

Abstract

Training simulations are one of the major applications areas for Virtual Environments (VEs). Simulation systems present an ideal means of transference of real world skills, particularly where real world training is either dangerous or expensive. It is essential, therefore, that skills gained in such a manner are truly representative of the real world tasks they simulate. It is for these reasons that there is much research ongoing research in the field of simulation fidelity metrics for VEs. The majority of VE fidelity metrics rely on task performance based measures. In this dissertation an alternate metric, based on human judgements of spatial memory awareness states is investigated. This metric focuses on *how* a task is achieved as opposed to *what* is achieved, by requiring participants to indicate how they completed spatial recollections after VE exposure by selecting one of four choices of awareness states. These awareness states choices are designed to identify whether the participant is employing implicit or explicit memory retrieval, thus providing insight to the cognitive strategies employed during memory encoding whilst exposed to the VE.

This paper describes the experimental use of this metric, comparing spatial memory awareness states participants exposed to either a realistic, radiosity shaded VE or a simple, flat shaded version. The study exposes a distribution of subject's memory awareness states where alternative metrics fail to reveal any significant differences.

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Chapter 1: Introduction

Virtual Environments offer certain advantages over conventional data and information display systems. In Virtual Environments, life-like changes in visual imagery occur in response to the participant's own actions [VRM, 1995]. In this way, VEs allow the use of the natural senses to understand and interact with their surroundings. Due to the high degree of realism innate to VE technologies, they have great potential in the enabling of the transference of skills learnt within the VE to the real world. This means that expensive or dangerous training tasks can be undertaken with significantly reduced risks, both in terms of safety and economics. The nature of the training tasks undertaken demands that any training gained within a VE is sufficiently analogous to the real world task, not only in terms of task performance and other palpable measures, but also in terms of the cognitive processes employed during the training process.

To date, simulation fidelity metrics research has focussed on either task performance based measures or self-report measures of subjective constructs such as presence. In this thesis, a methodology based on human judgements of memory awareness states is employed to differentiate between two different rendering conditions; one flat shaded, and one radiosity rendered. This metric is concerned with *how* information is committed to memory as opposed to *what* is committed, as is the case with traditional task performance based simulation fidelity metrics. This report details the background, design, implementation and execution of an investigation into the effect of varying rendering quality on spatial memory awareness states by means of a spatial memory recall questionnaire. The questionnaire requires the participants to answer questions on object types and locations, as experienced in the VE. Each question on the questionnaire is accompanied by a self-report measure of the memory awareness state employed during retrieval, offering the following options; Remember, Know, Familiar and Guess. The participants are also required to report on the confidence they have in their answer on a scale of 1 to 5 (no confidence to certain). Analysis of results using ANOVA show that although task performance scores were comparable across the two conditions, differing mental strategies for memory encoding and retrieval are identified.

1.1 *Dissertation Outline*

Chapter two presents background information pertinent to the experiment, starting with an overview of the basic principles of 3D models. The chapter goes on to describe the principle technological aspects of VE systems. There then follows a discussion of illumination and shading models for image synthesis, after which the relevant aspects of the human visual system (HVS) are described. The chapter concludes with a section on simulation fidelity metrics developed to date.

Chapter three describes the underlying psychological and statistical aspects of the simulation fidelity metric based on human judgements of memory awareness states used in this thesis. Relevant models of human memory are first described, after which the chapter goes on to describe how memory model concepts are utilised by the simulation fidelity metric. The chapter concludes with a description of the statistical analysis tools used and their application to the experiment.

Chapter four is a report on the design and implementation of the VE. First, the requirements for the system are given. Using the requirements as a guide, the technical specifications for the project are then identified. The remainder of the chapter is given over to implementation details, comprising a section on the workflow employed in the creation of the VE and a walkthrough for the BasicScript code used to add interactivity to the VE.

After a brief description of the pilot study, chapter five describes the experimental methodology employed in detail. The results of the study are then presented, together with a discussion of their implications.

The final chapter draws conclusions from the experimental results described in the preceding chapter, discussing implications of interesting effects observed.

Chapter 2: Background

The study of simulation fidelity metrics for Virtual Environments encompasses more than one discipline. The fields of computer graphics, photometry, biology and psychology all have their parts to play. The purpose of this chapter is to examine the roles of these disciplines in VE technology by explaining the more salient points. The chapter starts by giving a brief overview of model creation using 3D computer graphics. VE enabling technologies are then examined, with particular attention paid to the various input modalities and interfaces prevalent in VE systems. The pertinent aspects of the human visual system (HVS) are then presented, followed by an overview of the field of simulation fidelity metrics.

2.1 3D Models

Three dimensional computer graphics models are built using basic primitives: cubes, pyramids and spheres. Depending on the modelling tool used, various other primitives, such as cylinders and cones may also be available. Standard geometric transformations, such as move, rotate and shear, along with standard geometrical operations such as union, intersection and difference provide the means for modelling the form of the objects in 3D scenes. 3D models are represented by vertexes, surfaces and materials. Vertexes define points in 3D space to form object boundaries. Three or more vertexes combine to form a polygonal surface. Materials model the illumination properties of the real world material they represent. Once materials are applied to surfaces, the lighting for the scene can be rendered using one of the illumination models described in section 2.3.3 below. After rendering, the model is ready to have behaviours added thus completing the interactive VE.

The number of polygonal surfaces used to represent a model forms a useful definition of a model's size. The greater the polygon count, the greater the processing power required to interactively display the scene. The frame rate, measured in frames per second (fps), provides the trade off between the model's size and the computational power available. An increase in polygon count will result in a reduced frame rate. Conversely, an increase in computational power should increase the fps.

2.2 *Virtual Environment Technology*

VE technology is an approach to the design of human-machine interfaces that seek to provide users with a sense of immersion in computer-generated, synthetic worlds. VEs are characterised by their multi-sensory, naturalistic interfaces. The ultimate goal of VE technologies is to create a totally transparent human-machine interface that is virtually indistinguishable from reality. Intermediary goals include increasing the human – computer information bandwidth and the further validation of VEs as simulation and training platforms.

VEs are made up of interface elements to form a multi-sensory interface. These composite interface elements represent the four modalities thought to define a VE: visual, auditory, tactile and kinaesthetic. This section starts with a brief overview of contemporary applications of VEs before going on to describe these four VE input modalities. The section then concludes with a description the database, construction and maintenance systems necessary for VE realisation.

2.2.1 Applications of VEs

Since it's conception, VE technology has been found to suit a range of commercial applications where the safety and economic benefits of VE-based simulation and training have proved advantageous. In this section a review of these applications is presented.

Aircraft cockpit simulation is one of the better-known applications for VEs. The quality of modern flight training gained using a simulator is considered sufficient for pilot certification.

Although VE technology is not yet widely accepted by the medical profession, Virtual medical simulator devices are under review for surgical training. Virtual medical simulators allow healthcare providers to practice procedures without real dire consequences [Yonggao].

Psychotherapeutic applications of VEs employ systematic desensitisation for the treatment of phobias. Current research is towards the application of VEs in the treatment of phobias including vertigo, agoraphobia, arachnophobia, claustrophobia and general social phobias [VRET]. The idea that virtual environments could be used in the

diagnosis, prevention and intervention of various age-related diseases [VET 1999] is also currently under research.

Other current and projected applications of VEs include: Entertainment, education, teleconferencing, scientific visualisation, modelling and simulation in product design and architecture.

2.2.2 Visual Displays

Arguably, the two most prolific visual interfaces for VEs are the Head Mounted Display (HMD) and CAVE (CAVE Automated Virtual Environment), with the HMD being the more common of the two. The HMD provides stereo output to the eyes using the principle of stereopsis. Although the field of view is restricted, with the addition of a head tracking device, the field of regard is effectively increased 360°, thus providing a good deal of immersion. The first HMD was produced by Ivan Sutherland in the mid 1960's. The CAVE was developed at the Electronic visualisation Lab at the University of Illinois, Chicago in the early 1990's. A CAVE display is created by projecting the simulated scene onto four or more adjacent surfaces to form a vista around the user. Other forms of VE visual interface include workbenches and panoramic displays.

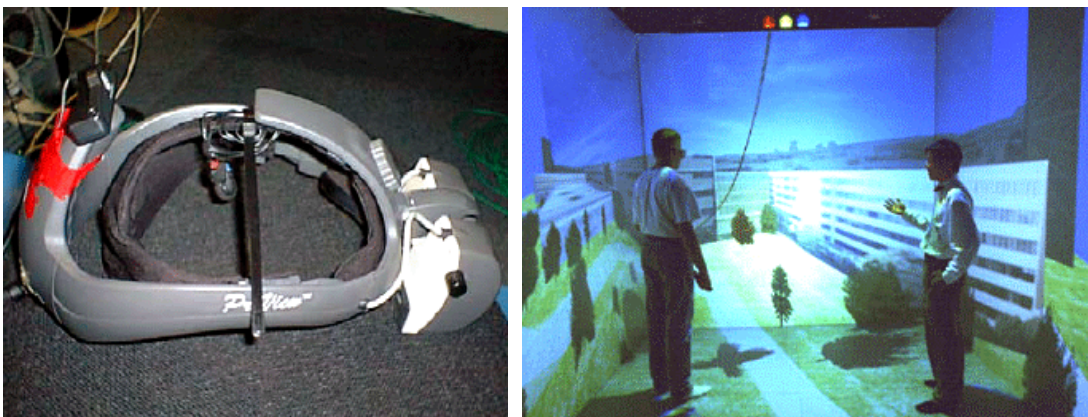


Figure 2.1: The Kaiser ProView 30 HMD and a CAVE at University of Michigan

2.2.3 Auditory Interfaces

Auditory interfaces are the least complex way of providing user feedback, and can prove a significant aid towards technological immersion. Although the technology to simply reproduce stereo audio is well established, there is a good deal research into

aspects such as the dynamic sound modelling for Virtual Environments [van den Doel, 2001] and advanced applications of spatialised 3D sounds [Shilling, 2003].

2.2.4 Tactile Interfaces

Tactile interfaces, as their names suggests, allow the user to touch or manipulate objects in a virtual scene. More specifically, tactile displays are used to present contact force, slip, texture, vibration and thermal sensations. Current tactile displays provide sensations to a very limited area. Tactile interfaces form a subclass of haptic interfaces. Applications for tactile devices include product visualisation and surgical training.



Figure 2.2: The application a tactile interface for product visualisation. With the stylus the user can 'feel' their way around a virtual object.

2.2.5 Kinaesthetic Interfaces

Kinaesthesia (sometimes called proprioception) provides humans with an awareness of the position and movement of body parts, whether such movement is self generated or externally imposed. The receptors that support this sense are found in the skin, joints and muscles. Kinaesthetic interfaces are also a subclass of haptic interfaces.

A prerequisite of VE technology is the ability to track the user's movements. A number of kinaesthetic interfaces are available. The head tracker device provides the VE user with naturalistic navigation. Data gloves are used to track hand gestures, thus allowing users to indicate choices or issue commands. Simpler, less naturalistic interface elements are also available in the forms of mouse, joystick and keyboard input.

Tracking system elements are often used in conjunction to provide positional navigation within VEs. An example of this is the combined use of a head tracker and data glove. The reason for this is that nature of naturalistic navigation requires the specification of both direction and displacement simultaneously. That is, a positional translation within a VE requires both distance and direction. Due to the complexity of such navigation, latency between user motion and its representation in the VE is a very common problem. This delay causes confusion between the user's proprioceptive and visual sensory channels, an effect known as adaptation. Adaptation is thought to be a contributing factor to simulator sickness [Knerr et al., 1998].

2.2.6 The Database, Construction and Maintenance system

The construction and maintenance system, usually a suite of software running on an IBM compatible PC, is required to produce a detailed and realistic model for the VE. A VE system is will include basic constraining behaviour, such as of collision detection and terrain following. These behaviours are implemented using the construction and maintenance system. The function of the database is to hold the models and associated information for rapid retrieval by the construction and maintenance system.

2.3 *Illumination and Shading*

2.3.1 The Nature of Light

In order that the basic principles of computer graphics shading models are understood, the behaviour of light must first be analysed. Analysis requires measurement. The science of measuring electromagnetic radiation is known as radiometry. Photometry is a variant of radiometry concerned with the measuring of visible light in units that are weighted according to the sensitivity of the human eye to light (380 to 780 nm). This weighting is presented as a luminous efficiency function for the HVS, and is shown in figure 2.3 below. Luminous exitance is defined as the total area density of luminous flux leaving a surface, and is the principle unit of measurement used by advanced shading and illumination models use to accurately model the behaviour of light, although the use of radiometric units (i.e. radiant exitance) is also commonplace.

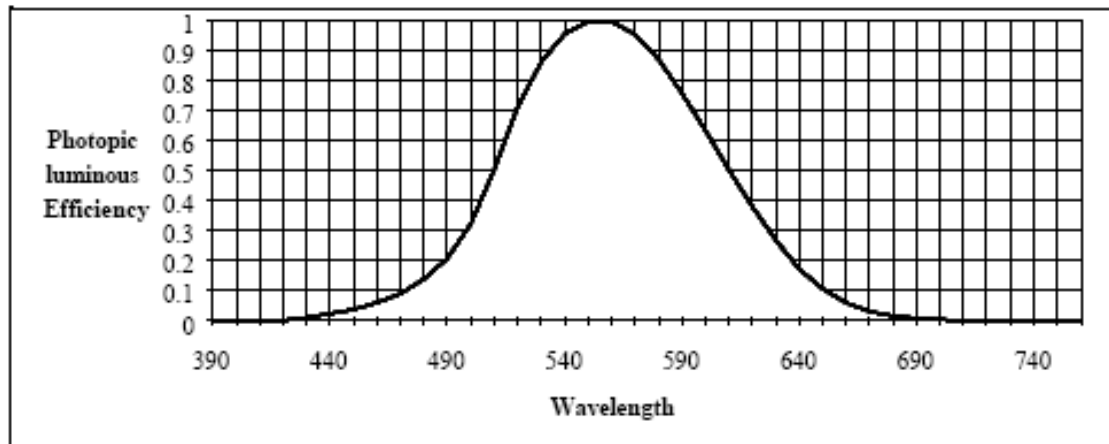


Figure 2.3: The luminous efficiency function of the HVS showing luminous efficiency against wavelength of light

2.3.2 Photorealism

It is commonly assumed that a photorealistic picture is the ultimate goal of a graphical system. This is not necessarily the case, as if the ultimate goal of a picture is to convey information, then a picture that is free of the complications of shadows and reflections may well be more successful than a *tour de force* of photographic realism [Foley et al 1997, pp105]. The measurement of the effect of variations in the quality of the output of the image generation system is central to this thesis. In general, the higher the simulation fidelity of the VE, the more computationally expensive it's realisation becomes. This situation leads to a trade off between simulation fidelity (in particular, graphical quality) and cost, both computational and financial, and so brings into question the necessity of photorealism in VE based training and simulation.



Figure 2. 4: A static image employing both radiosity and ray tracing.

2.3.3 Illumination Models

An illumination model is used to calculate the colour and intensity of light within a virtual scene. Illumination models that simply calculate the distribution of light that comes directly from the light source(s) are termed local illumination models. Ray tracing techniques are classed as a local illumination models. Global illumination models take into account all light interactions within the scene, modelling diffuse interreflections to create an image with soft shadows and colour bleeding effects. Global illumination models produce near photorealistic results. Currently, radiosity is the only global illumination model available. Near photorealism is achievable using radiosity and ray tracing in conjunction. Radiosity provides the diffuse interreflections, colour bleeding and soft shadows, and ray tracing provides the specular reflections and transparency. An example is given in figure 2.4 above.

There now follows an overview of the shading models currently available.



No shading: A model with simple ambient lighting. No shadows are formed by the geometry. Shading effects can be approximated using textures, as is evident on the blackboard. This is the simplest of the view independent solutions. Screenshot from Lightscape.

Flat Shaded: Flat shaded visualisations use only one colour per surface. This causes the Mach effect, where intensity in the vicinity of the edges is overestimated for light values and underestimated for dark values. This effect can be reduced by means of Gouraud [Gouraud, 1971] or Phong [Phong, 1975] shading. Shadows are not cast by geometry. Screenshot taken from 3DStudioMax.



Ray traced Shadows: Ray traced shadows produce very sharp, unrealistic shadows. Raytracing is most commonly associated with the modelling of specular highlights in static images. Raytracing cannot be computed real-time, and is therefore not suited to dynamic scenes. It is possible to project ray traced shadows onto textures for use in VEs, but radiosity produces far better results. Image taken from 3DStudioMax.

Radiosity rendering: Radiosity rendered solutions are view independent. This means that they are suitable for dynamic scenes. The diffuse interreflections and soft shadows produced using radiosity are considered essential to photorealism. Image taken from Lightscape.



2.3.4 Radiosity Principles Overview

Radiosity theory finds its roots in radiative heat transfer theory developed in the 1950s. In radiosity calculation, all surfaces are classed as absorbing, reflecting or transmitting. Most surfaces are modelled as a combination of absorbent and reflective, although any surface can also be modelled as transmitting (i.e. a light source). In modelling reflection, radiosity theory draws a further distinction between specular, diffuse and glossy materials. Specular materials are highly reflective, and cause specular reflections when lit. Radiosity methods are unable to recreate specular effects because of their view dependant nature. A diffuse material, as its name suggests, diffuses incident light arriving at its surface. Glossy materials are a blend of the properties of diffuse and specular surfaces. The visual effects of these different material properties are demonstrated in figure 2.5 below.

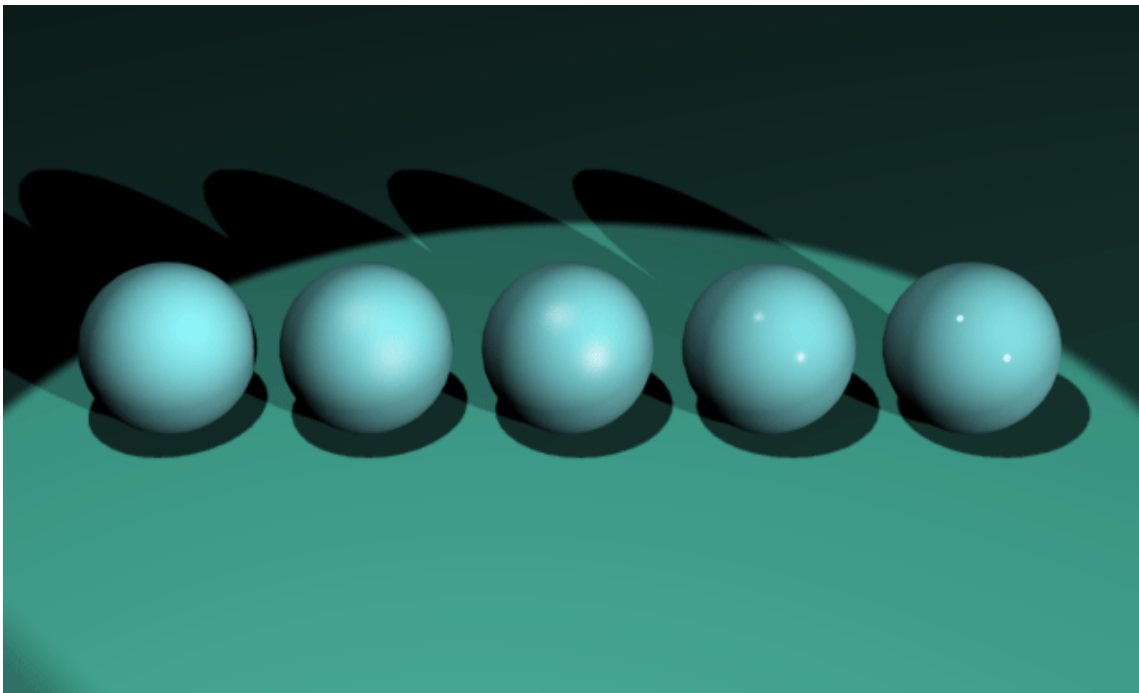


Figure 2.5: Diffuse (left), glossy (centre) and specular (right) reflection

For the purposes of radiosity calculation, diffuse surfaces are often referred to as Lambertian. Central to radiosity theory is the assumption that all surfaces are Lambertian in nature. A Lambertian surface is defined as a surface that has constant

radiance, such that when viewed from different directions (at the same angle), gives the same radiance [Tralvex 1997]. This idea is illustrated in figure 2.6 below.

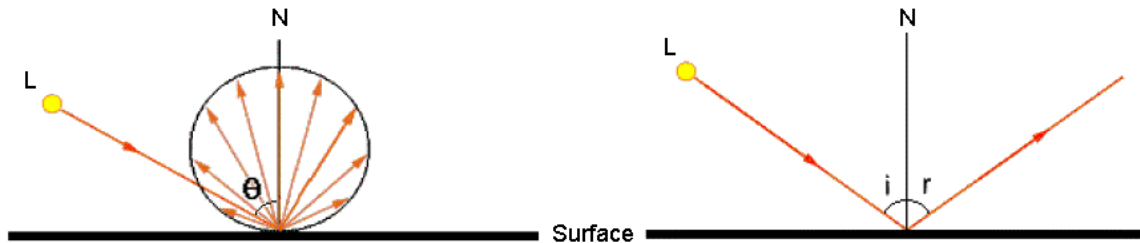


Figure 2.6: Diffuse and specular reflection. For a Lambertian surface, the brightness depends on the angle θ between the direction to the light source, L and the surface normal, N . A specular surface reflects a beam of incident light, such that $i = r$.

In rendering a radiosity solution, for each light emitting surface, calculation of the path of the photons emitted causes other surfaces to be lit. Surfaces are split into patches. Each patch will reflect and absorb light according to its material properties. Reflected light will continue on its path until another patch is hit and so on, until all (or at least most) of the energy has dissipated.

2.3.4 Radiosity Calculations

The amount of light reflected by a Lambertian surface is calculated using Lambert's cosine law. Lambert's cosine law states:

$$I_0 = I_n \cos \theta \quad \text{candela}$$

Where I_0 is the radiant intensity of each ray, and I_n is the radiant intensity of a ray leaving in the direction of the surface normal, and θ is the viewing angle. Thus, Lambert's law provides a mathematical basis for the concept of reflectance in radiosity calculations.

To speed up the radiosity rendering process, form factor algorithms are used. Form factor is defined as the fraction of energy leaving a given surface that arrives at a second surface directly and is the essence of radiosity [Cohen et al., 1993]. The form factor between all patches in the scene is calculated on commencement of the radiosity

calculations. The form factor between two patches is commutative i.e. the form factor between patches i and j is the same as for j to i , the realisation of which halves the number of form factor calculations, resulting in a time complexity, for n patches, of $O(n^2)$.

With the necessary background material covered, the radiosity equation is now described. For the total exitance of patch i :

$$\text{Exitance}_i = \text{Exitance}_{oi} + \text{Reflectance}_i \sum_{j=1}^n \text{Exitance}_j \cdot \text{FormFactor}_{ij}$$

Letting,

M_i be the total exitance of patch i ,

ε_i be the exitance produced by the surface should it be a light source,

ρ_i be the reflectance of the patch, with a value between 0 and 1,

M_j be the exitance of patch j

and F_{ij} be the Form factor between patch i and j .

We have,

$$M_i = \varepsilon_i + \sum_{j=1}^n M_j F_{ij}$$

Rearranging for ε_i we have,

$$\varepsilon_i = M_i - \sum_{j=1}^n M_j F_{ij}$$

This equation can then be expressed as a set of n simultaneous linear equations:

$$\begin{aligned}\varepsilon_1 &= M_1 - (\rho_1 M_1 F_{11} + \rho_1 M_2 F_{12} + \dots + \rho_n M_n F_{1n}) \\ \varepsilon_2 &= M_2 - (\rho_2 M_1 F_{21} + \rho_2 M_2 F_{22} + \dots + \rho_n M_n F_{2n}) \\ &\vdots \\ &\vdots \\ \varepsilon_n &= M_n - (\rho_n M_1 F_{n1} + \rho_n M_2 F_{n2} + \dots + \rho_n M_n F_{nn})\end{aligned}$$

Simultaneous linear equations can be represented using matrices:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} = \begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_n \end{bmatrix} \begin{bmatrix} 1 - \rho_1 F_{11} & -\rho_1 F_{12} & \dots & -\rho_1 F_{1n} \\ -\rho_2 F_{21} & -\rho_2 F_{22} & \dots & -\rho_2 F_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -\rho_n F_{n1} & -\rho_n F_{n2} & \dots & -\rho_n F_{nn} \end{bmatrix}$$

Using matrix shorthand:

$$\varepsilon = (\mathbf{I} - \mathbf{F}) \mathbf{M}$$

From this equation, the solution for \mathbf{M} can be computed by inverting the $(\mathbf{I} - \mathbf{F})$ term:

$$\mathbf{M} = \varepsilon (\mathbf{I} - \mathbf{F})^{-1}$$

Where:

\mathbf{M} is the final nx1 exitance vector,

\mathbf{I} is nxn identity matrix,

ε is the initial nx1 exitance vector,

and \mathbf{F} is an nxn matrix whose i, j th element is $\rho_i F_{ij}$

This is the most important result for the classical radiosity technique [Tralvex 1997], and can be solved using any of the standard iterative matrix solution algorithms.

2.3.6 Radiosity Optimisations

Adaptive subdivision is a radiosity solution quality optimiser that allows the specification of a maximum subdivision contrast level. Upon detecting a high contrast level across a patch, the algorithm iteratively subdivides the patch until the specified subdivision contrast level is achieved, thus reducing the Mach effect at patch boundaries.

A further optimisation of the form factor computation stage is by means of Monte Carlo methods. Standard radiosity calculations, as described above, calculate the angle of incidence for each photon or ray reflecting off a surface. The Monte Carlo method uses a random number generation algorithm to simulate ray dispersion. Due to the high number of calculations required for a radiosity solution, calculating ray incidences in this manner yield very similar results to more traditional methods. [Shirley, 1991] showed that the time complexity of the Monte Carlo method for radiosity rendering is reduced to $O(n)$, a huge improvement on traditional methods. The illumination solution tool used in this dissertation, Lightscape 3.2, uses a Monte Carlo algorithm for radiosity calculations.

Algorithm optimisation research has also focussed on perceptually driven rendering. [Meyer, 1992] showed that the controlled blending of achromatic and chromatic radiosity has little or no effect on the perceptual quality of the rendering whilst making a small, but significant computational saving.

2.3.7 Assumptions and Shortfalls of Radiosity Principles

Primarily, radiosity solutions are not capable of modelling specular reflections. In addition to this, the medium through which the light energy travels is not modelled. In other words the diffusing, absorbing and refracting properties of air are not taken into account when making radiosity calculations.

2.4 The Human Visual System (HVS)

The goal of photorealistic rendering is to convince the users HVS that what it perceives is real. In pursuance of this, a number of characteristics of the HVS need to be considered, and a sufficiently accurate model established. This section details the HVS characteristics required for such a model.

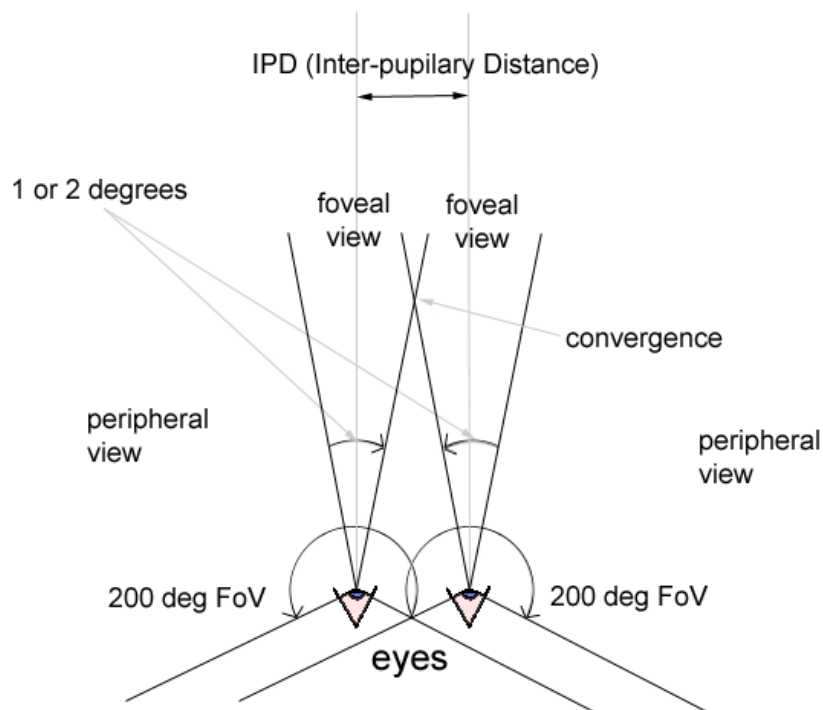


Figure 2.7: Human eye characteristics

2.4.1 The Eyes

Light enters the eye through the pupil and hits the retina at the rear interior of the eye. The retina is composed of two kinds of photoreceptors.

Rods, accounting for 94.5% of the photoreceptors on the retina, are sensitive to motion and dim, achromatic light. Rods provide peripheral (or parafoveal) vision.

Cones, accounting for only 4.5% of the photoreceptors on the retina, convey colour information and provide high visual acuity. Visual acuity is term for the ability to resolve detail in an image by detecting fine spatial pattern. Cones provide foveal vision.

The HVS is not a passive system. The two kinds of photoreceptor working in conjunction produce a variation in visual acuity over the retina, as shown in figure 2.8.

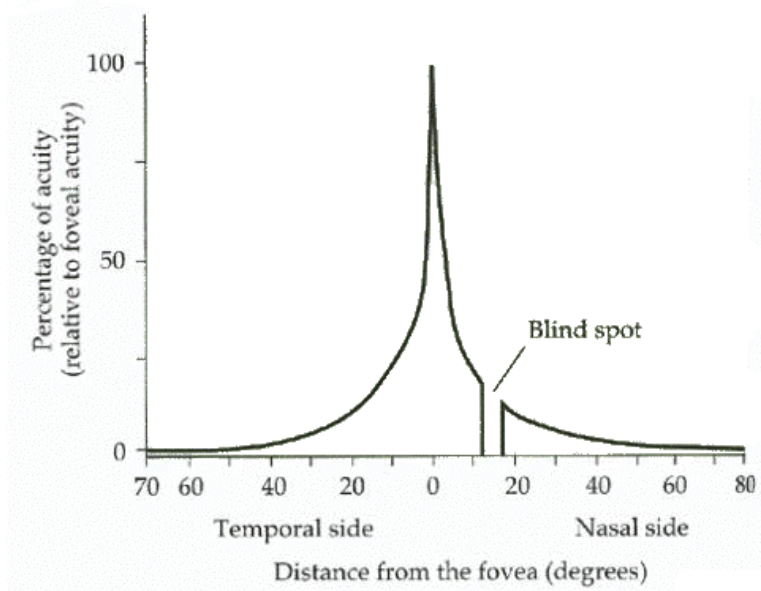


Figure 2.8: Variation of visual acuity over the retina

This variation across the retina creates the need for saccades, the name given to the rapid movements the HVS makes in order to probe its surroundings. It is by these means that the HVS actively gathers visual information across the full field of view. A user's inter pupillary

distance (IPD) is a measure of binocular disparity. The IPD value translates directly to the parallax setting of a VE viewed through an HMD.

2.4.2 Depth Perception

Stereopsis is the name of the effect of producing a three dimensional image as the product of overlapping fields by taking advantage of binocular disparity. The two views received by the eyes are called a *stereo pair*, and are fused into a 3D image by the HVS. The disparity between the views is greater for near objects, and less for objects further away. Disparity is proportional to depth, D but inversely proportional to the squared viewing distance, v (see figure 2.9). Since the HVS is sensitive to this effect, it serves as a depth cue. This form of depth cue is known as convergence, and is the primary way in which the HVS perceives stereo vision. A similar effect to convergence is head movement parallax, where view disparity is created as a result of head movement, thus forming another type of depth cue.

The HVS also perceives stereo by focal disparity between the eyes. For an object at point Q (see figure 2.9) each eye will adjust its focus by a differing amount. This effect is known as accommodation.

Accommodation is part of normal vision, but it is not reproducible in a VE using an HMD. Lack of accommodation is thought to be a contributing factor to cybersickness.

Other depth cues include linear perspective, shading and shadows, occlusion and texture gradient.

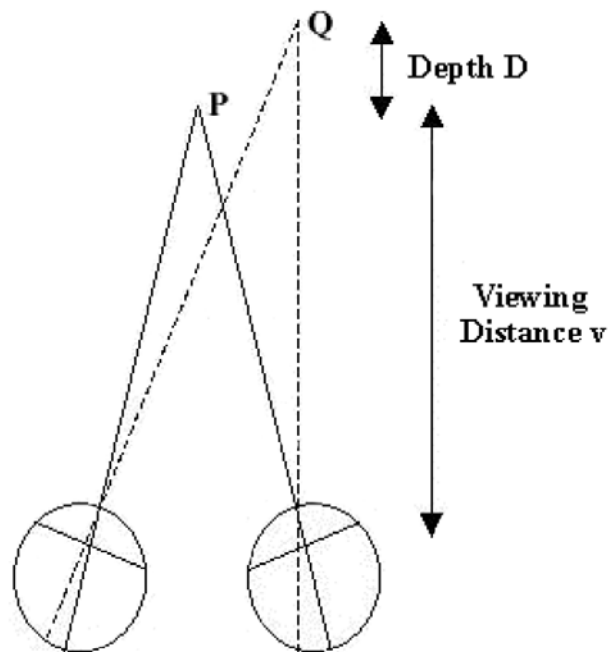


Figure 2.9: The geometry of binocular vision

2.5 Simulation Metrics

What are the factors that support effective acquisition of skills in VEs? One candidate factor is the fidelity of the simulation. Simulation fidelity metrics are the focus of this thesis. Simulation fidelity is defined as the extent to which a VE is indistinguishable from the reality it simulates. Does increased simulation fidelity enhance the training process? In order that this question be answered, it is essential that the quality of the training can be measured. To date, methods of assessing the suitability of a VE for a training task have identified immersion and presence as possibly measurable factors affecting the fidelity of a simulation. Tailored more to the idea of producing metrics solely for the assessment of training quality, research into the use of task performance measures has been undertaken in recent years.

This section first gives definitions of immersion and presence, before an overview of task performance based measures is presented. The section then goes on to describe the subjective responses to lighting conditions metric before concluding with a description of the simulator sickness questionnaire (SSQ), used to measure cybersickness.

2.5.1 Immersion

A user said to be in a state of immersion can be described as having a large proportion of sensory input coming from the VE. The term usually applies to displays that fill a user's vision, although it is equally applicable to any technological element found to increase immersiveness.

[Slater, 1997] discusses factors that contribute to immersion, including:

Inclusiveness - Extent to which physical reality is shut out

Extensiveness - Range of sensory modalities simulated / accommodated

Surrounding - Primarily the FOV, but also applies to audio

Vividness - Resolution, fidelity, richness, and quality of the modality stimulation

Matching - Corresponding head and body movements

Virtual Body - egocentric viewpoint rather than exocentric

Plot - Extent to which the context presents a story line

Currently, the most highly regarded immersion metric for VEs is the Immersive Tendencies Questionnaire (ITQ), intended as a complement to the Presence Questionnaire (PQ) developed by [Witmer, 1998].

2.5.2 Presence

Central to much recent research is the notion of presence within a VE. Presence is clearly required for operational effectiveness within a training simulation. Presence is a concept still under development – there is still much debate about its true nature. In the context of virtual environments, presence can be defined as the subjective experience of being in one place or environment, even when physically situated in another. Presence is thought to be an aid to the suspension of disbelief that a user needs in order to interact "naturally" within the VE. No definition is absolute, as the scientific community is yet to agree on a formal definition of the term. Some researchers support the idea that the amount of presence a subject feels within a virtual environment may be linked to enjoyment, although little evidence to has been presented to confirm this.

The need for a presence metric is considered essential for the optimisation of display systems towards specific training and simulation goals. Since presence is a subjective experience, research has focussed on the development of a subjective measure of presence, yielding various post-exposure self-assessment questionnaires. However,

subjective measures are known to be potentially unstable, with inconsistencies across different 'raters' and rating situations [Ijsselstein 2000]. It is for this reason that research is also undertaken in the pursuit of objective measures of presence, since objective measures may serve as corroboration of subjective results [Freeman2000].

There now follows an overview of the various measurement techniques that have been developed, all of which rely on a subjective self-measurement unless otherwise stated. This selection is by no means exhaustive - a thorough review of the literature on presence can be found in [Draper, 1998].

Presence Questionnaires: During the late 1990's significant effort was made into quantifying the concept of Presence. Two Presence questionnaires endured this period, namely the SUS Presence Questionnaire [Slater, 1994] from UCL, London and the Presence Questionnaire (PQ) [Witmer, 1998] from the MOVES Naval Research Centre in America. The degree of conjecture between the two camps is indicative of the deficiencies in the concept of questionnaire based subjective measures of presence.

Hand Slider Self Report Measurement: The participants in a study performed by [Freeman et al, 1999] used a hand slider, continuously updated by the participant, as a self-report measure of presence. This method has the obvious shortfall of reducing the sense of overall presence by ensuring the participant is constantly aware of one aspect of reality, namely the hand-held slider. Intuitively, this method is self-debasing to at least some immeasurable degree.

Breaks in Presence: A recent development by Slater et al at UCL is the measurement of breaks in presence (BIPs) where subjects are required only to report negative effects in presence. This method has the advantage that it is easier to report on a missing facet of an experience than it is to describe that same facet (i.e. presence) in detail.

Magnitude Estimation: In order to capitalise on the subject's impression immediately after exposure, a single number indicating overall level of presence is elucidated from the subject [Snow et al, 1998].

Ethnographic methods of presence measurement: An ethnographic study, in the form of participant observation and interview, aimed at quantifying presence was carried out [McGreevy 1993]. An object-orientated analysis framework for presence was developed, but little research in the area is evident since.

Measuring psychophysical effects: Often, events in a VE will provoke real world responses in the user. Measurable psychophysical quantities include Skin Conduction Response (SCR), also known as electrodermal activity (EDA) [Ijsselsteijn, 2000a], skin temperature [Meehan, 2000], posture, muscular tension, especially facial (measured using a electromyogram), monitoring of cardiovascular behaviour using an electrocardiogram (ECG), ocular responses [Barfield, 1993], cortical activity (EEG), respiration rate, blood pressure and pointing to targets [Lackner, 1994].

It has been observed that a reported increase in presence often accompanies an increase in task performance. The research community has made efforts to establish a link between presence and task performance. It is still unclear as to whether relationship is causal (i.e. increased presence and increased task performance just happen to occur under the same conditions) or correlational (i.e. an increase in presence is likely to result in increased task performance). Conflicting results between different studies, by the same research teams [Witmer, 1994] and [Bailey, 1994] highlight the unreliability of this notion, and so the community remains undecided on the matter.

2.5.3 Task Performance Based Measures

VEPAB: The virtual environment performance battery by [Lampton et al., 1994] is a move towards benchmarking VE performance. To facilitate measurement, only simple tasks are undertaken. The tasks are divided into five categories:

Visual tasks: Acuity, colour, search, object recognition, size estimation and distance estimation

Locomotion: Navigation, flying, searching

Tracking: Controlling the positions of cursors

Object manipulation: Dexterity, hand to eye coordination

Reaction tasks: Measuring reaction times

The evaluation of this platform indicated that participants were sensitive to practice effects and that individual characteristics of participants should be accommodated in the design of the tasks [Mania 2001]. Other measurable aspects of human performance efficiency under research include spatial ability / awareness, mental adaptability, personality traits and individual cognitive styles.

2.5.4 Subjective Responses to Lighting Conditions

Aside from the obvious function of providing visibility, lighting can have a strong impression on a user's perception. Lighting designs can be used to guide gaze and attention. The Subjective Responses to Lighting Conditions questionnaire can be used to reveal variation in lighting impressions between conditions.

2.5.5 Cybersickness

The Simulator Sickness Questionnaire (SSQ) was introduced by [Kennedy et al, 1993]. The questionnaire attempts to pick up on all aspects of discomfort associated with extended use of VEs: disorientation, nausea and oculomotor-related disturbances, with disorientation being the most common. Oculomotor-related disturbances are the least commonly reported by HMD users. 80 to 95% of individuals exposed to a VE system report some level of post-exposure symptomology [Stanney et al, 1998]. There are currently three theories as to the underlying causes of cybersickness.

Conflicting Sensory Input: It is thought that the simulation of motion within a VE produces confusing signals between the HVS and the vestibular system may be a cause of cybersickness.

The Poison Theory: Sensory confusion may lead the body to misread symptoms as those of toxic substance ingestion, thus producing an emetic response.

The Postural Instability Theory: A third theory suggests that the cause of cybersickness is prolonged postural instability.

Other factors thought to increase cybersickness include individual differences such as age, gender and health. Display and technology issues such as position tracking errors, sensor lag and display flicker will also increase the likelihood of cybersickness.

2.6 Summary

This first section of this chapter described the construction of a 3D model, detailing the associated structure and limiting factors.

After a brief discussion on the application of VEs, the essential concepts behind VE technology were investigated, with an overview of the various interface modalities found in a VE system also being presented.

The third section dealt with the nature of light and photorealism before going on to describe the more commonly employed illumination models. The section concluded with an insight into radiosity principles, including a derivation of the radiosity calculation. Aspects of the Human Visual System relevant to VE technology were then investigated, after which an overview of simulation fidelity metric research to date was presented.

Chapter 3: A Methodology based on Memory Semantics

In this thesis, a simulation fidelity metric based on human judgements of memory awareness states is used to reveal any differences in cognitive strategies employed during a memory retrieval task. This chapter explores the underlying psychology behind the metric before going on to describe its application to the field of simulation fidelity metrics. The statistical analysis tools employed by the methodology are also presented.

3.1 *Tulving's Memory Model*

In modelling human memory, [Tulving, 1992] draws a distinction between operational (procedural) memory and substantive (propositional) memory. Operational memory refers to that which is associated with perceptual motor skill and cognitive skills. Operational knowledge takes practice to acquire, and requires no thought during execution. Substantive memory refers to that which is associated with symbolic knowledge. There are two distinct categories of substantive memory: episodic and semantic. Episodic memory allows for introspection and reflection. Semantic memory is characterised by retentiveness, but not retrospection [Furlong, 1951].

3.2 *Memory Encoding and Retrieval*

[Tulving, 1992] goes on to describe the differences in the way episodic and semantic knowledge is encoded and retrieved. A semantic memory engram is encoded and recalled without any associated mental imagery. The retrieval cue simply causes the knowledge to 'pop up' in the subject's head – the subject just *knows* the answer. This form of retrieval is referred to as implicit memory retrieval. Episodic knowledge is encoded with a reference to context in both time and space. This is thought to be a factor in the formation of the mental imagery associated with the engram, and thus give the subject a 'mind's eye' view of the memory. Memories of this nature can be subjected to retrospection, as stated above. Recalling memories in this manner is referred to as *remembering*. This form of retrieval is also known as explicit memory retrieval.

3.3 *Human Judgements of Memory Awareness States*

Previous attempts to define simulation fidelity metrics using task performance measures have focussed on *what* as opposed to *how* a task is achieved. The simulation fidelity metric used for this thesis examines the cognitive strategies employed, by means of the addition of an awareness state self report measure associated with each question on a post exposure spatial memory task questionnaire. The self-report measure includes options for both the *remember* and *know* awareness states, and is intended to identify whether the memory retrieval method employed is implicit or explicit.

The two memory awareness states described above do not take account of situations where the participant is unsure of their answer. In the situation where the participant does not remember or know the answer, they may be tempted to choose the know response, since it is closer to their awareness state than remember (i.e. because they have no associated mental imagery with the recollection). To circumnavigate this problem, two more memory awareness states are introduced: *Familiar* and *Guess*. Under Tulving's model, these states could be classed as implicit retrieval of weakly encoded semantic memory engrams, but for the purposes of this study, they are not considered. In addition to the self-report measure for memory awareness state for each question, there is a confidence self report measure that asks the participant to rate their level of confidence in their answer on a scale of 1 (no confidence) to 5 (certain).

In order that positive or negative correlational evidence for the metric be produced, three other questionnaires are also to be administered: The Presence questionnaire, The Subjective Responses to Lighting Conditions questionnaire and the Simulator Sickness questionnaire (SSQ).

3.4 *Statistical Analysis*

3.4.1 *Background*

Prior Probabilities: The memory awareness states data is represented as *prior probabilities*. This notation does not follow the general Bayesian probability theory for prior probabilities. It is, however, going to be adopted as such in this thesis following the characterisations of [Koriat 1994] and [Conway et al, 1997]. The prior probabilities are obtained by calculating the proportions of correct answers falling in each of the four

memory awareness categories for every participant in a memory experimental study. The awareness states results are initially presented as prior probabilities. Here, prior probabilities are used to answer the following question: For each correct answer obtained, what is the probability that the participant has chosen a particular state on that question?

Correlation Analysis: This analysis tool provides a measures of correlation between two data sets. The calculation returns the covariance of two data sets divided by the product of their standard deviations. Correlation is used to determine whether large values of one set are associated with large values of the other (positive correlation), whether small values of one set are associated with large values of the other (negative correlation), or whether values in both sets are unrelated (correlation near zero) [Excel 2000]. For this experiment, the level of significance is 0.05 and the value of df is 7, requiring a value for significance of 0.582.

ANalysis Of VAriance: ANOVA procedures are powerful parametric methods for testing the significance of the differences between sample means where more than two conditions are used, or even when several independent variables are involved [Coolican 1993]. ANOVA is used to compare the variance between the two groups with the variability within each of the groups. This comparison is in the form of a ratio known as the F test. A high value for F indicates a strong effect i.e. the variance between groups is higher than the variance within the groups. The strength of the effect is given by the p value. The p value represents the probability that there is no between groups variance. This is called the null hypothesis, and is disproved if a value of p below 0.05 is returned.

3.4.2 Application to Experiment

Prior probabilities, correlation and ANOVA are to be used extensively in the processing of data obtained during the experiment. This section describes how these methods are applied, and the possible inferences that may be drawn. The spatial memory awareness test will produce 3 different data sets. As an aid to explanation, nomenclature for these data sets is defined in table 3.1 below.

Nomenclature	Description
Correct Answers	A tally of total number of correct answers, one for each participant in each condition
Prior Probabilities	A set of results, one for each of the memory awareness states, per participant in each condition, denoting the probability that, for each correct answer, the probability that it is correct.
Mean Confidence Scores	For each condition, a set of average confidence scores across all participants.

Table 3.1: Dataset nomenclature

Prior probabilities are calculated using Microsoft Excel. ANOVA tests are then performed on the memory test performance scores for both groups to check that there is no variance between the memory test performance scores between the groups. Should there be no effect found, a second test is performed on the prior probabilities to investigate any effects revealed between the two conditions.

Correlation analysis is performed on the mean confidence scores and prior probabilities. Correlation analysis is also performed on the mean confidence scores and the correct answers dataset. Both correlations are for the purpose of identifying confidence based variations between the two conditions.

ANOVA is also used in the analysis of the Subjective Responses to Lighting Conditions questionnaire results as a check to verify the similarity of the lighting impressions across the two conditions.

The Presence questionnaire results are also subjected to ANOVA to reveal any differences in perceived presence between the two groups, for the purposes of supporting or rejecting the hypothesis that a radiosity rendered VE will result in a higher degree of perceived presence.

The SSQ questionnaires, again analysed using ANOVA, are to be used to ensure differences between the two conditions are not significant.

Chapter 4: Realising the Virtual Environments

In this chapter, the requirements, specifications and implementation details for the creation of the VE are given. The implementation details include an overview of the workflow employed in the creation of the VE, and a walkthrough of the BasicScript code used to implement the behaviours within the VE.

4.1 Requirements

To perform the experiment, two VEs must be generated. One VE is to be flat shaded, and one radiosity rendered. The two VEs are to be identical in all other respects. The VEs must be of sufficiently low polygon count that real time navigation and interaction is possible. Two instances of audio feedback are required: One to accompany collision detection, and one to announce that the specified exposure time has elapsed.

4.2 Specifications

This section gives the specifications for the technology used in the realisation of the VEs. Despite the difference in poly count for the two VEs, both are to run at the same frame rate. In addition, the overall brightness of the VEs is to be matched.

Hardware: Hewlett-Packard X4000 Workstation

Dual Intel Xeon processor (2 x 1.8 GHz)

500MB Ram

Wildcat III graphics card

SCSI interface

Kaiser Pro-View 30 HMD

Sony PC speakers

Software: Autodesk 3DStudio Max version 5

Autodesk Lightscape version 3.2

Sense8 WorldUp r5 patch 6

Adobe Photoshop version 7

Standard OS (Windows 2000) and essential software (Microsoft Office)

Note: WorldUp r5 patch 5 will not function with Wildcat cards unless WorldUp 5 patch 6 (released 13th June 2003) is applied.

4.3 Implementation

The following section gives brief description of the workflow employed during the creation of the VE. Working knowledge of this type is time consuming to acquire, and so is given for the purposes of continued research.

4.3.1 Workflow

The rooms are modelled using 3DStudioMax version 5. The model is then exported from 3DStudioMax using the max2lp export plugin. This exports the model in .lp (Lightscape preparation) format ready for radiosity processing using Lightscape version 3.2. This export method also has the advantage that cameras within 3DStudioMax are converted to Lightscape 'views'. Having a number of well-chosen views within Lightscape provides a convenient way of navigating around the model.

Lightscape is then used to create both the flat shaded and radiosity rendered VEs. For a solution of any fidelity, the radiosity mesh produced is invariably too large for use by WorldUp, which has a limit of 50,000 polygons. By experimentation, it was found that frame per second rates above 20 are only possible with a polygon count of less than 15,000. To achieve this low polygon count, the mesh to texture tool in Lightscape is used to project the radiosity mesh onto the texture behind, thus saving the shading information before discarding the radiosity mesh.

To further optimise this process, prior to radiosity processing, all surfaces except the most visible have their surface processing parameters set to coarse (0.04). Then, for the principle, visible surfaces (walls, ceilings, floors, desktops and shelves) processing parameters are set to very fine (10). After radiosity processing, only the principle surfaces need their meshes converted to textures, thus producing a low poly-count model with a minimum of different textures.

Once the mesh to texture process is complete, the model is exported as a VRML file, suitable for importing into WorldUp r5 patch 6. The conversion process has the undesirable effect of combining all model elements with the same texture into the one geometry node. The logging process employed during the experiment will only register

different geometries, so in order that the user logs contain meaningful information, it is essential that different model elements (desktops, walls) have individual textures. This is a second good reason for using the mesh to texture tool in Lightscape.

Once the VRML model is imported into WorldUp the model rotated through 180° to account for WorldUp's unusual x,y,z orientation. Interactivity is then added to the simulation using the BasicScript API provided with WorldUp (see Appendix C for listing). For the purposes of the experiment, the only essential behaviours are collision detection, terrain following and simple navigation. The user script is then attached to the Viewpoint node in the scene graph view in WorldUP. The 'User Defined' button also has a short script attached. The script simply moves the viewpoint to the centre of the VE, and resets the simulation timers and logging variables ready for the next participant. The next section provides a walkthrough of the BasicScript code (See Appendix C2 for the script listing).

4.3.2 Code Walkthrough

A brief explanation of the BasicScript code is now presented in the form of a code walkthrough. All of the plug in behaviours shipped with WorldUp are deficient in some respect, and so this script contains script based behaviour for terrain following, collision detection and simple navigation. The BasicScript code is attached to the viewpoint node in the scene graph within WorldUp, and is run at the start of every frame. Variables declared as public are persistent. All other variables are limited to the scope of the script, and so are reset every frame.

The entry point for the script is `sub task(vp as viewpoint)`. After variable initialisation, the script checks for user input. The accepted user inputs are described in table 4.1 below.

Key	Function	User
S	Starts the experiment. First displays a dialog to obtain the participant's name. Then the simulation timer (2 minutes) and logging process are started.	Experimenter
H	Home key: Returns viewpoint to the centre of the VE, looking dead ahead.	Experimenter
8	Forwards: Moves the viewpoint forwards in increments specified in the code. Accessible from the navigation box	Participant
3	Backwards: Moves the viewpoint backwards in increments specified in the code. Accessible from the navigation box	Participant

Table 4.1: Input keys for the simulation.

Before actually performing any translation of the viewpoint's location, a number of tests are carried out to constrain any undesirable behaviour. First, the y value is fixed, so as to provide terrain following behaviour. Further behaviour is added by using the result of the `rayIntersect` call. This call is used to cast an invisible ray directly ahead, into the scene. The call returns the name of the first geometry hit and the distance back to the viewpoint. A test is then performed to see if the distance to the geometry ahead is less than a given threshold. If a collision has been detected, the user is informed via an aural cue, and the viewpoint position is reset. After a simple test on the elapsed time for the experiment, the frame rate of the simulation is clamped by ensuring that the fame is displayed for a specified duration. The returned result from the `rayIntersect` call is then used again, this time to log the name of the geometry ahead. The room in which the user viewpoint is located is also logged, after which the script terminates.

Chapter 5: Experiment and Results

A pilot study was initially carried out. This chapter starts by presenting the more salient points arising out of the pilot study. After this, the experimental methodology and procedure for the main study is presented. Finally, the results obtained are given, along with identification of effects observed.

5.1 *Pilot Study*

In this section the experimental methodology for the pilot study is briefly outlined. The purpose of the pilot study is to ascertain the ideal exposure time for the participants, so as to avoid floor and ceiling effects in the final memory recall test scores.

5.1.1 Methodology

Methods: The ideal time is deemed to be the amount of time, on average, that a participant needs to score ten out of twenty in the spatial memory test. This time was initially estimated to be two minutes.

Materials: The materials used for the pilot study are identical to those used for the main experiment, and so are not described here for reasons of brevity.

Procedure: A draft experimental procedure was produced. Since the procedure differs little from that used in the main experiment, it is not described here. The final version is described in detail in section xxx below, and is also reproduced in Appendix A.

5.1.3 Results and Discussion

The pilot study highlighted a number of necessary changes to the draft experimental procedure, namely that some participants were not aware of both rooms, and that the way in which the questionnaires are completed requires more explicit explanation. The actual scores from spatial memory awareness tests after a two-minute exposure were 7, 9 and 11 out of 20. After taking into account the aforementioned problems, two minutes was deemed an appropriate exposure time.

5.1.4 Summary

By means of a pilot study, the ideal exposure time and a number of experimental procedure problems were identified.

5.2 *Experimental Methodology*

5.2.1 Methods

For the main experiment, the spatial memory task is employed to investigate the effect of rendering quality on the cognitive strategies employed during memory encoding and retrieval. Two groups of 9 people participated in the study. A between groups design was employed, matching age, gender and technical experience. 89% of the participants were male, and all use computers in their daily activities.

Two VEs were rendered, one using simple flat shading, and one using advanced radiosity techniques. The two conditions are matched in terms of frame rate and brightness. The VEs each contain two interconnected rooms, each 4 metres squared by 3 metres high. The rooms are based on the seminar room at the University of Bristol used for the original experiment [Mania 2001]. In addition to commonly found features such as skirting boards, both rooms are furnished with tables and shelves. Certain features are added to aid discrimination between the rooms. Room one (see appendix B) has a window and a computer on the desk. Room 2 is characterised by a door and two pot plants. Each room has 10 simple objects (boxes, pyramids, spheres) placed in a random manner around the room.



Figure 5.1: The radiosity rendered condition and mesh outline





Figure 5.2: The flat shaded condition and mesh outline



5.2.2 Materials

All participants were given the same set of questionnaires, namely the memory Recall Task questionnaire, the Presence questionnaire, the Subjective Responses to Lighting Conditions questionnaire and the standard Simulator Sickness questionnaire (SSQ). Copies of the questionnaires can be found in Appendix E. The questionnaires were administered in the same order:

1. SSQ (before exposure)
2. (experiment)
3. Memory Test
4. Presence
5. SSQ (post exposure)
6. Subjective Responses to Lighting Conditions

A plan view of the two rooms (see figure 5.3 below) was also presented as a cue for during testing (i.e. filling out questionnaires) so as to aid retrieval.

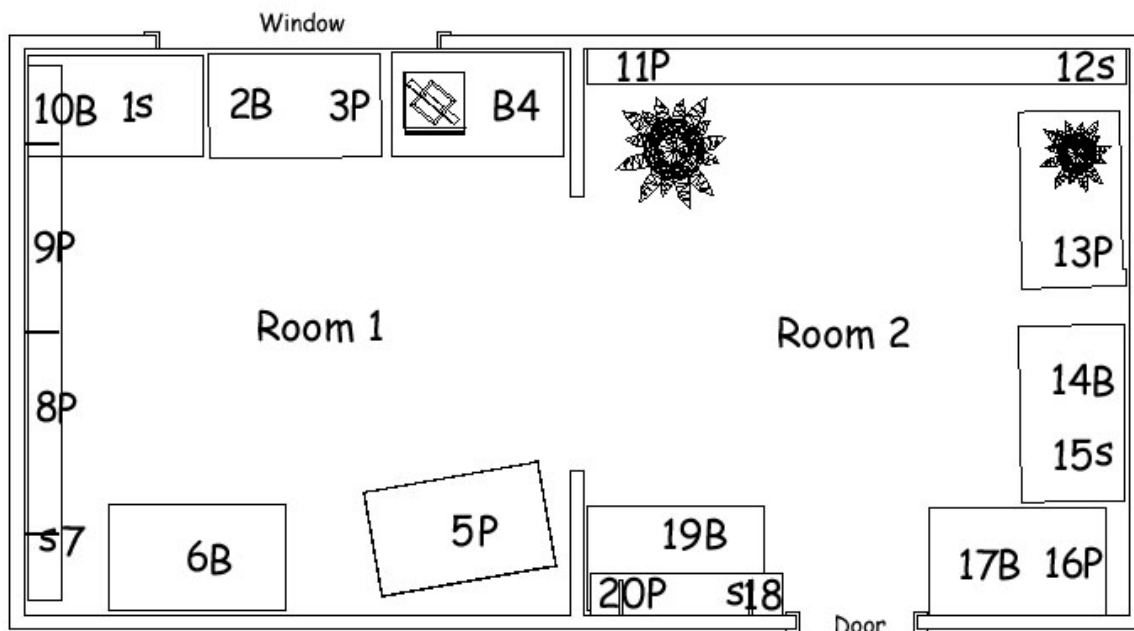


Figure 5.3: Plan view of the VE

Memory Recall Task

This questionnaire, taken from [Mania 2001], tests the participant's ability to remember the locations of the 20 objects scattered around the VE using the background theory presented in the previous chapter. It is administered with a diagram showing the layout of the VE, with numbered positions denoting object locations. Participants were asked to indicate if the object at the numbered location is a box, sphere or pyramid. Then, for each location, the participant is asked to rate their confidence in their choice. Most importantly, the questionnaire then asks for a choice of memory awareness state employed during recall. Descriptions of the four memory awareness states follow:

REMEMBER means that you can visualise clearly the object in the room in your head, in that particular location. You virtually 'see' elements of the rooms in your mind.

KNOW means that you just 'know' the correct answer and the alternative you have selected just 'stood out' from the choices available. In this case you can't visualise the specific image or information in your mind.

FAMILIAR means that you did not remember a specific instance, nor do you know the answer. It may seem or feel more familiar than any of the other alternatives.

GUESS means that you may not have remembered, known, or felt that the choice you selected have been familiar. You may have made a guess, possibly an informed guess, e.g. you have selected the one that looks least unlikely.

These choices are representative of the memory awareness states described in chapter 3. The format of each question is given below in figure 5.4.

Object location number: 10 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Figure 5.4: A sample question from the Memory Recall Task Questionnaire.

Presence Questionnaire

The amount of presence a subject feels within a virtual environment may be linked to factors such as task performance and enjoyment. As such, a need for a presence metric is essential for the optimisation of display systems towards specific goals. In pursuance of these goals, the SUS Presence questionnaire was developed [Slater, 1994].

The SUS presence questionnaire is comprised of 14 questions, each answered on a Likert scale of 1 to 7. The questionnaire is designed to give a subjective measure of presence, as defined in chapter 2.

Subjective responses to lighting conditions

The Subjective Responses to Lighting Conditions Questionnaire is administered to confirm that no significant effects from lighting disparities between the two conditions are evident. The Subjective Responses to Lighting Conditions Questionnaire is given in Appendix D.3.

Simulator Sickness (SSQ)

The SSQ questionnaire was developed by [Kennedy et al, 1993] to measure simulator after-effects such as nausea, disorientation and proprioceptive disturbance. For each of the 15 categories there are four choices from which the participant rates the symptom described: None, Slight, Moderate, Severe.

Viewpoint Logging

For each participant, for each frame spent in the VE, the room in which the participant is in is logged. In addition, for each frame, the object directly ahead of the viewpoint is logged. These logs are created for data validation purposes, e.g. for situations where the cause of erroneous data from the questionnaires needs identification.

5.2.3 Procedure

Differences in rendering quality aside, the experimental procedures for each condition are identical, and so are not considered separately here. The simulation is first reset from the previous participant's exposure by pressing the user defined action button in WorldUp. The participant's IPD (Inter Pupillary Distance) is then measured using a ruler. The participant's IPD and name, as well as the date and time are then written on the front of their questionnaire pack. The participant is then asked to fill out just the pre-exposure SSQ questionnaire, before the following instructions are then read out:

There are two interconnected rooms in the virtual environment. I am going to leave you for two minutes to view the rooms. You can move around the space freely using the navigation box provided. I would like you to look around as much as you can for this time. Please, be observant of the layout of the room and the symmetry and positioning of all of the blue objects you are going to see scattered around.

When the specified time has passed you are going to be asked to complete certain questionnaires on positioning and symmetries of the different object categories you are going to see. The entire process should take no more than twenty minutes. So, please, be observant of the layout of the room and of all the objects in it.

A verbal check is then made to ensure the subject has corrected any uncorrected eyesight, and that they understood the instructions. The participant's IPD is then entered into the parallax setting on the viewpoint node in WorldUp. The viewpoint is then rotated to point at the ceiling, so as to avoid the overexposing the participant to the VE. The participant is then given a brief verbal overview of the various adjustments on the HMD and the use of the navigation box. The participant is then left to fit the HMD and make any necessary adjustments. Once the participant is comfortable with the equipment, they are asked to look ahead, with their eyes level and to press the reset button on top of the head tracking device. This action, performed simultaneously with the pressing of the 'H' key synchronises the participant's real-world head position with a level point of view within the VE. The simulation is then started by pressing 'S' to display the welcome dialog. The participant's name is entered in the dialog, and subsequently used as the filename for their log file. As the dialog is dismissed, the participant is informed that the experiment is underway. Once two minutes have passed, the exposure period is announced by an audio cue. The participant is then led to another room, and the remaining questionnaires are presented, along with a plan view of the VE. Once complete, the questionnaires are checked for errors or omissions. The participants are then thanked for taking part in the experiment.

5.3 Results and discussion

In this section the results of the experiment are presented, separately for memory recall and awareness states, presence and simulation sickness.

5.3.1 Spatial Memory Awareness States

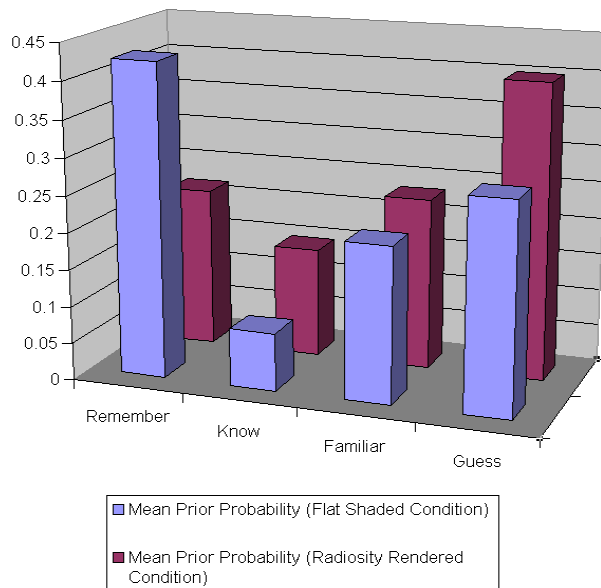


Figure 5.5: Mean Prior Probabilities across the conditions

response for the radiosity rendered condition were identified. The mean confidence scores correlated with the prior probabilities and memory performance scores for the know response in the flat shaded condition also showed significant positive effects, although interestingly, there was a far higher number of correct answers for the remember state for this condition. A significant negative effect was found in the correlation of the mean confidence scores with the prior probabilities and memory performance scores for the guess response for both conditions.

ANOVA: Two ANOVA tests were performed on the data. First, the memory test scores were subjected to analysis to check that there was no significant variance in scores between the groups. Results obtained support this hypothesis, with no effects showing $p < 0.25$. A second test, performed on the prior probabilities revealed a significant effect

Mean prior probabilities:

The mean prior probabilities indicated disparity between all conditions, the strongest effect appearing in the Remember category (See figure 5.5). Mean prior probabilities do not take account of variance within groups, and so are indicative only.

Correlation Analysis:

Positive correlations of mean confidence with memory performance scores and prior probabilities for the remember

towards the remember states for the flat shaded condition ($F(1,17) = 5.177, p < 0.05$). This is an important result, and is discussed in chapter 6.

5.3.2 Subjective Responses to Lighting Conditions

Analysis by ANOVA did not reveal any significant effects. This implies that the lighting impressions did not significantly differ over the two conditions, and so any variance in the memory awareness states scores cannot be attributed to this. Differences between average scores for each response type revealed certain subjective biases, as can be seen if figure 5.6 below.

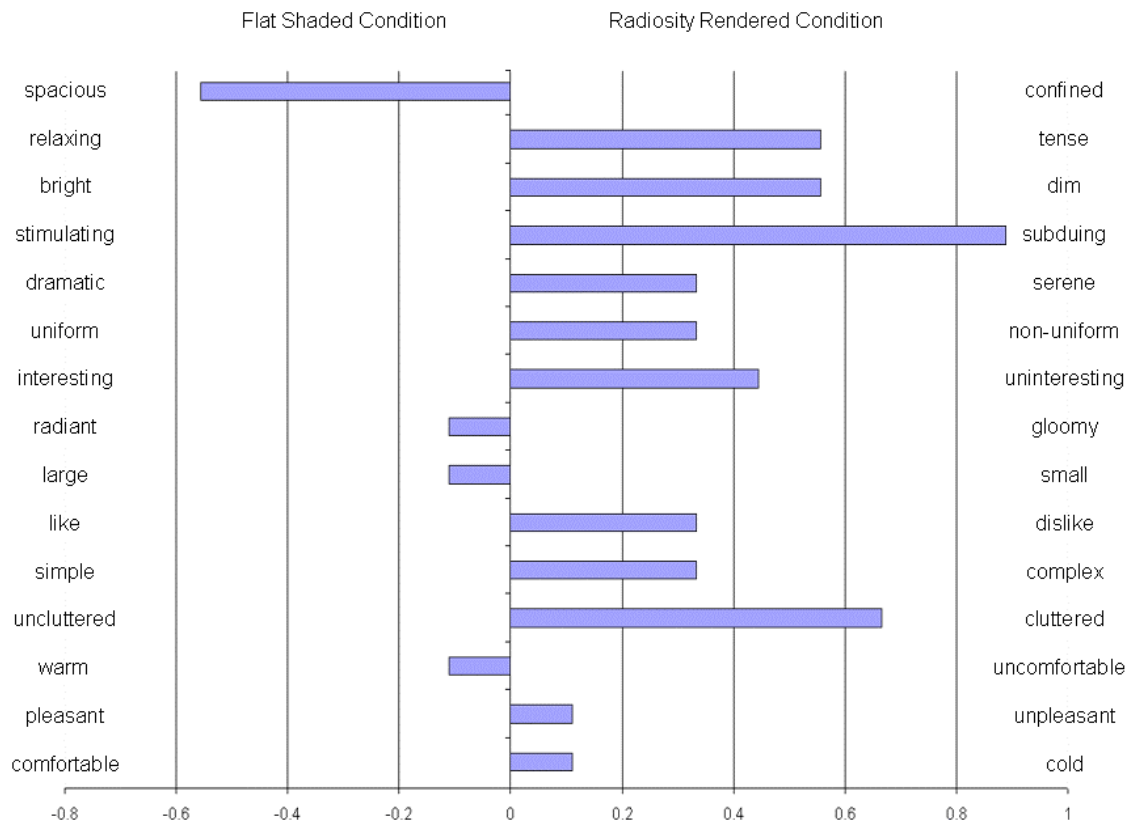


Figure 5.6: Means differences for Subjective Responses to Lighting Conditions between the two rendering conditions.

5.3.3 Presence

Statistical analysis using ANOVA did reveal a significant effect for question 10 ($F(1,17) = 6.154, p < 0.05$), indicating that the participants exposed to the radiosity rendered condition felt that they had done better at the task than those exposed to the

flat shaded condition. A tendency towards significance for the flat shaded condition, $F(1,17) = 4.238$, $p=0.056$, was revealed for question 8:

“Have you ever experienced virtual reality / 3D applications / games?”

This is unlikely to be of interest, since the question posed is quite ambiguous in its nature, and many participants asked for it’s clarification. Overall, the presence questionnaire results were quite consistent over the two conditions, as can be seen in figure 5.7 below.

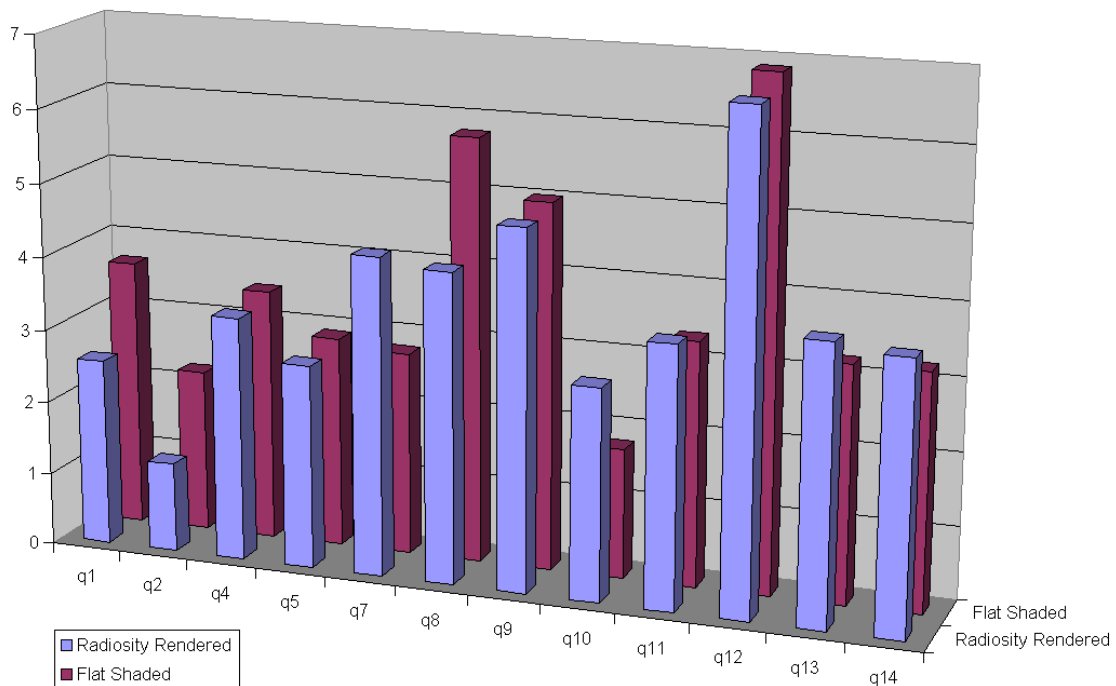


Figure 5.7: Presence questionnaire results showing little variation across conditions.

5.3.4 Cybersickness

The changes in mean reported cybersickness for the two conditions are given below in figure 5.8. The negative value for general discomfort in the flat shaded condition can be attributed to one participant whose level of general discomfort appears to have been alleviated by exposure to the VE. This result is considered erroneous, and highlights the need for more sophisticated analysis methods such as ANOVA.

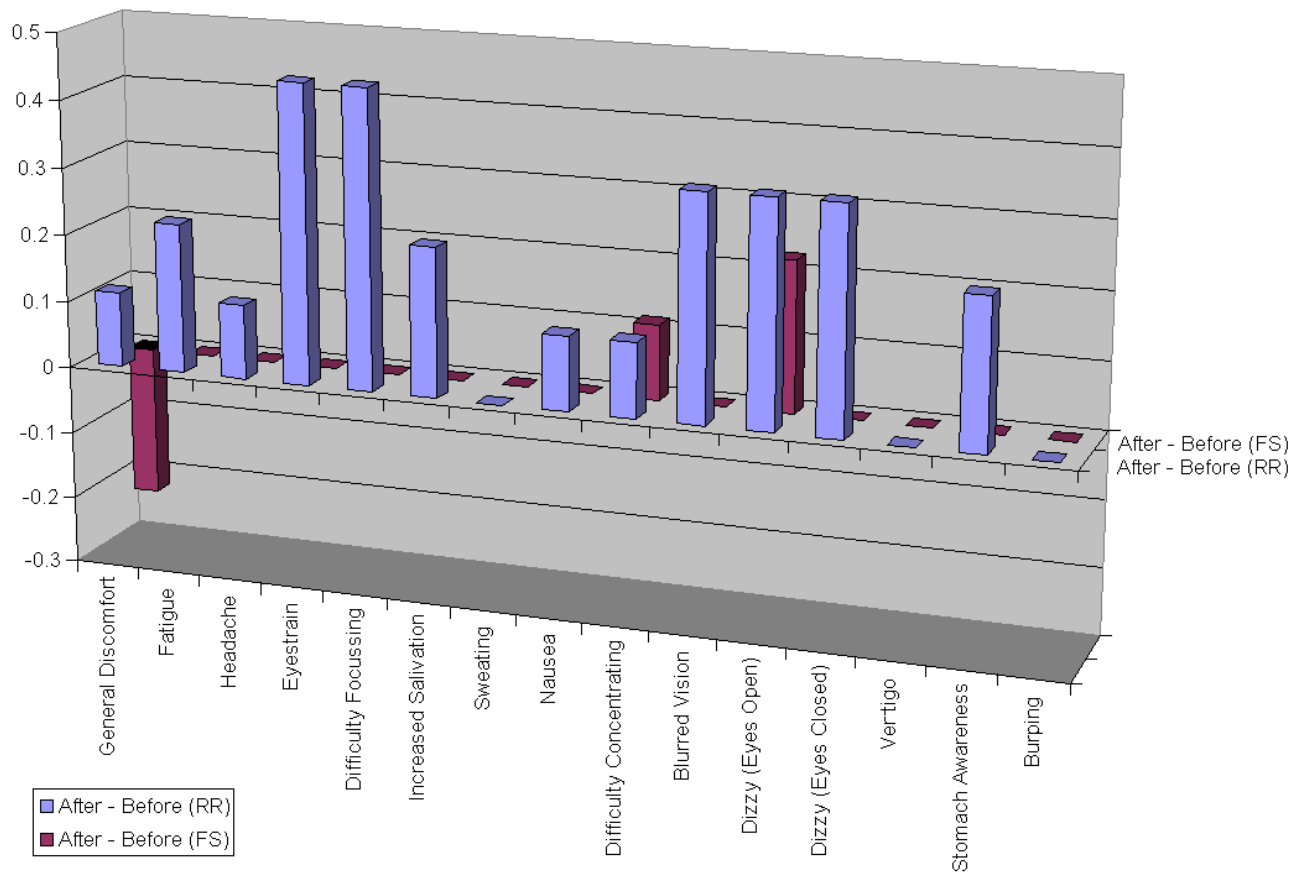


Figure 5.8: Changes in mean reported cybersickness for the two conditions.

The before and after ratings for each condition are then analysed separately using ANOVA. Neither condition showed a significant effect. Performing ANOVA tests on all four groups (flat shaded before, flat shaded after, radiosity rendered before, radiosity rendered after) revealed significant effects in the radiosity rendered group for blurred vision ($F=4.226$, $p < 0.05$) and eyestrain ($F=2.977$, $p < 0.05$). A tendency towards significance, again for the radiosity rendered condition was revealed for difficulty focussing ($F=2.885$, $p=0.51$) and dizzy (eyes closed) ($F=2.493$, $p=0.078$). However, the values of the means were minimal, which is a common result due to the short exposure time, and are not considered significant.

5.3.5 Navigation Monitoring

Log files were produced for each participant, and the average time spent in each room calculated for each group. This is performed as an additional check for homogeneity

between the two groups. The mean time spent in each room for each group is shown in figure 5.9 below.

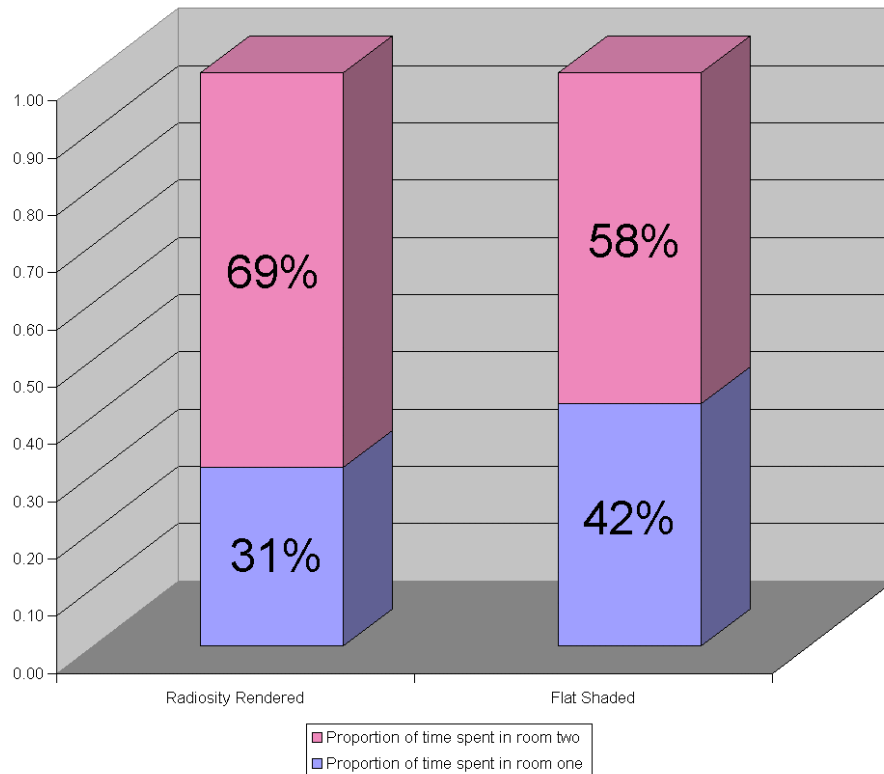


Figure 5.9: Distribution of time spent in each room for the two conditions.

5.3.6 Qualitative Analysis of Participants Comments

The experiment's participants highlighted several diminishing factors:

- Field of view was too narrow
- The right hand lens image deteriorated
- The navigation was too 'jerky'
- The HMD cord restricted movement

Some participants interrupted their experiences by asking if the door in room 2 could be opened. It is recommended that doors are not modelled in subsequent research. Should, for reasons of realism, it be deemed desirable to include a door, a simple 'no exit' sign may prove advantageous.

5.4 Summary

The results of the spatial memory test were first checked for between group's variations using ANOVA to ensure homogeneity of results. Prior probabilities were then calculated for the results, and correlation analysis revealed effects for the remember response in the radiosity rendered condition, and the know response in the flat shaded condition. The prior probabilities were then subjected to ANOVA tests revealing a significant higher proportion of correct remember responses associated with the flat shaded condition. The subjective responses to lighting conditions questionnaire was employed as a check that the lighting impressions between the two groups did not vary to any significant degree. Analysis of the results using ANOVA did not reveal any significant effects. For the presence questionnaire results, ANOVA revealed a significant effect for two questions, but due to the nature of the questions, this is not considered a significant result. Analysis of the SSQ questionnaires revealed a significant effect towards more reported symptoms of cyber sickness for the radiosity rendered condition, particularly for the categories of blurred vision and eyestrain. The participants exposed to the radiosity rendered VE also showed a tendency towards significance for the difficulty focussing and dizzy with eyes closed symptoms. On average, most participants in both groups were found to favour spending time in room two.

Chapter 6: Conclusions and Future Work

The aim of this thesis was to further investigate the applicability of the metric based on human judgements of memory awareness states to the measurement of differences in cognitive strategies employed during completion of a spatial memory awareness task across VEs of varied rendering quality. The metric has been shown to identify differences in cognitive strategies employed during memory retrieval where traditional simulation fidelity metric failed to reveal any.

The metric was first described in [Mania 2001]. The original experiment presented a metric, based on human judgements of spatial memory awareness states for assessing the simulation fidelity of a VE implementation in relation to its real scene counterpart. This thesis forms an adaptation of this framework, where the simulation fidelity of two VEs of differing rendering quality are compared, thus increasing the validity of the use of this metric for the appraisal of differing rendering qualities for simulation and training in VEs.

6.1 *Experimental Results*

In the main experiment, spatial memory awareness states were compared between a realistic, radiosity rendered VE and a simple, flat shaded version. In addition to the memory recall task, participants were required to differentiate between retrieval processes by selecting between four choices of possible awareness states ('remember', 'know', 'familiar' and 'guess'). The option chosen depends on the level of mental imagery involved during retrieval, the familiarity of the recollection and also includes guesses, even if they are informed. The underlying psychological rationale to these options is presented in chapter 3. Presence questionnaires were also administered to illustrate the point that self-report measures of this kind will not reveal differences where the simulation fidelity metric based on human judgements of memory awareness states will. Thus, the extent to which judgements of human memory recall, memory awareness states and presence in the physical and VE are similar provides a fidelity metric of the simulation in question [Wooldridge, 2003].

6.1.1 Pilot Study

The pilot study proved a useful tool in the establishment of experimental variables, namely the number of objects the participants are asked to remember and the exposure time for the simulation. The pilot study also highlighted necessary changes to the experimental procedure, especially with regard clarity of instructions given to participants.

6.1.2 Spatial Memory Awareness Test

The scores for accurate memory recall across the two conditions did not reveal a significant effect across conditions, thus establishing homogeneity of the results. This result is not a surprise, as it was expected that task performance based measures would not identify differences between the two conditions. The prior probabilities for the awareness states indicated a bias towards the remember state by participants in the flat shaded condition. Further analysis of the prior probabilities using ANOVA across conditions revealed a significant effect for the remember state for the flat shaded condition. These results are in keeping with previous studies [Mania, 2001], where the remember condition was found to be associated with less naturalistic interfaces.

The positive correlation of mean confidence with memory performance scores and prior probabilities for the remember response and for the radiosity rendered condition indicates that participants had more confidence in their correct answers when making recollections involving mental imagery under the radiosity rendered condition. Conversely, the confidence scores correlated with the prior probabilities and memory performance scores for the know response in the flat shaded condition indicates that participants in the flat shaded condition had a high level of confidence in their correct answers when using implicit memory retrieval, although interestingly, the flat shaded environment provoked more correct explicit recollections.

6.1.3 Subjective Responses to Lighting Conditions

Further support for the homogeneity of the two groups was provided by the results from the subjective responses to lighting conditions questionnaire. Although the distribution of means differences of scores between the groups showed some variation, analysis by ANOVA did not identify any significant effects.

6.1.4 Presence and SSQ

Analysis by ANOVA of the results for the presence questionnaire failed to reveal any significant discrepancies between the two groups, thus adding impetus to the growing body of evidence that a simulation fidelity metric based on human judgements of memory awareness states will expose differences where traditional simulation fidelity metrics fail to reveal any.

The deteriorated image in one lens of the HMD may have caused the oculomotor disturbances reported in the SSQ questionnaires.

6.2 Future work

6.2.1 Computer Graphics Rendering System

The computer graphics generation software used for this experiment did not make full utilisation of the hardware provided. The polygon limit imposed by WorldUp (50,000) is hugely restricting. The frame rates achieved by WorldUp do not compare well with graphics hardware benchmarks performed on the same system.

The display of radiosity rendered solutions is best implemented using Vertex Shaders. With the advent of DirectX 8.0 and the OpenGL Vertex Programs, vertex shaders now the form *de facto* advanced lighting method. Vertex shaders provide significantly more realism due to their dynamic nature. It is expected that a far more realistic VE could be produced using more modern, games orientated technology. It is also a point of note that these superior technologies are available freely e.g. the Half-Life II game engine, due for release on open source Autumn 2003.

6.2.2 Experiment Design

The overall average scores for the spatial memory task was 9.3, indicating that a longer exposure time may have been appropriate. Two of the questionnaires employed have a section for further comments, where only one is required.

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Appendix A: Experimental procedure

- 1) Reset simulation
- 2) Measure IPD
- 3) Write participants details (Name, IPD, date, time, VE rendering quality) on form
- 4) Give SSQ questionnaire. (note number, type, when given, where given)
- 5) Read subject instructions, confirm they understand. Check uncorrected vision is corrected.
- 6) Enter IPD and set simulation viewpoint to point at ceiling (to avoid overexposure)
- 7) Fit subject with HMD and navigation box
- 8) Dim lights
- 9) Ask user to look ahead, with eyes level. Synchronise viewpoint.
- 10) Start simulation (run, press S)
- 12) Take participant to nearby room
- 13) Give Plan view, Memory test, Presence questionnaire, SSQ questionnaire and Subjective responses to lighting questionnaire.

Subject instructions:

There are two interconnected rooms in the virtual environment. I am going to leave you for two minutes to view the rooms. You can move around the space freely using the navigation box provided. I would like you to look around as much as you can for this time. Please, be observant of the layout of the room and the symmetry and positioning of all of the blue objects you are going to see scattered around.

When the specified time has passed you are going to be asked to complete certain questionnaires on positioning and symmetries of the different object categories you are going to see. The entire process should take no more than twenty minutes. So, please, be observant of the layout of the room and of all the objects in it.

Appendix B: The Model



Flat Shaded version (top) Radiosity Rendered Version (bottom)



Appendix C: WorldUp BasicScript Code

C.1 Main Script (Attached to Viewpoint)

```
public lastPosition as vect3d
public lastFrameTimeStamp as double
public startTime as double
public timeRoomOne as double 'measured in frames, not seconds
public timeRoomTwo as double
public timeTotal as double
public simRunning as single

Begin Dialog UserDialog ,,176,90,"Welcome"
    OKButton 132,56,40,14
    TextBox 8,56,104,16,.TextBox1,,"Arial",12
    Text 24,36,88,12,"User Name",.Text1,"Arial",12,ebBold
    Text 8,20,108,12,"Please Enter Your",.Text2,"Arial",12,ebBold
End Dialog

sub task(vp as viewpoint)

    dim key as string ' user input key
    dim steps as single ' size of movement increments
    dim tra as vect3d ' our vector to add to the viewpint position
    dim pos as vect3d ' viewpoint position
    dim frameDuration as double
    dim ouch as sound ' audio feedback
    dim tada as sound
    dim DLG as UserDialog
    dim FileName as string

    'rayintersect vars
    dim rayOrigin as vect3d
    dim rayDirection as vect3d
    dim polygonHit as long
    dim searchNode as root
    dim geometryHit as geometry
    dim distance as single

    vp.getPosition lastPosition
    steps = 0.2
    'set inter = GetInterSense("InterSense-1")
    key = getkey()

    if key = "s" and simRunning = 0 then

        Dialog DLG
        FileName = "C:\Results\" + DLG.TextBox1 + ".txt"
        Open FileName For Output as #1
        Write #1,DLG.TextBox1
        timeRoomOne = 0
        timeRoomTwo = 0
```

```
        timeTotal = 0
        simRunning = 1
        startTime = Timer
    end if

    if key <> "" = true then

        select case key

            ' go forwards
            case "8"
                tra.z = tra.z + steps

            ' go backwards
            case "3"
                tra.z = tra.z - steps

            ' go home
            case "h"
                dim uniMatrixZero as vect3d
                dim deadAhead as vect3d
                dim wayForward as orientation

                uniMatrixZero.x = 0
                uniMatrixZero.y = -1.65
                uniMatrixZero.z = 0

                deadAhead.x = 0
                deadAhead.y = 0
                deadAhead.z = 1

                wayForward.x = 0
                wayForward.y = 0
                wayForward.z = 0
                wayForward.w = 1

                vp.setPosition uniMatrixZero
                vp.setOrientation wayForward
                vp.setDirection deadAhead

        end select

    end if

    ' move our viewpoint and constrain in y plane
    vp.translate tra,LocalFrame
    vp.getPosition pos
    pos.y = -1.55
    vp.setPosition pos

    ' now check for collisions using rayintersect (assumes no collision @ start)
    vp.getPosition rayOrigin          ' use view position as ray origin
    vp.getDirection rayDirection      ' use view direction as ray direction
    vect3dNorm rayDirection           ' normalise the vector
    set searchNode = getFirstRoot()   ' set rayintersect to whole scene

    polygonHit = rayIntersect(searchNode, rayOrigin, rayDirection, _
                               geometryHit, distance)
```

```
' collide movable using rayintersect result
if polygonHit <> 0 and distance < 0.2 then
    'message "Geometry hit: " + geometryHit.name
    set ouch = getSound("oww")
    ouch.play
    vp.setPosition lastPosition
end if

' limit exposure to 120 seconds
if Timer - startTime > 120 and simRunning > 0 then
    set tada = getSound("tad")
    tada.play
    message "Time up!"
    message "Room 1: " &timeRoomOne
    message "Room 2: " &timeRoomTwo
    message "Total : " &timeTotal
    Print #1,"Time room 1 = ",timeRoomOne
    Print #1,"Time room 2 = ",timeRoomTwo
    Print #1,"Total time = ",timeTotal
    simRunning = 0
    Close #1
end if

' clamp fps
frameDuration = Timer - lastFrameTimeStamp
if frameDuration < 0.5 then
    sleep (0.035 - frameDuration) * 1000
end if
lastFrameTimeStamp = Timer

' log frame info
if polygonHit <> 0 and simRunning > 0 then

    if rayOrigin.z > 0 then
        timeRoomOne = timeRoomOne + 1
        timeTotal = timeTotal + 1
        Print #1,int(timeTotal),"room 1",geometryHit.name
    end if

    if rayOrigin.z <= 0 then
        timeRoomTwo = timeRoomTwo + 1
        timeTotal = timeTotal + 1
        Print #1,int(timeTotal),"room 2",geometryHit.name
    end if

    message "Geometry: " + geometryHit.name

end if

end sub
```

C.2 Reset Simulation Script. Attached to User Defined Button

```
public timeRoomOne as double
public timeRoomTwo as double
public timeTotal as double
public simRunning as single

sub main()

    dim vp as viewpoint
    dim uniMatrixZero as vect3d
    dim deadAhead as vect3d
    dim wayForward as orientation

    set vp = getViewPoint("ViewPoint-1")

    uniMatrixZero.x = 0
    uniMatrixZero.y = -1.55
    uniMatrixZero.z = 0

    deadAhead.x = 0
    deadAhead.y = 0
    deadAhead.z = 1

    wayForward.x = 0
    wayForward.y = 0
    wayForward.z = 0
    wayForward.w = 1

    vp.setPosition uniMatrixZero
    vp.setOrientation wayForward
    vp.setDirection deadAhead

    simRunning = 0
    timeRoomOne = 0
    timeRoomTwo = 0
    timeTotal = 0

end sub
```

Appendix D: Materials Pack

D.1 Spatial Memory Awareness States Questionnaire

Instructions

This is an example:

Object location number: 1 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Please, select **one** answer and put a cross in the box next to that answer. (see above)

Next **indicate how confident you are** that your answer is CORRECT by placing a cross in one of the confidence boxes. (see above)

It is very important that you respond accurately. Your awareness could be:

- 1) **REMEMBER** means that you can visualise clearly the object in the room in your head, in that particular location. You virtually 'see' elements of the rooms in your mind.
- 2) **KNOW** means that you just 'know' the correct answer and the alternative you have selected just 'stood out' from the choices available. In this case you can't visualise the specific image or information in your mind.
- 3) **FAMILIAR** means that you did not remember a specific instance, nor do you know the answer. It may seem or feel more familiar than an of the other alternatives.
- 4) **GUESS** means that you may not have remembered, known, or felt that the choice you selected have been familiar. You may have made a guess, possible an informed guess, e.g. you have selected the one that looks least unlikely.

Please check **ONE** of the boxes for **Remember, Know, Familiar or Guess**

Object location number: 1 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 2 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 3 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 4 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 5 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 6 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 7 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 8 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 9 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 10 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 11 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 12 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 13 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 14 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 15 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 16 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 17 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 18 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 19 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

Awareness Remember Know Familiar Guess

Object location number: 20 Box Sphere Pyramid

Confidence No conf. Low conf. Moderate conf. Confident Certain

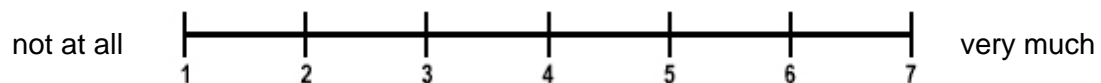
Awareness Remember Know Familiar Guess

D.2 Presence Questionnaire

Instructions

The following questions relate to your experience. Please circle the appropriate step on the scale from 1 to 7, for each question. In this questionnaire, there are 15 questions of the following form:

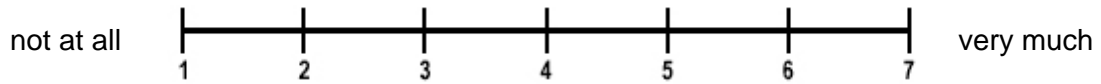
Please rate how thirsty you are feeling at the moment



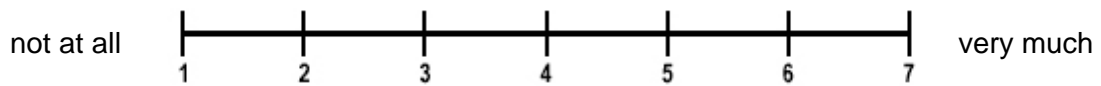
The mark close to 'very much' indicates that you are quite thirsty indeed.

Questions

1 Please rate the extent to which you were aware of background sounds in the room in which this experience was actually taking place. Rate this on the following scale from 1 to 7 (where for example 1 means that you were hardly aware at all of a any background sounds).



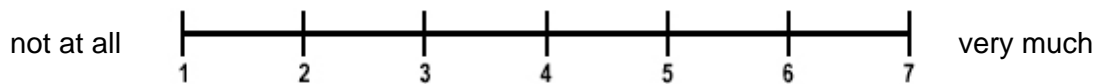
2 How dizzy, sick or nauseous did you feel resulting from the experience, if at all? Please, answer on the following 1 to 7 scale.



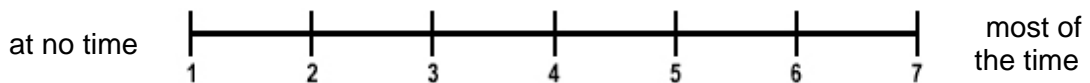
3 Gender

- Male
- Female

4 Please rate your sense of being in the virtual reality rooms, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place.



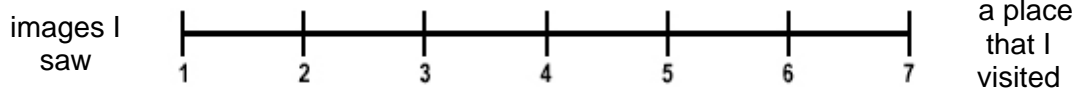
5 To what extent were there times during the experience when the virtual reality rooms were the reality for you?



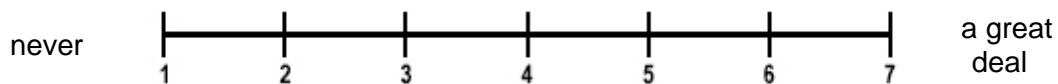
6 Status

- Undergraduate student
- Masters student
- PhD student
- Research Assistant/Fellow
- Staff member / Technical staff
- Faculty
- Other (please specify)

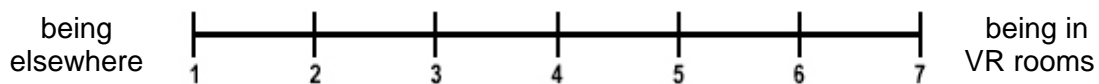
7 When you think back about your experience, do you think of the virtual reality rooms more as images that you saw, or more as somewhere that you visited?



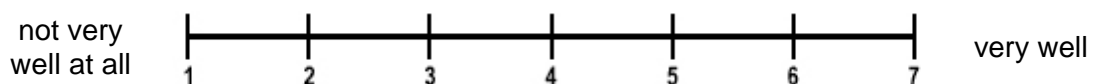
8 Have you ever experienced virtual reality / 3D applications / games?



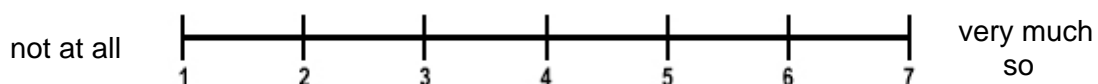
9 During the time of the experience, which was the strongest on the whole, your sense of being in the virtual reality rooms, or of being elsewhere?



10 Overall, how well do you think that you achieved the experimental task?



11 Consider your memory of attending the seminar. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By structure of memory consider things like the extent to which you have a visual memory of the field, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.



12 To what extent do you use a computer in your daily activities?

not at all 1 2 3 4 5 6 7 very much
so

13 During the time of the experience, did you often think to yourself that you were actually in the virtual reality rooms?

not very often 1 2 3 4 5 6 7 very often

14 Were you involved in the experimental task to the extent that you lost track of time?

not at all 1 2 3 4 5 6 7 very much
so

15 Further comments

Please write down any further comments that you wish to make about your experience. What things helped to give you a sense of 'really being' in the space, and what things acted to 'pull you out' of this?

Thank you very much for participating in this study. All the answers will be treated entirely confidentially.

D.3 Subjective Responses to Lighting Conditions

Questionnaire

Name:.....

Instructions

The following questions relate to your impression of the 3D rooms. Please, circle the most appropriate step on the scale from 1 to 7, for each question.

spacious	1	2	3	4	5	6	7	confined
relaxing	1	2	3	4	5	6	7	tense
bright	1	2	3	4	5	6	7	dim
stimulating	1	2	3	4	5	6	7	subduing
dramatic	1	2	3	4	5	6	7	serene
uniform	1	2	3	4	5	6	7	non-uniform
interesting	1	2	3	4	5	6	7	uninteresting
radiant	1	2	3	4	5	6	7	gloomy
large	1	2	3	4	5	6	7	small
like	1	2	3	4	5	6	7	dislike
simple	1	2	3	4	5	6	7	complex
uncluttered	1	2	3	4	5	6	7	cluttered
warm	1	2	3	4	5	6	7	uncomfortable
pleasant	1	2	3	4	5	6	7	unpleasant
comfortable	1	2	3	4	5	6	7	cold

Further comments

Please write down any further general comments that you wish to make about your experience. For example, what things helped to give you a sense of 'really being' in the room, and what things acted to 'pull you out' of this?

Thank you very much for participating in this study. All the answers will be treated entirely confidentially.

D.4 Simulator Sickness Questionnaire (SSQ)

Name:.....

IPD.....

Date.....

Time.....

Instructions

Please, circle the most appropriate term to describe your physical state, for each symptom.

General Discomfort:	none	slight	moderate	severe
Fatigue:	none	slight	moderate	severe
Headache:	none	slight	moderate	severe
Eyestrain:	none	slight	moderate	severe
Difficulty Focusing:	none	slight	moderate	severe
Increased Salivation:	none	slight	moderate	severe
Sweating:	none	slight	moderate	severe
Nausea:	none	slight	moderate	severe
Difficulty Concentrating:	none	slight	moderate	severe
Blurred Vision:	none	slight	moderate	severe
Dizzy (Eyes open)	none	slight	moderate	severe
Dizzy (Eyes closed)	none	slight	moderate	severe
Vertigo	none	slight	moderate	severe
Stomach Awareness	none	slight	moderate	severe
Burping	none	slight	moderate	severe