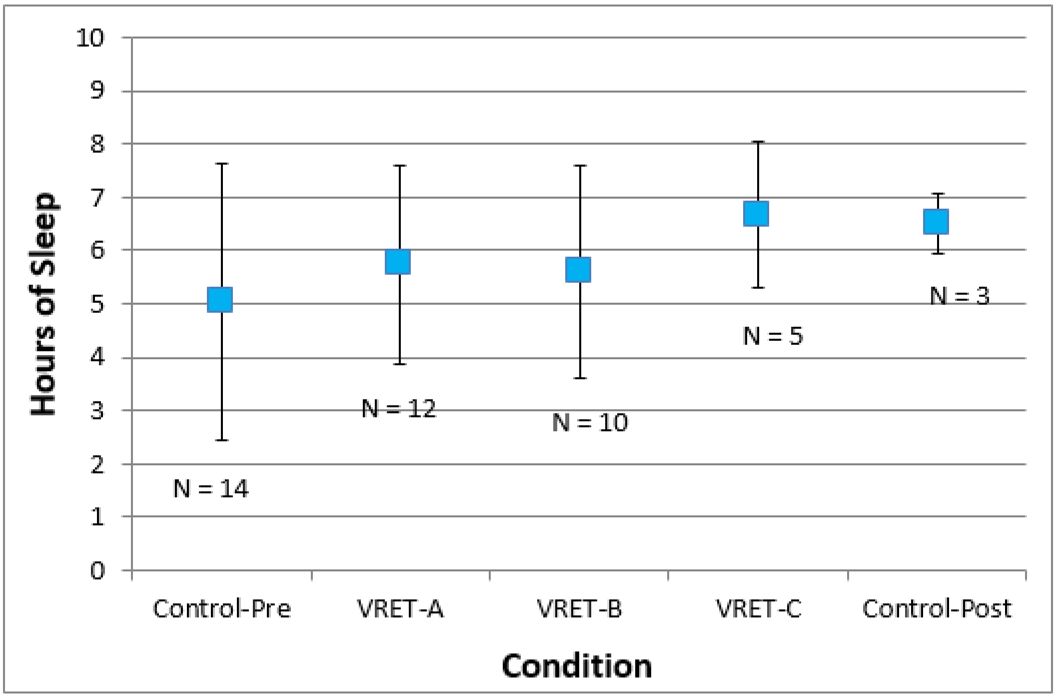

Figure 7.2 Average Hours of Sleep (Y-bars indicate standard deviation of the average value. N indicates number of participants in each condition.)

These results suggest that use of an interactive VR-based system, in the form of a prototype virtual restorative environment therapy system (VRET), can lead to relaxation and improved sleep quality for patients being treated on ICU. However, this is still an ongoing study; more participants are yet to be recruited, in order to increase the sample size and to subject the data to a thorough statistical analysis.

As shown in Figure 7.3, average SUS scores for the three VRET conditions rated by staff and patients were close to 80 which was relatively good. Paired-Samples t-Tests showed that there was no significant difference in SUS rating between the conditions or between participant groups ($p>0.05$).

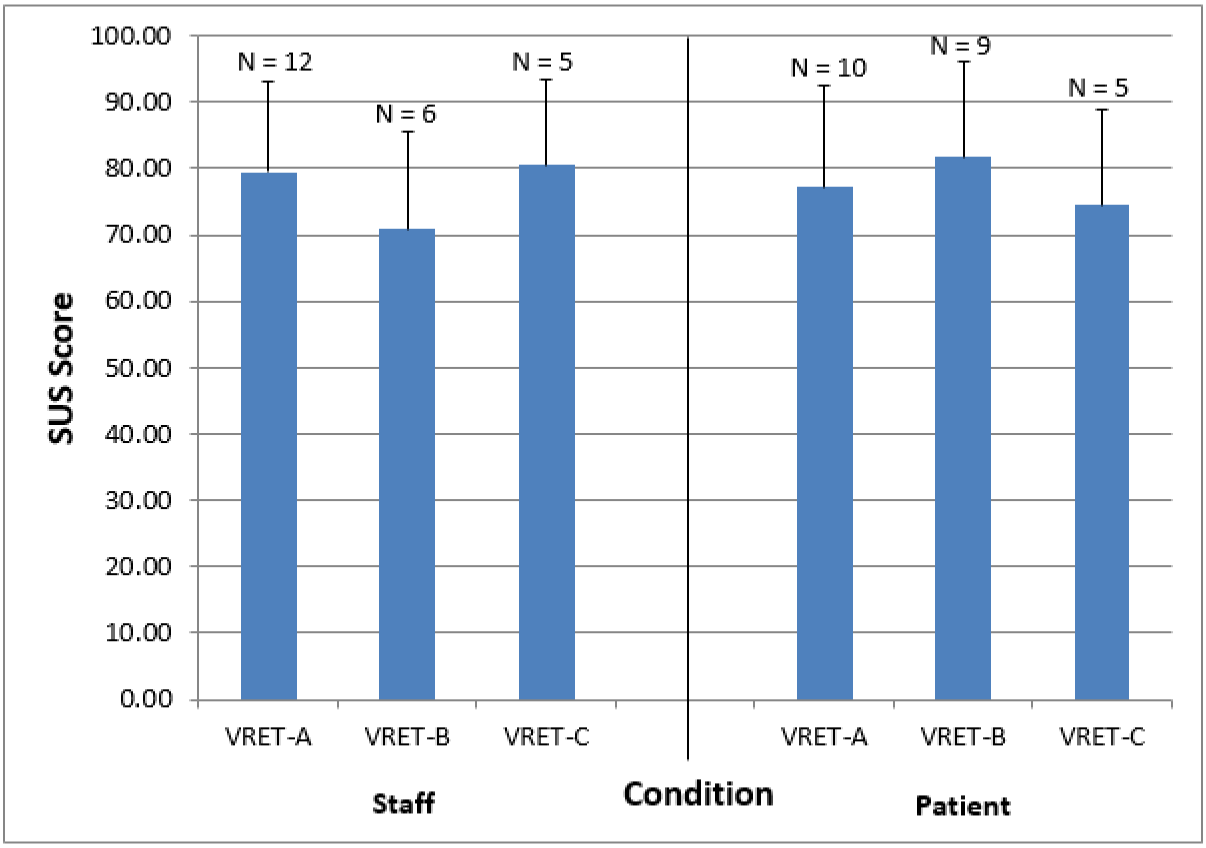

Figure 7.3 Average SUS Scores for the Three VRET Conditions Rated by Staff and Patients (Y-bars indicate standard deviation of the average value. N indicates number of participants in each condition.)

Based on the participants' comments, most of them provided very positive responses and were quite supportive of the prototype VRET system and underlying concept. Some participants recommended that they would like to have activities or tasks to do during use of the VRET system as they would find it more interesting. Again, as this is study is still ongoing, some of the above ideas are already being developed, as are new forms of user interface. Activities such as virtual fishing on a cabin cruiser, canoeing, hand-gliding and even a virtual barbecue on the Wembury beach will be developed, all based on user demand.

Based on the feedback from critical care staff, most of them would recommend the VRET system for other patients. Frere et al. (2001) suggest that the VR systems are mostly beneficial for patients receiving long-term repeated procedures or care. This supports the thoughts of some staff at the QEHB that the VRET system would be helpful especially for long-term patients "in the side rooms", who typically have to endure long periods of isolation. They believed that the VRET system could improve patient experience, reduce sensory deprivation and distract patients from their clinical environment in a positive way. They also mentioned that the VRET system needed to be used "selectively", as it "may not be to everyone's taste".

Chapter 8 Conclusions and Future Work

8.1 Discussion

The aim of this thesis, which has described a range of related studies as part of an investigation into what is a very new area for research and human science, was to determine and demonstrate some principles for the development of virtual natural environments, using low-cost commercial-off-the-shelf (COTS) simulation technologies, for bedside and clinical healthcare applications. This research was also carried out in order to investigate the development and exploitation of new digital technology approaches based on virtual natural environments (VNEs), supporting the cost-effective generation of engaging and distributable scenarios that can be modified and updated relatively easily, and with minimal resources, thereby delivering a system that can be regularly modified and updated to meet the needs of individual patients. The aim of the research was further split into six specific objectives.

The first objective was to demonstrate that virtual natural and urban environments of an appropriate fidelity could be developed using appropriate COTS software and hardware tools and technologies. Evaluations of the latest simulation technologies, including game engines, 3D modelling software and texture processing tools was systematically conducted to choose the appropriate 3D software development tools for development and exploitation of three virtual environments (VEs) – a large-scale virtual coastal environment ("Virtual Wembury"), a smaller-scale urban enclave (i.e. a virtual town model) and a large-scale forest and lake environment

("Virtual Burrator").

Furthermore, a number of new VE features were developed for both the coastal and forest/lake environments. One of these features was the 24-hour day-night cycle system, which procedurally controlled the presence of natural and artificial objects with regard to the the virtual time of day, which could also be synchronised with the real time of day (an important feature for those hospital patients who may be confined to cubicles with no visual contact with the outside world). Other features included two new methods allowing users to choose their locations to watch environmental changes (i.e. switching between viewpoints by using a graphical user interface or a "Jump-and-Watch" function), the simulation of a "virtual window" using virtual curtain material effects (to start or end a session in a familiar way), the driving of a virtual *pedalo* (water boat) representation using non-contact motion sensors, and, finally, a suite of fully animated virtual animals, introduced to improve the contextual fidelity of the two VEs. Additionally, graphical user interface (GUI) systems were developed to actuate and control these and other experimental features functions. Finally, one important experimental feature to note here was the creation of a user exploration tracking/logging system which was integrated into the two virtual settings. During exposure to the VEs, the users' movements and on-screen views were recorded in real time, whilst user interaction functions such as the number of location changes and time spent in navigation were logged.

The second objective was to compare the differences of influence of natural (Virtual Wembury) and urban (the virtual town scenario) VR set-ups on participants' ratings of anxiety and relaxation, and to investigate any potential restorative effects related to the use of realistic background sounds in both VEs. It was found that, when urban sound, such as moving traffic, was included to the virtual town scene, the ratings of anxiety increased, whilst those for relaxation dropped. In contrast, with the sound of the coastal area, such as lapping waves and gentle wind, a reduction of anxiety and an increased rating of relaxation were revealed. Therefore, the VEs developed in the subsequent research focused on the recreation of natural scenes and included naturalistic environmental sounds.

The third objective was somewhat speculative in nature, given the levels of maturity of the COTS products available, but involved an investigation into the technical and methodological issues of integrating odours into a VE. Given the significance of the human olfactory sense in the elicitation of emotions and memories, this part of the research set out to discover whether or not odours would evoke a physiological response that could be detected, logged and measured objectively and inconspicuously in real time. The results of the odour study suggested that the presence of smell could be detected and reported by participants, and that most of the electrodermal activities due to the existence of olfactory stimuli were discernible in the skin conductance response data. However, a number of methodological issues were discovered, such as the uncontrollable and inconsistent delay between triggering and the detection of smells, the slow removal and dispersal of odours, and mismatches between the odours and their descriptions by participants. In addition, the capacity of the cartridge of the COTS product used for these investigations, the US-sourced ScentScape system, was very limited. The replacement of this cartridge is, at the time of writing, both inconvenient and expensive (requiring the whole cartridge to be returned to its US supplier). Therefore, it was concluded that the technology of olfactory displays was still very immature and odours would not be used in the further development of VEs described within this thesis.

The fourth objective was to investigate fidelity-related elements of the virtual coastal environment (Virtual Wembury), and its effects on human judgements of presence, quality and realism. The results of the fidelity study showed that the improvement of visual fidelity in the Virtual Wembury scenarios was accompanied by increases in reports of presence, quality and realism, although this tendency appeared less obvious between conditions of medium visual quality and high visual quality fidelity. The inclusion of auditory stimuli, including ambient and context-relevant sounds, plus walking sound effects, had a significant positive impact on user presence ratings. Therefore, further developments in the creation of virtual natural environments will include high-fidelity spatial sound and will investigate the use of walking sound effects based on different under-foot materials. Visual fidelity will also be improved using the latest VR techniques available from the games engine developers and gaming communities (having first conducted a human-centred study of the appropriateness and relevance of new computer-generated effects; Stone, 2008, 2012), with the aim of not only delivering VEs that are sensorially engaging and affordable to users in the healthcare domain (as was the main focus of the present research), but also to deliver VEs that have been designed in order to maintain a balance between sensory qualities and the host system's real-time rendering performance.

The fifth objective was to identify usability issues with four different COTS control devices selected as potential candidates for use by a range of patients who may present with differing perceptual, cognitive and residual motor capabilities when interacting with virtual restorative environments. Of the four commercial off-the-shelf input devices or controllers used in the research (Xbox controller, keyboard-and-mouse combination and joystick), the Xbox controller was rated highest overall in terms of usability ratings, whilst participants with hand injuries preferred using the conventional joystick. The Keyboard-and-mouse combination scored the lowest ratings from all participants and for hand injured participants in particular. Therefore, in the later applications of the VE systems, the Xbox controller and joystick were chosen as the standard input devices for end users.

The sixth and final objective was to investigate whether or not participants, living locally to the real-world area modelled during the VE development process, would navigate and accept (or be critical of) a virtual natural environment based on that area differently than a VE based on a non-local area. The results demonstrated that real-world-based virtual natural environments were shown to increase the reported presence and realism ratings on the part of participants who lived locally to the reconstructed scenes. This was quite an important finding and suggested that the participation of local inhabitants in the development of nearby VEs may be crucial for the subsequent acceptance and adoption of those VEs for local purposes, which could range from educational uses in local schools to the development of virtual heritage or historical scenarios.

8.2 Contributions

This section lists the key research contributions from this thesis.

8.2.1 Principles for the Development of Virtual Natural Environments

This project has contributed to future research in the very new field of simulation-based healthcare restoration by determining the principles for the development of virtual natural environments. Whilst conducting the literature searches in support of this study, there was significant absence of research for virtual reality-based restorative environments. No one study in this area had, at the time of these searches, evaluated the exploitation of VR techniques in support in the development or evaluation of appropriate immersive virtual environments.

A series of studies have been conducted to systematically investigate different aspects of the VNEs. The principles of development of such environments are listed as follows.

- Naturalistic environmental spatial sounds can have a positive impact on a user's stress level and sense presence, and should be included in future VNEs.
- Improvements in visual fidelity in VEs are accompanied by increases of reported presence, quality and realism. Visual fidelity should be improved by using the latest VR techniques (following a human-centred design evaluation of appropriateness (Stone, 2008, 2012) and resources should be prioritised within budget and host computer performance limits.
- In order to maximise the re-use and longevity of a VNE, it could be developed based on real-world places, as real-world-based VNEs can increase the reported presence and realism ratings on the part of participants who live locally to the reconstructed scenes and will enable the VE to be exploited for education, heritage, conservation, tourism and other applications, as well as the healthcare focus of the present research.
- The choice of input devices has a significant impact on usability. The choice of controller depends on user's physical condition and preference. A human-centred evaluation – on a user-by-user basis – should be undertaken prior to selecting a control device for interaction with VEs, especially in the case of hospitalised patients.

8.2.2 Techniques for Development of Low-Cost and Effective Virtual Natural Environments

Appropriate 3D software development tools were chosen for the development and exploitation of two VNEs – a large-scale virtual coastal environment (Virtual Wembury) and a large-scale forest/lake environment (Virtual Burrator). Additionally, a number of features have been developed for both the coastal and forest environments. These are:

- A 24-hour day-night cycle system,
- Virtual animals with a virtual path-finding system,
- A simulated "virtual window" view with animated curtains,
- A user exploration tracking/logging system.

These tools and techniques are highly transferrable and, as such, will be able to support the conversion of a range of Unity-compatible VR scenarios to match the "standard" requirements defined throughout the present research for experimentation and future healthcare applications.

8.3 Related Virtual Heritage Work

Since 2003, the University of Birmingham's Human Interface Technologies (HIT) Team has been investigating the development of VR, Augmented Reality (AR), "serious games" and interactive media technologies for varies areas including Virtual Heritage (VH). The definition of Virtual Heritage is "the use of computer-based interactive technologies to record, preserve, or recreate artefacts, sites and actors of historic, artistic and cultural significance, and to deliver the results openly to a global audience in such a way as to provide formative educational experiences through electronic manipulations of time and space" (Stone, 1999). As part of the HIT team research, the work described in this present study has also had an impact on VH projects, particularly in the reconstruction of historical sites and artefacts related to maritime and industrial archaeology. The importance of these "spin-out" efforts is that they also assist in the development of techniques, effects and new technologies, not to mention the provision of interesting tasks for patients, all of which can be re-used to improve and extend the main virtual rehabilitation projects described herein.

8.3.1 Virtual Reconstruction of "the Wembury Docks That Never Were"

In 1909, a scheme for the construction of an enormous passenger and commercial port within Wembury Bay was proposed (see Figure 8.1A and B), to challenge the domination of the docks at Liverpool and Southampton (Stone, 2014). The port was to consist of breakwaters, several quays, dry docks and railways including a station. It was fortunate that this proposal was rejected by the House of Lords finally, as Wembury, today an Area of Outstanding Natural Beauty (AONB), was saved. VR and Augmented Reality (AR) technologies were used to implement the Dock project virtually, in order to demonstrate the possible impact on this area if the proposal had been approved.

Figure 8.1 The Virtual Wembury Dock Project. Image A (House of Lords, 1909): An early plan of the Wembury Dock; Image B (Broughton, 2000): An early sketch of the Wembury Dock; Image C: The area that Wembury Dock could cover; Image D and E: VR reconstruction of Wembury Dock; Image F: AR representation of Wembury Dock.

As shown in Figure 8.1D, the virtual dock was built using the terrain model of the original Virtual Wembury project (see Section 3.3 of this thesis). A number of vessels that might have been to the dock were "anchored" alongside the quays, including Royal Navy's first submarine, *Holland 1*, HMS *Amethyst*, HMS *A7* submarine, a Sunderland flying boat patrol bomber, an old sailing boat, even the RMS *Titanic*. An AR demo with a dedicated graphical user interface (GUI) of the Wembury Dock model was also built in Unity3D, in order to evaluate the technologies and appropriateness of using AR software library (e.g. ARToolKit) for building AR applicants with large-scale high polygon models on mobile platforms (e.g. an iPad). In particular, this project investigated issues related to different aspects of the AR demo, such as visual latency (frame rate), outdoor marker/geometrical feature recognition, and usability of the GUI. The outcome of this project provided valuable methodological guidelines for the following VH projects.

8.3.2 Virtual Heritage in Burrator

As an extended research to the VNT project of Virtual Burrator (see Section 5.8), a series of VH projects were conducted by the author to reconstruct a number of the historical sites around Burrator. One of these projects is the Virtual Burrator & Sheepstor Halt (see Figure 8.2), which was part of the Yelverton-to-Princetown Railway and was operational from 1924 to 1956. A virtual recreation of the halt together with a petrol-powered Wickham Trolley has been added to the Virtual Burrator scene.

Figure 8.2 Virtual Burrator & Sheepstor Halt

Other historical sites has also been recreated using VR and AR techniques, such as the temporary suspension bridge (existed during the 1920s whilst the dam was being raised to increase the Reservoir's water capacity, as shown in Figure 8.3A and B) and its remaining anchor points (Figure 8.3C), a secluded historical area called "Wembley Walk" together with two footbridges (Figure 8.3D), two explosive storage huts (Figure 8.3E), South West Lakes' new Discovery Centre (Figure 8.3F), the old Yelverton Reservoir (Figure 8.3G) and Burrator Lodge (Figure 8.3H). All of these heritage developments were based upon the original Burrator model, as modified and enhanced during the execution of the main research effort described within this thesis. The results of these "spin-out" activities were presented at the Official Launch of South West Lakes Trust's new Discovery Centre on the shore of the reservoir (July 2014; see Section 7.5.2) and at a special local village event held within the nearby Sheepstor Village Church in January 2015 and were very well received by local inhabitants. Work continues to date to extend the heritage features of this large virtual environment.

Figure 8.3 Virtual Recreation of Historical Sites in Burrator. Image A: virtual representation of the suspension bridge using AR technology; Image B: the suspension bridge in Virtual Burrator; Image C: virtual anchor points; Image D: the virtual Wembley Walk and a footbridge; Image E: a virtual explosive hut; Image F: 3D model of South West Lakes' new Discovery Centre; Image G: virtual Yelverton Reservoir; Image H: virtual Burrator Lodge.

8.4 Public Engagement

As part of the HIT Team VRET and Heritage projects, surveys and technology trials were conducted at real-world locations, offering the opportunities for engagement with local residents and "Digital Inclusion". According to Stone (Stone, 2014), "Digital Inclusion" is defined as the "ability of individuals and groups to access and make effective use of information and communication technologies (ICT), with occasional reference to the availability of appropriate hardware and software, the provision of relevant content and services, and the delivery of effective digital skills training." However, such inclusion may be weakened by some factors such as geographical remoteness, attitudes (cost, complexity, etc.) and stereotypes (e.g. elderly citizens' "fear" of, or innate lack of confidence with ICT). The engagement with locals and visitors shows that it is more likely for them to be inspired and motivated to explore the real world if this area is reconstructed using appropriate VR and AR technologies with places of interests (e.g. historical sites, artificialities, landscapes etc.). Additionally, the showcases of VH and Virtual natural environment in real world and through appropriate media (websites, local newspapers and magazines) can also encourage cross-generation and cross-community engagement and give the opportunities to collect and preserve valuable written and verbal information and resources. Two of these engagements – both of relevance to the VEs developed and reported herein – were a Virtual Wembury evening event and a Virtual Burrator/South West Lakes Trust event.

8.4.1 Virtual Wembury Evening Event

To promote Digital Inclusion, help raise funds for the QEHB Charity and to collect feedback and potential additional information and assets relevant to the future extension of the VE, a

“Virtual Wembury event” was held by HIT team in the Wembury Village Hall in December 2012. Over 120 local villagers and the South Hams local government representatives attended this event. The attendees were shown a number of author’s HIT team’s VH and VRET projects, including the up-to-date versions of Virtual Wembury and Virtual Burrator (see Chapter 5), the virtual pedalo demo (see Section 5.7), Virtual Wembury Dock (Section 7.4.1) and related Virtual Heritage projects. The villagers were given the opportunity to experience the VEs using a range of interface technologies. For example, they were given opportunities to “walk” along the virtual coastal path or dock quays displayed on large screens or HMDs using COTS hand controllers (see Figure 8.4). Numerous comments were gathered through verbal exchanges and questionnaires on the evening and two data-gathering websites (www.virtual-wembury.net and www.virtual-burrator.net) were also constructed. These data are being evaluated at the time of writing

Figure 8.4 Photographs of Virtual Wembury Event

8.4.2 Virtual Burrator Event

As part of the official opening event of South West Lakes' new Discovery Centre in July 2014, the latest Virtual Heritage and VRET projects were brought to Burrator (see Figure 8.5). Using Xbox hand controllers and large screens or Oculus Rift HMDs, the locals and visitors were able to explore these scenes, including the up-to-date versions of Virtual Wembury and Virtual Burrator, and two scenes of Burrator Halt during day and night (See Chapter 5).

Figure 8.5 A Photograph of HIT Team Members at Virtual Burrator Event

8.5 Limitations and Future Work

The quantitative parameters recorded by the user exploration tracking/logging system for the post-session analysis of ease of navigation and use of the controller were judged to be quite limited. Future work will seek to introduce appropriate factors and metrics to support more detailed usability studies. For example, the distance that users deviate from the path that they are instructed to follow may be sampled at a certain frequency. Greater deviation from the path may indicate poorer usability of controller or navigation in a VE.

During the development of the driving of a virtual *pedalo* representation using non-contact motion sensors, an issue was identified relating to the resolution of the Microsoft Kinect's inbuilt depth sensor. When users – and particularly hospitalised users – are sitting in a high-back chair or lying in a bed, the body of the user cannot be distinguished from the background surface (e.g. the back of the chair or bed sheets). Consequently, suitable inputs could not be generated for the interaction with the VE (specifically limb motion, or the motion of the stumps of amputees). Future work will seek to find possible solutions to overcome this issue, such as using motion sensors with higher depth resolution (e.g. Microsoft Kinect v2), or using other motion capture systems as substitutions (e.g. OptiTrack, Leap Motion, etc.).

In terms of requirements for visual quality, although the results of the experiments showed in general that higher visual quality increased the reported sense of presence, the influences of individual visual settings (such as texture, shadow, image effect, etc.) on presence still require systematic and detailed study. Future work will seek to compare specific factors of the quality settings in terms of presence, in order to assist in the design and optimisation of virtual restorative environments.

One of the most concerning limitations during the execution of some of the experiments (as reported in Chapter 6) was the incidence of a range of simulator sickness symptoms (from "queasiness" to actual vomiting), especially in the experiment conducted in collaboration with Wembury villagers. A number of possible causes of such side effects have been discussed, including age, VR gaming background, visual display characteristics and the delay between user input and system response. Solutions including increasing the display frame rate, offering additional control means or a different level of interaction (e.g. free roam, "Jump-and-Watch", which has been used in the ongoing sleep study described in Chapter 7) and lowering the system delay. These have, since the Wembury experimentation, been implemented to minimise the possibility of inducing simulator sickness in the future.

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Appendix A: Usability Study Questionnaires

Controller

How often have you used, or do you use, this type of controller?

Never	
Little experience / Rarely	
Occasionally / Sometimes	
Often	
Frequently / Always	

Please rate your level of agreement to the following statements:

	Strongly disagree	Moderately disagree	Slightly disagree	Undecided	Slightly agree	Moderately agree	Strongly agree
I found the controller easy to use							
I would have preferred an alternative controller							
The response to my input was acceptable							
The controller was ideal for interacting with the virtual environment							
I kept making mistakes using the controller							
I had the right level of control over what I wanted to do							
The controller was too complicated to use effectively							
I found it easy to move or reposition myself in the virtual environment							
The controller gave me a feeling of smooth motion							
The controller behaved in a manner that I expected							
The controller was comfortable to use							
It was easy to grip/hold the controller							
The controls on the controller were easy to reach							
The controls on the controller were easy to actuate (i.e. press, move)							
Using the controller was awkward							
The move forward/back control was easy to use							
The turn left/right control was easy to use							

	Too low -3	-2	-1	OK 0	1	2	Too high 3
The force required for pressing buttons or manipulating the controls was:							
The sensitivity of the controller was:							

	Low 1	2	3	4	5	6	High 7
Overall ease of use of the controller was:							
My overall satisfaction with the controller was:							

Please add any comments you have about the usability of the controller:

Display

	Strongly disagree	Moderately disagree	Slightly disagree	Undecided	Slightly agree	Moderately agree	Strongly agree
I found the display appropriate for the task							
The amount of lag (delay) in the image affected my performance							
The display resolution was adequate							
I was aware of distortion in the image							
The quality of the image affected my performance							
There were no glitches in the display							
Objects in the virtual environment were realistic							
I had difficulty getting used to the display							

	Too small -3	-2	-1	OK 0	1	2	Too big 3
The display size was:							
The image field of view was:							

	Too close -3	-2	-1	OK 0	1	2	Too far 3
The position of the display was:							

	Too low -3	-2	-1	OK 0	1	2	Too high 3
The position of the display was:							

	Low 1	2	3	4	5	6	High 7
Overall satisfaction with the display was:							

Please add any comments you have about the display:

Workload

Mental demand
How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching etc.)? Was the task easy or demanding, simple of complex, exacting or forgiving?

Low High

Physical demand
How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc)? Was the task easy or demanding, slow or brisk, slack or strenuous, stressful or laborious?

Low High

Temporal demand
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Low High

Performance
How successful do you think you were in accomplishing the goals set out by the experimenter. How satisfied were you with your performance in accomplishing these goals?

Low High

Effort
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low High

Frustration
How insecure, discouraged, irritated, stressed and annoyed verses secure, gratified, content, relaxed and complacent did you feel during the task.

Low High

Rating of Strain or Discomfort Using the Controller

0	Nothing at all
0.5	Very, very weak (just noticeable)
1	Very weak
2	Fairly weak
3	Moderate
4	Somewhat strong
5	Strong
6	
7	Very strong
8	
9	
10	Very, very strong (almost max)
•	Maximal

Using the scale above, please rate the intensity of any sensations of strain or discomfort you felt when interacting with the controller.

Fingers	
Hand	
Wrist	
Forearm	
Upper arm	
Shoulder	
Neck	
Other	

Comments:

Background Information Questionnaire

This background information questionnaire is all about your interest in playing computer/video games.

1. Do you play computer/video games? *(Please select one option)*

- ❑ Yes
- ❑ No *(If no, you are not required to complete the rest of the form)*

2. For how long have you been playing computer/video games?

__________ years __________ months

3. How often do you play computer/video games? *(Please select one option)*

- ❑ Every day
- ❑ 5 – 6 times per week
- ❑ 3 – 4 times per week
- ❑ 1 – 2 times per week
- ❑ 1 - 2 times per month
- ❑ Once every two months
- ❑ Once every six months
- ❑ Less than once every six months

4. When you play computer/video games, how long is each game play session (ie how many hours do you play games for at any one time)?

__________ hours

5. On which of the following do you play computer games? *(Select all that apply)*

- ❑ PC
- ❑ Games console eg Xbox and Playstation
- ❑ Handheld e.g. PSP
- ❑ PDA
- ❑ Mobile phone
- ❑ Interactive TV
- ❑ Arcade
- ❑ Other *(Please specify)*

6. What type of computer games do you play? *(Select all that apply)*

Please turn to last page for game definitions

- ❑ First Person Shooter
- ❑ Fighting
- ❑ Role Playing Games
- ❑ Vehicle Simulations
- ❑ Other *(Please specify)*
- ❑ Real Time Strategy
- ❑ Sports
- ❑ Arcade
- ❑ Puzzles

7. Which actual games do you play? *(Please specify)*

____

____

____

____

____

8. What features are important to you when you play a video game?
(*Select all that apply*)

- ❑ Graphics
- ❑ Music/Soundtrack
- ❑ Storyline
- ❑ Realism
- ❑ Fantasy/make-believe
- ❑ Having clear rules (what you can/can't do)
- ❑ Having clear goals/objectives
- ❑ Immediate feedback
- ❑ Humour
- ❑ Other *(Please specify)*
- ❑ Rewards/penalties
- ❑ Simple to play (easy to pick up)
- ❑ Hard to play (requires practice)
- ❑ Variety of levels/progressive challenge
- ❑ Chance to win
- ❑ Control (being in control)
- ❑ Problem solving activity
- ❑ Challenge
- ❑ Competition/contest

9. In which of the following environments do you play? (*Select all that apply)*

- ❑ Single player
- ❑ Dual player, on the same computer
- ❑ More than two on the same computer
- ❑ Other *(Please specify)*
- ❑ Multiplayer locally networked
- ❑ Multiplayer Internet games
- ❑ MMPGs (Massively Mulitplayer (Online) Games)

Game Definitions

First Person Shooter	Three dimensional shooter games with a first person perspective (i.e. looking down the barrel of a gun, as in *FarCry*, *Half-Life 2*, etc.)
Fighting	Games which simulate hand-to-hand combat, usually between pairs of fighters, modelled on Asian martial arts techniques (e.g. *Mortal Combat*).
Real Time Strategy	Games which allow the player to command some type of operation, typically a military operation, involving the player in planning a series of actions and managing resources to build or expand a community, army or empire (e.g. *Civilisation*).
Vehicle Simulators	Simulations which create the feeling of driving or flying a vehicle (either real or imaginary) in a realistic situation (e.g. Microsoft's *Flight Simulator*).
Sports	Games which simulate some aspect of a real or imaginary athletic sport (e.g. *Winning Eleven*).
Role Playing	With role-playing games, players manage either a person or a team through a series of quests, in a fantasy or science fiction setting, building the character's power, and abilities and inventories to meet increasing and evolving conflicts (e.g. *Dungeons and Dragons*, *EverQuest*).
Arcade	Often coin-operated entertainment machines, often installed in pubs and video arcade (e.g. *Space Invaders*).
Puzzles	Games in which puzzle solving is the primary activity (e.g. *Tetris*).

Appendix B: Fidelity Study Questionnaires

Presence

1. I had a sense of "being there" on the coast.

Not at all | Very much

2. There were times during the experience when the coast was the reality for me.

At no time | Almost all the time

3. The coast seems to me to be more like.

Images that I saw | Somewhere that I visited

4. I had a stronger sense of...

Being in the lab | Being on the coast

5. During the time of the experience, did you think to yourself that you were actually on the coast?

Not at all | Very much

Quality

1. How would you rate the quality of the ***sky***?

Very low | Low | Moderate | High | Very high

2. How would you rate the quality of the ***lighting***?

Very low | Low | Moderate | High | Very high

3. How would you rate the quality of the ***sea/water***?

Very low | Low | Moderate | High | Very high

4. How would you rate the quality of the ***ground cover*** (path, ground textures, grass, etc)?

Very low | Low | Moderate | High | Very high

5. How would you rate the quality of the ***plant and tree life***?

Very low | Low | Moderate | High | Very high

6. How would you rate the quality of the ***buildings***?

Very low | Low | Moderate | High | Very high

7. How would you rate the quality of the other ***man-made objects*** (e.g. boats, bridge)?

Very low | Low | Moderate | High | Very high

Realism

1. Overall how realistic was the ***landscape*** (e.g. grass, trees, water, sky)?

Not at all Very

2. Overall how realistic were the ***man-made objects*** (e.g. buildings, boats, bridge etc)?

Not at all Very

3. How realistic was ***your movement*** within the virtual environment?

Not at all Very

4. How realistic was the ***sound of walking*** *(if applicable)*?

Not at all Very

5. How realistic were the ***movements of the nature elements*** (e.g. waves, grass, trees etc) *(if applicable)*?

Not at all Very

6. How realistic were the ***ambient sounds*** (e.g. waves, water, birds etc) *(if applicable)*?

Not at all Very

7. Overall how realistic did the ***virtual world*** seem to you?

Not at all Very

Appendix C: Satisfaction and Accuracy Questionnaires

Satisfaction

Overall my experience with the virtual forest was:

Dull Stimulating

Unpleasant Enjoyable

Boring Interesting

Unimpressive Remarkable

Negative Positive

Fidelity and Accuracy to Wembury

1. How well do you know with the area of coastline between Wembury Point and Gara Point?

Not at all | Slightly | Somewhat | Considerably | Very

2. Overall how would you rate the fidelity of **Virtual Wembury**? How accurate is it to the real place?

Low — High

3. How would you rate the fidelity of the **landscape**?

Low — High

4. How would you rate the fidelity of the **buildings and other man-made structures**?

Low — High

5. How would you rate the fidelity of the **plant life**?

Low — High

6. How would you rate the fidelity of the **animal life**?

Low — High

7. How would you rate the fidelity of the **sound content** (e.g. wind, waves, birds)?

Low — High

8. Do you think any inaccuracies in Virtual Wembury affected your experience?

Not at all — Very much

9. Do you think exploring a virtual environment that you recognised improved your experience?

Not at all — Very much

Appendix D: Page 1 of the Protocol of the Sleep Study

PROTOCOL[1]

1. TITLE OF STUDY

Short title: Restorative Virtual Environments for Rehabilitation (REVERE) Full title: Restorative Virtual Environments for Rehabilitation: Does Virtual Nature Therapy enhance sleep on the Intensive Care Unit?

2. TRIAL REGISTRATION

TBC

3. PROTOCOL DATE/VERSION

Date: 1 January 2014	Version: 5

4. FUNDING

Joint Medical Command Medical Directorate, Ministry of Defence

5. ROLES AND RESPONSIBILITES

a. Chief Investigator: Dr Charlotte Small Principal Investigator (QEHB): Dr Catherine Snelson b. Human Factors & Simulation Lead: Prof Bob Stone Technology Development, Integration and Evaluation: University of Birmingham Human Interface Technologies Team; Dr James Knight, Vishant Shingari, Cheng Qian Academic supervisors: Prof Bob Stone, Prof Julian Bion (University of Birmingham) c. Sponsor: Application made to Dr Sean Jennings, University of Birmingham.

[1] Written according to Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) 2013 guidelines. Chan A-W, Tetzlaff J.M., Gotzsche P.C. et al. (2013) SPIRIT 2013 explanation and elaboration: guidance for protocols of clinical trials. BMJ Research Methods and Reporting. 346; e7586

Appendix E: System Usability Scale

	Strongly disagree 1	2	3	4	Strongly agree 5
1. I think that I would like to use this system frequently					
2. I found the system unnecessarily complex					
3. I thought the system was easy to use					
4. I think that I would need the support of a technical person to be able to use this system					
5. I found the various functions in this system were well integrated					
6. I thought there was too much inconsistency in this system					
7. I would imagine that most people would learn to use this system very quickly					
8. I found the system very cumbersome to use					
9. I felt very confident using the system					
10. I needed to learn a lot of things before I could get going with this system					